JOURNAL OF MANAGEMENT AND BUSINESS SOLUTIONS

Examining the Lean Production Process in Industry 4.0

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ABSTRACT

The purpose of the present article is to examine the lean production process in Industry 4.0. In terms of its objective, the research is applied, and in terms of data collection, it adopts a mixed-methods (qualitative–quantitative) approach. The statistical population in the qualitative phase consisted of university faculty members, experts in the fields of technology and production, and senior research and development managers in the dairy industry, from whom 10 participants were selected using purposive sampling. The quantitative phase of the study included all managers and employees working in the production and information technology departments of dairy manufacturing companies in Tehran, from whom 361 respondents were selected as the sample using stratified random sampling. Data collection instruments included interviews in the qualitative phase and a researcher-developed questionnaire in the quantitative phase. The face and content validity of the questionnaire were confirmed by several experts, convergent validity was assessed by calculating the Average Variance Extracted (AVE), and discriminant validity was confirmed by calculating the square root of AVE. The reliability of the questionnaire, assessed using Cronbach's alpha, was 0.86 for the entire instrument. Data analysis was conducted using Cronbach's alpha, the Kolmogorov–Smirnov test, and confirmatory factor analysis. Among the 29 indicators (items), five main components were identified. The results showed that the primary dimensions of the lean production process in Industry 4.0, in order of importance, include lean quality management, smart supply chain, lean process management, smart customer orientation, and smart human resources. In addition, the model fit was also examined.

Keywords: lean production, production process, smartness, dairy industry, Industry 4.0.

Introduction

Over the past decade, manufacturing systems have undergone profound transformations driven by rapid technological advancements, intensified global competition, and rising expectations for efficiency, flexibility, sustainability, and resilience. Among the most influential paradigms shaping this transformation are lean production and Industry 4.0. Lean production, rooted in the elimination of waste and the continuous improvement of value-creating processes, has long been regarded as a cornerstone of operational excellence. Industry 4.0, by contrast, represents a digitally driven industrial paradigm characterized by cyber–physical systems, the Internet of Things (IoT), advanced data analytics, artificial intelligence, and intelligent automation. While each paradigm has independently demonstrated significant benefits, contemporary research increasingly emphasizes their interaction, integration, and mutual reinforcement in modern manufacturing environments (1, 2).

Article history:
Received 12 November 2025
Revised 01 February 2026
Accepted 08 February 2026
First Published 10 February 2026
Final Publication 01 September 2026

How to cite this article:
Pourtofigh, S. H., Janatifar, H., & Ameri Dehabadi, E. (2026). Examining the Lean Production Process in Industry 4.0. *Journal of Management and Business Solutions, 4*(5), 1-12. https://doi.org/10.61838/jmbs.183

Lean production emerged as a systematic response to inefficiencies embedded in traditional mass production systems, emphasizing principles such as waste elimination, flow optimization, pull-based production, standardization, and respect for people. These principles have been extensively adopted across industries due to their proven impact on cost reduction, quality improvement, and customer satisfaction. However, the growing complexity of products, shorter life cycles, volatile demand, and globalized supply chains have challenged the effectiveness of purely traditional lean tools. In this context, digital technologies associated with Industry 4.0 are increasingly viewed as enablers that can extend, reinforce, and transform lean principles rather than replace them (3, 4).

Industry 4.0 is commonly understood as the fourth industrial revolution, characterized by the integration of physical production systems with digital technologies to create smart, interconnected, and adaptive manufacturing environments. Technologies such as IoT, cloud computing, big data analytics, robotics, digital twins, and artificial intelligence enable real-time data collection, decentralized decision-making, predictive control, and enhanced system transparency. These capabilities have direct implications for lean production practices, particularly in areas such as value stream mapping, quality management, process control, customer responsiveness, and human–machine collaboration (5, 6).

A growing body of empirical and conceptual research suggests that lean production and Industry 4.0 are not competing paradigms but rather complementary approaches whose integration can generate synergistic outcomes. Mapping studies and systematic literature reviews have demonstrated that Industry 4.0 technologies can strengthen lean tools by increasing process visibility, reducing variability, enabling faster feedback loops, and supporting continuous improvement initiatives (1, 6, 7). Conversely, lean principles provide a structured managerial and cultural foundation that guides the purposeful and value-driven adoption of digital technologies, preventing technology-driven waste and misalignment (8, 9).

Despite this growing consensus, the integration of lean production and Industry 4.0 remains complex and context-dependent. Empirical studies highlight that digital technologies do not automatically enhance lean performance and may even introduce new forms of waste if implemented without a clear understanding of lean objectives. Tensions may arise between standardization and flexibility, automation and human involvement, or data abundance and decision-making clarity. These dialectical tensions underscore the need for nuanced frameworks that conceptualize lean production development within Industry 4.0 rather than treating technology adoption as a purely technical exercise (2, 9).

Research focusing on the operational dimensions of lean production under Industry 4.0 has identified several critical domains. Quality management has been one of the most frequently examined areas, with studies demonstrating how digital monitoring, predictive analytics, and smart sensors can enhance defect prevention, root cause analysis, and continuous improvement initiatives. The concept of Quality 4.0 explicitly reflects this convergence, emphasizing data-driven quality assurance and intelligent feedback systems (3, 10). Similarly, process management benefits from digitalization through real-time process control, automated value stream mapping, and adaptive scheduling, enabling faster response to disturbances and customer demand variability (5, 11).

Supply chain integration represents another critical dimension of lean production development in Industry 4.0. Smart supply chains leverage digital connectivity, real-time information sharing, and predictive analytics to reduce lead times, improve coordination among partners, and enhance responsiveness across the value network. Empirical studies indicate that Industry 4.0 technologies can significantly strengthen lean supply chain practices by supporting just-in-time delivery, inventory optimization, and synchronized planning across organizational boundaries (11, 12). These capabilities are particularly relevant in industries characterized by perishability, high demand uncertainty, and strict quality requirements, such as the food and dairy sectors.

Customer orientation, a core principle of lean production, is also transformed under Industry 4.0 conditions. Digital platforms, data analytics, and intelligent interfaces enable manufacturers to capture real-time customer feedback, anticipate future demand, and customize products and services more effectively. Relational and data-driven marketing models increasingly align with lean objectives by ensuring that production activities are tightly coupled with actual customer value rather than forecast-based assumptions (12, 13). This shift from reactive to proactive customer orientation reinforces the strategic role of lean production in competitive manufacturing environments.

Human resources and organizational capabilities constitute another essential pillar of lean production development in Industry 4.0. Contrary to early concerns that digitalization would marginalize human labor, recent research emphasizes the growing importance of skilled, adaptable, and digitally competent employees. Smart manufacturing environments require workers who can interact with advanced technologies, interpret data, and engage in continuous improvement activities. Human–machine collaboration, decision-support systems, and intelligent training platforms redefine the role of human resources within lean systems, making organizational learning and capability development central to sustainable performance (14, 15).

At the strategic level, several studies have proposed readiness assessment models and roadmaps to guide organizations in aligning lean production with Industry 4.0 initiatives. These models emphasize the importance of evaluating technological, organizational, cultural, and infrastructural dimensions before large-scale implementation. Readiness frameworks highlight that successful integration depends not only on technology availability but also on leadership commitment, process maturity, data governance, and alignment with strategic objectives (16, 17). Without such alignment, organizations risk fragmented investments and suboptimal outcomes.

In emerging economies, the integration of lean production and Industry 4.0 presents both opportunities and challenges. Comparative studies show that manufacturers in developing contexts often face constraints related to infrastructure, skills, investment capacity, and regulatory environments, which influence the pace and form of digital transformation. At the same time, these contexts offer significant potential for leapfrogging through targeted adoption of smart technologies aligned with lean priorities (2, 14). National and sector-specific studies further illustrate how contextual factors shape integration pathways in industries such as energy, aviation, textiles, and food processing (18-20).

The food and dairy industries, in particular, provide a compelling context for examining the development of lean production processes under Industry 4.0. These industries operate under strict quality and safety standards, face high demand variability, and manage time-sensitive supply chains. Digital technologies such as IoT-enabled cold chains, real-time quality monitoring, and intelligent logistics systems have been shown to enhance lean performance by reducing waste, improving traceability, and ensuring customer satisfaction (11, 20). However, empirical research that systematically identifies and validates the dimensions and components of lean production development in Industry 4.0 within this context remains limited.

Although prior studies have examined specific tools, technologies, or relationships between lean and Industry 4.0, several gaps persist in the literature. First, many studies adopt a fragmented perspective, focusing on isolated practices rather than a holistic process-oriented framework. Second, there is limited empirical validation of integrated models that capture both managerial and technological dimensions of lean production development. Third, sector-specific and region-specific analyses, particularly in developing and transitional economies, remain underrepresented. Addressing these gaps requires mixed-method approaches that combine expert knowledge, qualitative insights, and quantitative validation (7, 21).

Recent contributions have called for more integrative and theory-informed approaches that conceptualize lean production development in Industry 4.0 as a dynamic, multi-dimensional process. Such approaches recognize the interdependence of quality management, process management, supply chain integration, customer orientation, and human resources within digitally enabled production systems. They also emphasize the need to move beyond descriptive analyses toward validated measurement models that can inform managerial decision-making and policy development (9, 15).

In response to these theoretical and empirical challenges, the present study seeks to contribute to the literature by systematically identifying, structuring, and validating the dimensions and components of lean production process development within the context of Industry 4.0, drawing on expert insights and empirical evidence from manufacturing organizations, with the aim of proposing and validating a comprehensive model of lean production development in Industry 4.0.

Methods and Materials

Given that the present study examines the dimensions and components of the development of the lean production process in Industry 4.0, the research method is applied in terms of purpose, mixed-methods (qualitative–quantitative) in terms of data type, and descriptive–correlational in terms of data collection method, nature, and overall research design.

The statistical population consisted of university faculty members, experts in the fields of technology and production, and senior research and development managers in the dairy industry in the qualitative phase, as well as all managers and employees working in the production and information technology departments of dairy manufacturing companies in Tehran in the quantitative phase. The sample size in the qualitative phase was determined based on theoretical saturation (10 participants) using purposive sampling, and in the quantitative phase, 361 participants were selected using stratified random sampling. Data collection instruments included semi-structured interviews in the qualitative phase and a researcher-developed questionnaire in the quantitative phase.

"Qualitative data analysis was conducted based on document analysis and semi-structured interviews using the grounded theory approach. Data collection instruments included interviews in the qualitative phase and a researcher-developed questionnaire based on a five-point scale in the quantitative phase. The face and content validity of the questionnaire were confirmed by several experts, convergent validity was assessed by calculating the Average Variance Extracted (AVE), and discriminant validity was confirmed by calculating the square root of AVE. The reliability of the questionnaire, assessed using Cronbach's alpha, was 0.968 for the entire instrument. Data analysis was performed using Cronbach's alpha, Average Variance Extracted (AVE), the square root of the AVE matrix, the Kolmogorov–Smirnov test, and confirmatory factor analysis using PLS software."

Based on the obtained data, the reliability of the dimensions was confirmed, as Cronbach's alpha and composite reliability coefficients were greater than 0.70, and AVE values exceeded 0.50. Convergent validity was also confirmed because CR > 0.70, CR > AVE, and AVE > 0.50. Discriminant validity was confirmed as well, given that MSV < AVE and ASV < AVE.

Findings and Results

In the quantitative phase of this study, 27% of the respondents were female and 63% were male. In terms of educational level, 67% held a bachelor's degree, 18% a master's degree, and 15% a doctoral degree. In addition, 40% of the respondents were employees, 20% were senior managers, 10% were middle managers, and 30% were first-line managers in the food industry.

"In identifying the dimensions and components of the lean production process in Industry 4.0, interviews were conducted with 10 experts, and the interviews were analyzed using MAXQDA software, which is a professional tool for analyzing data collected through qualitative and mixed-methods approaches. Following open, selective, and axial coding, the components were identified." The results of the factor analysis indicated that, after content analysis and expert interviews, the dimensions and components of the development of the lean production process in Industry 4.0 are as follows.

Table 1. Dimensions and Components of the Development of the Lean Production Process in Industry 4.0 Based on Expert Opinions

Component	Indicator
Lean Quality Management	Creating a culture of improvement through organizational intelligence
	Using smart methods to reduce production process errors
	Planning to reduce waste through intelligence
	Identifying existing waste in the production process
Smart Customer Orientation	Dependence of production speed on customer demand through smart equipment
	Communicating current and future customer demand between the marketing unit and the production unit to align equipment and enhance intelligence
	Customer feedback on product quality
	Customer visits to the smart production unit
Lean Process Management	Enhancing cooperation and communication among departments, suppliers, and customers through the horizontal integration of processes
	Shortening the production process using smart equipment to respond rapidly to customers
	Statistical control of processes and equipment
	Reconsideration of job tasks
	Implementation of lean and smart engineering
Smart Supply Chain	Capability for bidirectional communication is essential in Industry 4.0
	Appropriate responsiveness across the supply chain by all members
	Precise evaluation of communication performance among supply components
	Determination of safety stock to prevent shortages in the chain
	Capability for online responsiveness to resolve potential errors
	Online collection of customer perspectives
	Meeting customer expectations throughout the chain from supplier to final consumer
	Ease of use for system users
Smart Human Resources	Adaptation of robots to the work environment to improve productivity in this industry
	High decision-making capability in robots
	Flexibility in smart control requiring effective robot control
	Speed of user interaction with the work environment using Industry 4.0 technologies
	Efficiency in the performance of remote systems
	Accuracy of reports as a fundamental issue among smart employees
	Warning employees about potential errors and preventing error occurrence
	Intelligent correction of potential errors and provision of suggestions to remove work-related obstacles

The dimensions and components of the development of the lean production process in Industry 4.0 are measured using 29 items. First, an exploratory factor analysis was conducted on the core category.

The standardized parameter estimates shown in the figure below indicate that all indicators are statistically significant and that their factor loadings are at a high level. Examination of the goodness-of-fit indices indicates an acceptable fit of the model.

Table 2. Confirmed Items of the Dimensions and Components of the Development of the Lean Production Process in Industry 4.0

Component	Item	Item Label	Factor Loadings	t-value	Item Status	Indicator Ranking
Lean Quality Management	Question 1	Q1	0.761	22.089	Confirmed	2
	Question 2	Q2	0.836	30.820	Confirmed	3
	Question 3	Q3	0.899	72.997	Confirmed	1
	Question 4	Q4	0.823	32.072	Confirmed	4
Smart Customer Orientation	Question 5	Q5	0.783	21.506	Confirmed	2
	Question 6	Q6	0.858	38.691	Confirmed	3
	Question 7	Q7	0.885	50.621	Confirmed	1
	Question 8	Q8	0.845	33.336	Confirmed	4
Lean Process Management	Question 9	Q9	0.834	35.536	Confirmed	2
	Question 10	Q10	0.813	28.764	Confirmed	3
	Question 11	Q11	0.684	12.453	Confirmed	5
	Question 12	Q12	0.810	27.362	Confirmed	4
	Question 13	Q13	0.836	38.348	Confirmed	1
Smart Supply Chain	Question 14	Q14	0.731	19.606	Confirmed	8
	Question 15	Q15	0.858	43.281	Confirmed	1
	Question 16	Q16	0.830	33.542	Confirmed	4
	Question 17	Q17	0.850	42.382	Confirmed	3
	Question 18	Q18	0.856	39.431	Confirmed	2
	Question 19	Q19	0.759	22.068	Confirmed	7
	Question 20	Q20	0.789	22.220	Confirmed	6
	Question 21	Q21	0.813	30.472	Confirmed	5
Smart Human Resources	Question 22	Q22	0.740	21.939	Confirmed	8
	Question 23	Q23	0.760	25.115	Confirmed	7
	Question 24	Q24	0.817	30.981	Confirmed	5
	Question 25	Q25	0.864	36.842	Confirmed	2
	Question 26	Q26	0.869	45.516	Confirmed	1
	Question 27	Q27	0.801	27.439	Confirmed	6
	Question 28	Q28	0.855	40.019	Confirmed	3
	Question 29	Q29	0.841	34.532	Confirmed	4

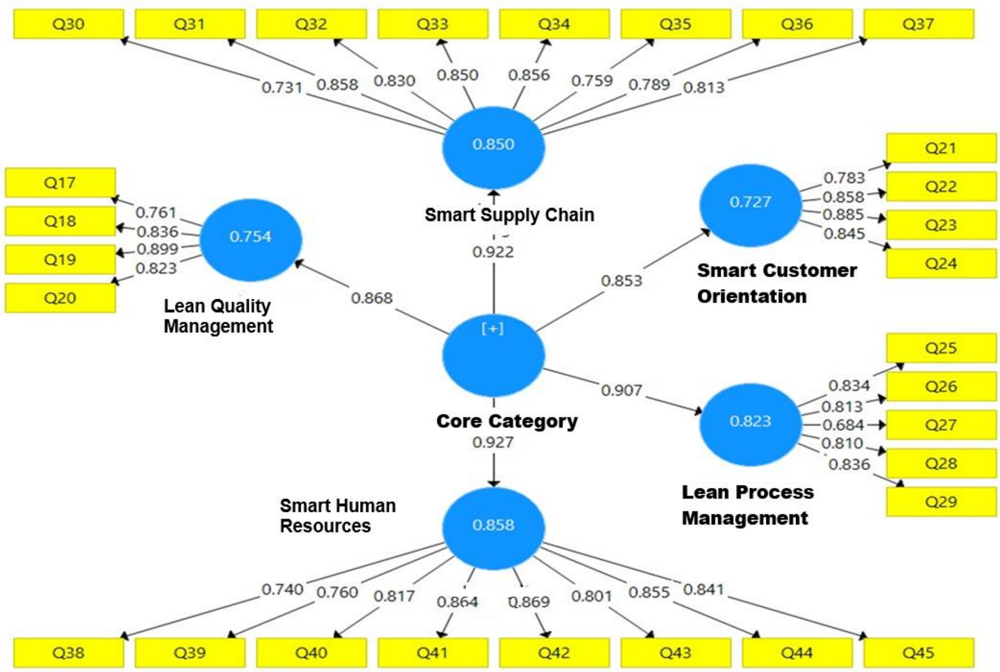

Figure 1. Model of the Components and Indicators of the Development of the Lean Production Process in Industry 4.0 in the Standardized Coefficients Mode

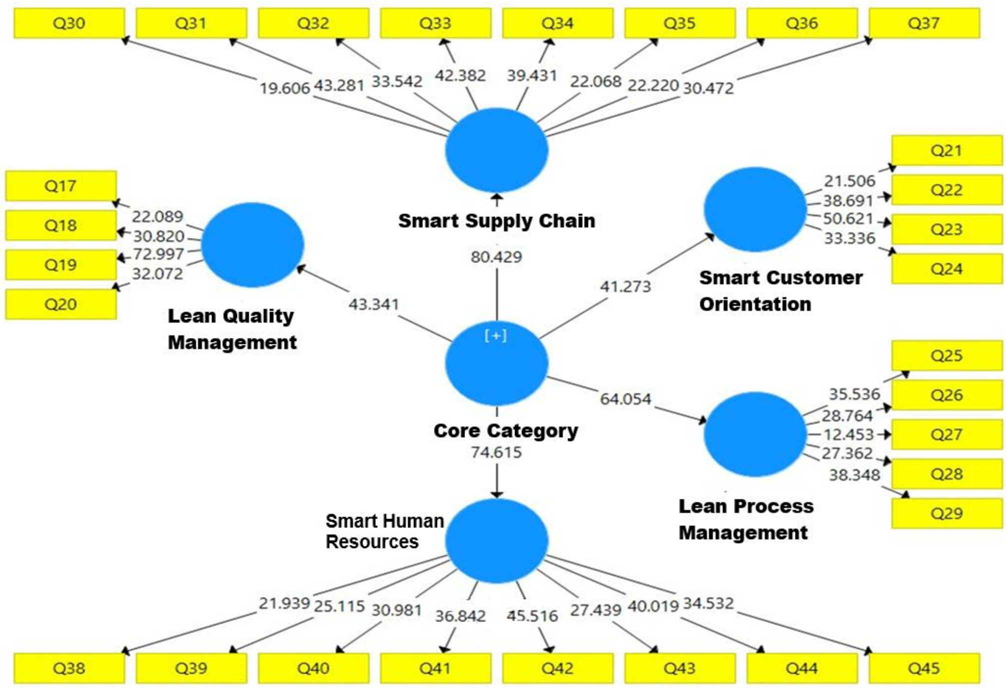

Figure 2. Model of the Components and Indicators of the Development of the Lean Production Process in Industry 4.0 in the Significance (t-value) Mode

Figure 2 presents the research model in the absolute significance (t-value) mode. According to this model, all t-statistic values are greater than 1.96. The results indicate that all factor loadings are statistically significant at the 95% confidence level.

Table 3. Validity and Reliability Indices of the Final Model of the Development of the Lean Production Process in Industry 4.0

Latent Variables	AVE	CR	R^2	Cronbach's Alpha			GOF
Lean Quality Management	0.691	0.899	0.754	0.849	0.820	0.895	0.733
Smart Customer Orientation	0.712	0.908	0.727	0.864			
Lean Process Management	0.636	0.897	0.823	0.855			
Smart Supply Chain	0.659	0.939	0.850	0.925			
Smart Human Resources	0.672	0.942	0.858	0.930			
Core Category	0.546	0.972		0.970			

Table 3 presents the validity and reliability indices for all research variables. Discriminant validity is also considered in the present study, meaning that the indicators of each construct should ultimately provide adequate differentiation in measurement relative to other constructs in the model. In simpler terms, each indicator should measure only its own construct, and their combination should be such that all constructs are clearly distinguished from one another. Using the Average Variance Extracted (AVE) index, it was found that all studied constructs have AVE values greater than 0.50. Composite reliability (CR) and Cronbach's alpha were used to assess the reliability of the questionnaire, and reliability is confirmed when these indices exceed the threshold of 0.70. All these coefficients are greater than 0.70, indicating that the measurement instrument is reliable.

The Goodness-of-Fit (GOF) index represents the compatibility between the quality of the structural model and the measurement model and is calculated as:

In this equation, the mean AVE and the mean R^2 are used. A GOF value greater than 0.40 indicates an acceptable model fit, and values exceeding 0.40 demonstrate good model fit. In simpler terms, when the GOF value is greater than 0.40, the data of this study show an appropriate fit with the factor structure and the theoretical foundation of the research, indicating alignment between the questionnaire items and the theoretical constructs.

Discussion and Conclusion

The findings of the present study provide a comprehensive and empirically validated understanding of the dimensions and components underlying the development of the lean production process in the context of Industry 4.0. The results of the confirmatory factor analysis confirmed that lean quality management, smart customer orientation, lean process management, smart supply chain, and smart human resources constitute the core dimensions of lean production development in Industry 4.0, with all associated indicators demonstrating statistically significant and strong factor loadings. This result supports the argument that lean production in the digital era is no longer limited to traditional waste elimination techniques, but rather evolves into an integrated socio-technical system in which managerial philosophies and digital technologies are tightly interwoven. This finding is consistent with prior research emphasizing that the effectiveness of Industry 4.0 initiatives depends on their alignment with lean principles and structured process thinking rather than isolated technology adoption (1, 2).

Among the identified dimensions, lean quality management emerged as one of the most influential components, indicating that quality remains the central pillar of lean production even under advanced digital conditions. The high factor loadings associated with indicators such as intelligent error reduction, waste minimization through smart systems, and the development of a culture of continuous improvement highlight the critical role of data-driven quality practices. These results align with studies suggesting that Industry 4.0 technologies significantly enhance quality management by enabling real-time monitoring, predictive quality control, and closed-loop feedback mechanisms (3, 4). The present findings further support the growing literature on Quality 4.0, which conceptualizes quality management as a digitally enabled, analytics-driven function embedded within lean production systems (10).

The strong empirical support for smart customer orientation underscores the transformation of customer-centricity in Industry 4.0-enabled lean systems. The results indicate that responsiveness to real-time customer demand, integration of marketing and production data, and systematic use of customer feedback are essential for the development of lean production processes. This finding is in line with research emphasizing that digital technologies enable a shift from forecast-driven production to demand-driven, customer-integrated value creation (12, 13). The results suggest that smart customer orientation functions as a dynamic interface between internal production processes and external market signals, reinforcing lean principles such as value definition and pull-based production in increasingly volatile markets.

Lean process management also demonstrated a substantial contribution to the overall model, reflecting the importance of digitally supported process integration, statistical control, and task redesign. Indicators related to horizontal integration across departments, suppliers, and customers, as well as the use of smart equipment to shorten production cycles, highlight the role of Industry 4.0 technologies in enhancing process flow and flexibility. These findings are consistent with prior studies showing that digital tools such as automated value stream mapping, real-time process analytics, and cyber–physical systems can significantly strengthen lean process management by reducing variability and improving coordination (5, 11). The results further reinforce the argument that lean automation, rather than automation for its own sake, is emerging as a dominant paradigm in advanced manufacturing environments (8).

The smart supply chain dimension exhibited strong empirical validity, emphasizing the expanded scope of lean production beyond the factory floor. Indicators related to bidirectional communication, online responsiveness, safety stock determination, and end-to-end customer satisfaction suggest that lean production development in Industry 4.0 requires a digitally connected and highly responsive supply network. This finding aligns with empirical evidence demonstrating that Industry 4.0 technologies enhance lean supply chain practices by enabling real-time information sharing, improved coordination, and faster response to disruptions (11, 12). The results are particularly relevant for industries characterized by time sensitivity and perishability, such as food and dairy manufacturing, where smart supply chain integration directly contributes to waste reduction and service reliability (20).

Smart human resources emerged as another critical dimension, highlighting the central role of people in digitally enabled lean systems. The confirmation of indicators related to human–robot interaction, decision-making capabilities, system usability, error prevention, and intelligent support mechanisms indicates that Industry 4.0 does not diminish the importance of human resources but rather reshapes their role. These findings are consistent with studies emphasizing that successful lean–Industry 4.0 integration depends on skilled, empowered, and adaptable employees who can effectively interact with advanced technologies and participate in continuous improvement activities (14, 15). The results challenge purely technology-centric perspectives and support socio-technical views of lean production development in the digital era.

At the model level, the strong values of composite reliability, Cronbach's alpha, and average variance extracted confirm the robustness and internal consistency of the proposed framework. The satisfactory goodness-of-fit index further indicates that the empirical data align well with the theoretical structure of lean production development in Industry 4.0. This supports previous calls for validated, multidimensional models that capture the complex interplay between technological, managerial, and human factors in digital lean transformation (7, 9). The findings extend prior empirical work by offering an integrated measurement model that moves beyond fragmented analyses of individual technologies or practices (6, 22).

From a comparative perspective, the results are consistent with studies conducted in both developed and emerging economies, which indicate that while contextual factors influence implementation pathways, the core dimensions of lean–Industry 4.0 integration remain largely consistent across settings (2, 14). At the same time, the emphasis on smart supply chains, customer orientation, and human resources reflects the specific operational and market conditions of the studied context, reinforcing arguments that sectoral and regional characteristics shape the relative importance of lean–digital dimensions (16, 17).

Overall, the discussion of results demonstrates that the development of lean production in Industry 4.0 should be understood as a holistic transformation process rather than a linear technological upgrade. The empirical evidence supports the view that digital technologies act as enablers that amplify lean principles when embedded within coherent managerial frameworks, aligned processes, and supportive organizational cultures. This finding echoes recent theoretical perspectives that frame lean–Industry 4.0 integration as a dynamic and dialectical process involving continuous alignment between efficiency, flexibility, human agency, and technological capability (9, 15).

Despite the contributions of this study, several limitations should be acknowledged. First, the empirical data were collected from a specific industrial and geographical context, which may limit the generalizability of the findings to other sectors or regions. Second, the cross-sectional design of the study restricts the ability to capture the dynamic and evolutionary nature of lean production development in Industry 4.0 over time. Third, although expert input and robust statistical techniques were employed, the study relied on perceptual measures, which may be subject to respondent bias.

Future research could extend the present work by applying the proposed model in different industrial sectors and national contexts to test its external validity and comparative robustness. Longitudinal studies could provide deeper insights into how lean production dimensions evolve as Industry 4.0 technologies mature and organizational learning progresses. Additionally, future studies may integrate objective performance indicators and advanced analytical techniques, such as system dynamics or machine learning, to further explore causal relationships among the identified dimensions.

From a practical perspective, managers and policymakers should view lean production development in Industry 4.0 as a strategic and integrated transformation rather than a set of isolated initiatives. Organizations are encouraged to align digital investments with lean priorities, strengthen human capabilities alongside technological upgrades, and foster cross-functional and supply chain collaboration. Emphasizing customer-centric data utilization, smart quality management, and continuous learning can enhance the sustainability and resilience of lean production systems in increasingly complex and digitalized manufacturing environments.

Acknowledgments

We would like to express our appreciation and gratitude to all those who helped us carrying out this study.

Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

All ethical principles were adheried in conducting and writing this article.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

Funding

This research was carried out independently with personal funding and without the financial support of any governmental or private institution or organization.

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