KMAN PUBLISHING INSTITUTE

Article history:
Received 16 November 2023
Revised 15 January 2024
Accepted 23 January 2024
Published online 01 March 2024

Journal of Resource Management and Decision Engineering

Volume 3, Issue 1, pp 72-83

Presenting a Process Model of Lean Manufacturing in Industry 4.0 Based on a Mixed-Methods Research Approach

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A r t i c l e I n f o

Article type:
Original Research

How to cite this article:
Pourtofigh, S. H., Janatifar, H., & Ameri Dehabadi, E. (2024). Presenting a Process Model of Lean Manufacturing in Industry 4.0 Based on a Mixed-Methods Research Approach. *Journal of Resource Management and Decision Engineering, 3*(1), 72-83.
https://doi.org/10.61838/kman.jrmde.3.3.10

A B S T R A C T

This study aims to present a process model of lean manufacturing in Industry 4.0 based on a mixed-methods research approach. In terms of purpose, the study is applied, and in terms of data collection, it is classified as mixed-methods research (qualitative–quantitative). The statistical population in the qualitative section included university faculty members, experts in the fields of technology and manufacturing, as well as senior managers of production and research and development in the dairy industry. In the quantitative section, the population consisted of all managers and employees of the production and information technology departments of dairy manufacturing companies in Tehran. The sample size in the qualitative section was determined based on theoretical saturation (10 participants) using purposive sampling, while in the quantitative section, a sample of 361 participants was estimated using stratified random sampling. Data collection instruments included interviews in the qualitative section and a researcher-developed questionnaire in the quantitative section. The validity and reliability of the questionnaire were confirmed. Data analysis was conducted using SmartPLS 3 software. The results led to the identification of 28 components and 112 indicators. The variables of lean quality management, smart supply chain, lean process management, smart customer orientation, and smart human resources were considered as the core categories. The variables of technical factors, environmental factors, organizational factors, and operational factors were identified as causal conditions. The variables of employee competency, employee flexibility, employee knowledge management, and employee intelligence and awareness were identified as contextual conditions. The variables of internal uncertainty and competitors were considered as intervening conditions. The variables of financing, downsizing and mergers, employee empowerment, appropriate infrastructure, and the approval and modification of regulations were identified as strategies. Finally, the variables of cost reduction, increased productivity, just-in-time production and reduced production time, quality improvement, improved operational performance, mass customization, flexibility, and increased customer satisfaction were identified as outcomes.

Keywords: *Lean manufacturing, production process, intelligence, dairy industry, Industry 4.0.*

1. Introduction

The manufacturing sector is undergoing a profound transformation driven by the convergence of lean production philosophies and the technological paradigms of Industry 4.0. Lean production, originally developed to eliminate waste, enhance value creation, and improve operational efficiency, has long been recognized as a dominant managerial and operational approach in manufacturing systems (Hopp, 2018; Kovacs, 2020). At the same time, Industry 4.0 introduces advanced digital technologies such as cyber–physical systems, artificial intelligence, the Internet of Things, big data analytics, and intelligent automation, fundamentally reshaping how production systems are designed, managed, and optimized (Moeuf et al., 2020; Silvestri et al., 2022). The interaction between these two paradigms has attracted increasing scholarly attention, as organizations seek to understand whether digitalization reinforces lean principles or, conversely, challenges their foundational assumptions.

Early studies emphasized that lean production and Industry 4.0 should not be viewed as competing logics but rather as potentially complementary approaches. Lean production focuses on process discipline, standardization, flow, and continuous improvement, while Industry 4.0 provides technological enablers that enhance transparency, responsiveness, and decision-making capabilities across the value stream (Buer et al., 2018; Rossini et al., 2019). From this perspective, digital technologies can act as catalysts that amplify lean practices by reducing variability, improving real-time control, and enabling data-driven improvement cycles (Rosin et al., 2020). However, the integration of these paradigms is not automatic and requires careful managerial alignment and systemic redesign.

Recent bibliometric and systematic reviews highlight a rapid growth in research addressing the integration of lean manufacturing and Industry 4.0, reflecting both academic interest and practical relevance (Kumar et al., 2024; Silvestri et al., 2022). These studies reveal that most existing research focuses on identifying conceptual linkages, mapping technologies to lean tools, and exploring performance outcomes. For instance, several authors have demonstrated one-to-one relationships between specific Industry 4.0 technologies—such as IoT, advanced analytics, and automation—and traditional lean techniques like value stream mapping, just-in-time production, and total quality management (Ciano et al., 2021; Wang et al., 2021). Nevertheless, the literature also indicates fragmentation, with limited consensus on how these relationships unfold as an integrated process model rather than isolated technological interventions.

A critical stream of research examines lean automation as a bridge between lean thinking and Industry 4.0. Lean automation emphasizes the selective and purposeful use of automation to support human-centered, waste-reducing processes rather than replacing them indiscriminately (Dombrowski et al., 2017; Kolberg et al., 2017). Empirical evidence from European and international manufacturers suggests that firms adopting lean automation strategies achieve superior operational performance compared to those implementing digital technologies without a lean foundation (Rossini et al., 2022; Vlachos et al., 2023). This highlights the importance of viewing Industry 4.0 technologies as enablers of lean processes rather than ends in themselves.

Another important dimension concerns organizational and human factors. Lean production has always emphasized employee involvement, continuous learning, and problem-solving capabilities, whereas Industry 4.0 introduces new skill requirements related to data literacy, digital competence, and system integration (Sancha et al., 2020; Valipour Khatir et al., 2022). Studies indicate that without adequate employee competency, flexibility, and knowledge management, investments in advanced technologies may fail to deliver expected performance gains (Kamble et al., 2023; Moeuf et al., 2020). This suggests that the successful development of lean production in an Industry 4.0 context depends not only on technical infrastructure but also on contextual conditions related to human resources and organizational culture.

In emerging economies and developing industrial contexts, the integration of lean production and Industry 4.0 presents additional challenges. Empirical comparisons between developed and emerging economies show significant differences in technological readiness, regulatory frameworks, and managerial capabilities, which affect how lean and digital practices are adopted and combined (Rossini et al., 2019; Tortorella et al., 2021). Research conducted in Iran and similar contexts emphasizes constraints such as limited access to advanced technologies, skill shortages, and regulatory barriers, while also highlighting opportunities for leapfrogging through targeted digital–lean initiatives (Abbasi Meybodi & Mohibi, 2023; Danesh Naroui, 2021). These findings underscore the need for context-sensitive models that account for environmental, organizational, and operational contingencies.

The role of advanced technologies such as artificial intelligence further complicates and enriches the lean–Industry 4.0 relationship. AI-driven systems can enhance production planning, quality control, and predictive maintenance, aligning closely with lean objectives of waste reduction and continuous improvement (Eshaghi Kheyroudkenar, 2023). However, scholars caution that excessive reliance on technology without a clear lean logic may increase complexity and undermine process simplicity, a core lean principle (Hopp, 2018; Rosin et al., 2020). This tension reinforces the argument that a structured, process-oriented model is necessary to guide the development of lean production under Industry 4.0 conditions.

Despite the growing body of literature, several gaps remain. First, much of the existing research adopts a fragmented perspective, focusing on individual technologies or isolated lean tools rather than holistic process models (Bavarzad & Daniali, 2022; Kumar et al., 2024). Second, empirical studies often emphasize performance outcomes without sufficiently explicating the causal mechanisms and strategic pathways through which lean production evolves in a digital environment (Kovacs, 2020; Sancha et al., 2020). Third, there is limited use of theory-building methodologies capable of capturing complex, multi-level interactions among causal conditions, strategies, contextual factors, and outcomes.

Grounded theory offers a valuable methodological approach to address these gaps by enabling the inductive development of process models rooted in empirical evidence. By systematically integrating qualitative insights with quantitative validation, grounded theory can reveal how lean production practices are reconfigured in response to Industry 4.0 technologies and contextual pressures (Kamble et al., 2023; Rossini et al., 2019). Such an approach is particularly suitable for exploring emerging phenomena where established theoretical frameworks remain underdeveloped.

Accordingly, there is a clear need for a comprehensive, empirically grounded process model that explains how lean production can be developed and sustained within the Industry 4.0 paradigm, taking into account technical, organizational, environmental, and human dimensions, as well as their strategic and performance implications (Kumar et al., 2024; Silvestri et al., 2022; Vlachos et al., 2023).

The aim of this study is to develop and validate a grounded, process-oriented model for the development of lean production in the context of Industry 4.0.

2. Methods and Materials

Given that the present study aims to develop a lean manufacturing model in Industry 4.0 using the grounded theory approach, the research method was classified as applied in terms of purpose; qualitative–quantitative in terms of data type; and descriptive–correlational in terms of data collection method, nature, and overall research design.

The statistical population in the qualitative section included university faculty members, experts in the fields of technology and manufacturing, as well as senior managers of production and research and development, managers, heads, and supervisors of production lines in various units of dairy manufacturing companies. In the quantitative section, the population consisted of all managers, heads, and supervisors of production lines in the production and information technology units of dairy manufacturing companies in Tehran. The sample size in the qualitative section was determined based on theoretical saturation (10 participants) using purposive sampling, and in the quantitative section, a sample of 361 participants was selected using stratified random sampling. Data collection instruments included semi-structured interviews in the qualitative section and a researcher-developed questionnaire in the quantitative section. Qualitative data analysis was conducted based on document analysis and semi-structured interviews using the grounded theory method. At this stage, 10 interviews were conducted on the topic of lean manufacturing development with an Industry 4.0 approach, and the results obtained from the three stages of coding using MAXQDA software are presented below.

The data coding process (identification of concepts, categories, and their relationships, or the overall data analysis procedure) was implemented concurrently with data collection. Initially, the recorded interview audio files were transcribed verbatim. For open coding, the interview texts were read several times, core concepts were extracted, and codes were assigned accordingly. Subsequently, similar codes were grouped into categories, resulting in the identification of 112 open codes at this stage. During axial coding, categories were linked to their axial categories in order to provide more precise and comprehensive explanations of the phenomenon. In this phase, the initial categories formed during open coding were compared, and those with conceptual similarities were organized around shared axes, leading to the identification of 28 codes, as shown in Table 1. Finally, in selective coding, categories were integrated and refined, and one category was selected as the core category (development of lean manufacturing in Industry 4.0). Based on this core category, the proposed model was developed and, overall, classified into six categories: the central phenomenon, causal conditions, consequences, strategies, contextual factors, and intervening conditions.

To ensure the qualitative rigor of the study, three criteria—credibility, confirmability, and dependability—were applied as follows. With regard to credibility and verification of findings, interview transcripts and the research report were sent to a number of participants (six individuals) to obtain their feedback on the interview questions. Based on their comments, the questions were reviewed and finalized. To ensure dependability of the findings, efforts were made to clearly and systematically document the research processes and decisions throughout the study. Regarding confirmability, the findings were compared with prior research, and theoretical discussions were used to substantiate their interpretation. In addition, to assess validity, the research findings were presented to the participants, the theoretical text was reviewed by them, and their perspectives were incorporated. At the final stage, the study was reviewed by academic experts involved in the research, and suggestions for revising or modifying the final theory were provided. Furthermore, to calculate interview reliability using the inter-coder agreement method, a doctoral-level statistics student was invited to participate as a research collaborator (coder). The necessary training and coding techniques for analyzing the interviews were provided to this collaborator.

3. Findings and Results

In this study, the primary sources of data were the review of upstream (policy and strategic) documents and interviews. The initial interviews were exploratory and descriptive in nature. Gradually, after each interview, the resulting data were coded, and through the constant comparative method, theoretical codes emerged via open coding. Following this process, the coding of all 10 interviews and the upstream documents was completed, the results of which are presented in Table 1.

First research question: What are the indicators, components, and dimensions of lean manufacturing in Industry 4.0?

Based on the findings derived from the grounded theory analysis, lean manufacturing in Industry 4.0 consists of five components: lean quality management, smart supply chain, lean process management, smart customer orientation, and smart human resources.

Table 1

Selective, Axial, and Open Coding Derived from the Research Findings

Selective Coding (Core Category)	Axial Coding	Open Coding
Core Category	Lean Quality Management	Creating a culture of continuous improvement through organizational intelligence
		Using smart methods to reduce errors in the production process
		Planning for waste reduction through intelligent systems
		Identifying existing wastes in the production process
	Smart Customer Orientation	Dependence of production speed on customer demand through smart equipment
		Communicating current and future customer demand between marketing and production units to align machinery and enhance intelligence
		Customer feedback on product quality
		Customer visits to smart production units
	Lean Process Management	Enhancing collaboration and communication among departments, suppliers, and customers through 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	Bidirectional communication capability is essential in Industry 4.0
		Appropriate responsiveness across the supply chain by all members
		Accurate evaluation of communication performance among material suppliers

		Determining safety stock to prevent shortages in the supply chain
		Capability for online responsiveness to address potential errors
		Receiving customer viewpoints online
		Fulfilling customer expectations throughout the supply 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 of robots should be emphasized
		Flexibility in smart control requires effective robot control
		Speed of user interaction with the work environment using Industry 4.0 technologies
		Emphasis on efficiency in the performance of remote systems
		Accuracy of reports as a key issue in smart employees
		Warning employees about potential errors and preventing their occurrence
		Intelligent correction of potential errors and proposing solutions to eliminate work obstacles

The results indicated that, following content analysis and expert interviews, the factors influencing lean manufacturing in Industry 4.0 were categorized into technical factors, environmental factors, organizational factors, and operational factors.

Table 2

Selective, Axial, and Open Coding of Influencing Factors Derived from the Research Findings

Selective Coding	Axial Coding	Open Coding
Causal Conditions	Technical Factors	Establishing an appropriate database to record large volumes of complex information
		Defining appropriate product quality levels to enhance control and monitoring in the lean production process
		Minimal need for repair or replacement through proper and intelligent design
		Achieving the highest production standards through intelligent updating of processes affecting lean manufacturing
		Online system support and resolution of potential system issues
	Organizational Factors	Absence of resistance to intelligent change in line with organizational culture and values
		Conducting training programs for senior managers, middle managers, and responsible experts
		Institutionalizing innovation and intelligent change within the organization and managing it effectively
		Utilizing talented, young, and specialized personnel in technological intelligence
	Environmental Factors	Localization of smart production equipment has rarely been implemented
		Up-to-date experience and knowledge are highly important for commissioning production equipment in lean manufacturing processes
		Limited access to new and essential training due to sanctions
		Insufficient attention to culture-building and trust-building for the adoption of smart lean manufacturing
	Operational Factors	Alignment of system reports with work processes must be considered by technology
		Applying value engineering to improve operational execution within the organization
		Reducing product development processes through smart production pathways

The results showed that, following content analysis and interviews with experts, the components affected by lean manufacturing in Industry 4.0 included cost reduction, increased productivity, just-in-time production and reduced production time, quality improvement, improved operational performance, mass customization, flexibility, and increased customer satisfaction.

Table 3

Selective, Axial, and Open Coding of Affected Factors Derived from the Research Findings

Selective Coding	Axial Coding	Open Coding
Outcomes	Flexibility	Production aligned with customer needs
		Alignment with technological changes
		Flexibility in production
		Flexibility in responding to changes in demand
	Quality Improvement	Maximum quality must be ensured in the production process
		Enabling data analysis, learning from data, decision-making, and performing actions that typically require human intelligence has transformed machines, which can lead to increased efficiency, productivity, and quality
		The use of smart devices with advanced technologies in smart factories leads to higher productivity and improved quality
	Cost Reduction	Minimal waste should exist in the production process
		Minimal rework should exist in the production process
		Minimum raw materials should be used in the production process
	Increased Customer Satisfaction	Reduction in product return rates
		Increased level of customer satisfaction
		Decrease in customer complaints regarding product quality and delivery time
	Increased Productivity	Demand-based production using smart forecasting
		Minimizing inventory levels on the production line through smart line balancing
		Reduction of production downtime through smart production planning
		Alignment with production schedules and intelligent reduction of potential mismatches
	Improved Operational Performance	Intelligence at the lean production level reduces risk and facilitates transaction execution
		Intelligence at the lean production level enables better resource allocation
		Intelligence at the lean production level increases gross domestic product
		Achieving predefined goals using Industry 4.0 intelligence in the lean production process
		Intelligence at the lean production level enables continuous monitoring and tracking of business trends
	Mass Customization	Updating orders within the industry to prevent shortages and spoilage
		Smart factories can produce customized goods that more precisely meet the needs of individual customers
		Many industrial sectors and manufacturers seek more cost-effective methods of product customization
	Just-in-Time Production and Reduced Production Time	Time savings are critically important for smart lean production
		Ease of using remote-working applications to reduce non-value-added time
		Smartization of the lean production process reduces production time and ultimately increases customer satisfaction
		Reducing product design time through intelligence in industrial production is highly important

Based on the research background, theoretical foundations, expert interviews, and analysis of the status of dimensions, components, and indicators, the mechanisms or strategies for implementing the lean manufacturing development model in Industry 4.0 are presented in the table below.

Table 4

Selective, Axial, and Open Coding of Implementation Mechanisms (Strategies), Contextual Factors, and Barriers Derived from the Research Findings

Selective Coding	Axial Coding	Open Coding
Strategy	Appropriate Infrastructure	Quality management, workforce management, production strategy, organizational characteristics, and product design must be in place for the smart lean production process
		Companies now possess stronger knowledge for more effective decision-making regarding the implementation of lean manufacturing and Industry 4.0 and their implications for sustainability
		Without the necessary infrastructure for implementing Industry 4.0 in the lean production process, sufficient efficiency and effectiveness cannot be achieved
	Approval and Amendment of Regulations	Barriers and directives exist for obtaining licenses to use modern production equipment due to high energy consumption
		Disruptive laws and regulations must be reformed
		Lean automation and smartization are affected by organizational regulations, leading to increased time waste
	Financing	Deviations must be identified in production processes, strategy implementation, budgets, and all organizational aspects, and their interrelationships must be understood
		A lean company can not only reduce the social damages of its activities but also play a significant role in meeting societal needs due to its strong financial and managerial capabilities
		The company’s financial capability to equip production lines for implementing smart lean manufacturing is of critical importance
	Employee Empowerment	Supporting employee self-efficacy
		Increasing employees’ intrinsic motivation plays a significant role in implementing the smart lean production process
		Creating a sense of competence and control among employees accelerates the implementation of lean production lines through smart production equipment
	Downsizing and Integration	Facilitating interpersonal and work-related relationships through technology
		Reducing workforce size while increasing workforce quality
		Integration and information flow across different departments lead to higher productivity and effectiveness of the smart lean production system
Contextual Factors	Employee Intelligence and Awareness	Possessing extensive information about near and distant environmental factors
		Ability to generate new ideas by employees
		Orientation toward learning and self-development
		Employee responsiveness to changing customer needs
	Employee Competency	Speed and accuracy in analyzing information obtained from various sources
		Acquisition of essential skills for changes in business processes
		Speed of innovation in managerial skills
		Responsiveness to specific conditions
	Employee Flexibility	Ability to predict methods for producing new products
		Improving personal abilities to solve new problems
		Participation in decision-making processes
		Using threats as opportunities
	Employee Knowledge Management	Competition among supply chains
		Ability to respond under changing conditions and create value
		Mastery over change and uncertainty
		Significant increase in customer satisfaction
Intervening Conditions	Competitors	Imitation of patterns, noise, and sources of confusion in data
		Sampling for deep learning
		Imitation of emerging and market-entering technologies
	Internal Uncertainty	Positive non-cooperative behaviors
		Presence of distrust within the environment
		Lack of accountability combined with individual independence and freedom
		Absence of an entrepreneurial mindset

Second Research Question: What model can be proposed for the development of lean manufacturing in Industry 4.0?

Using grounded theory, the final research model is presented as follows. In this section, path analysis was conducted using PLS software.

Figure 1

Conceptual model of the research in the standardized coefficients estimation mode.

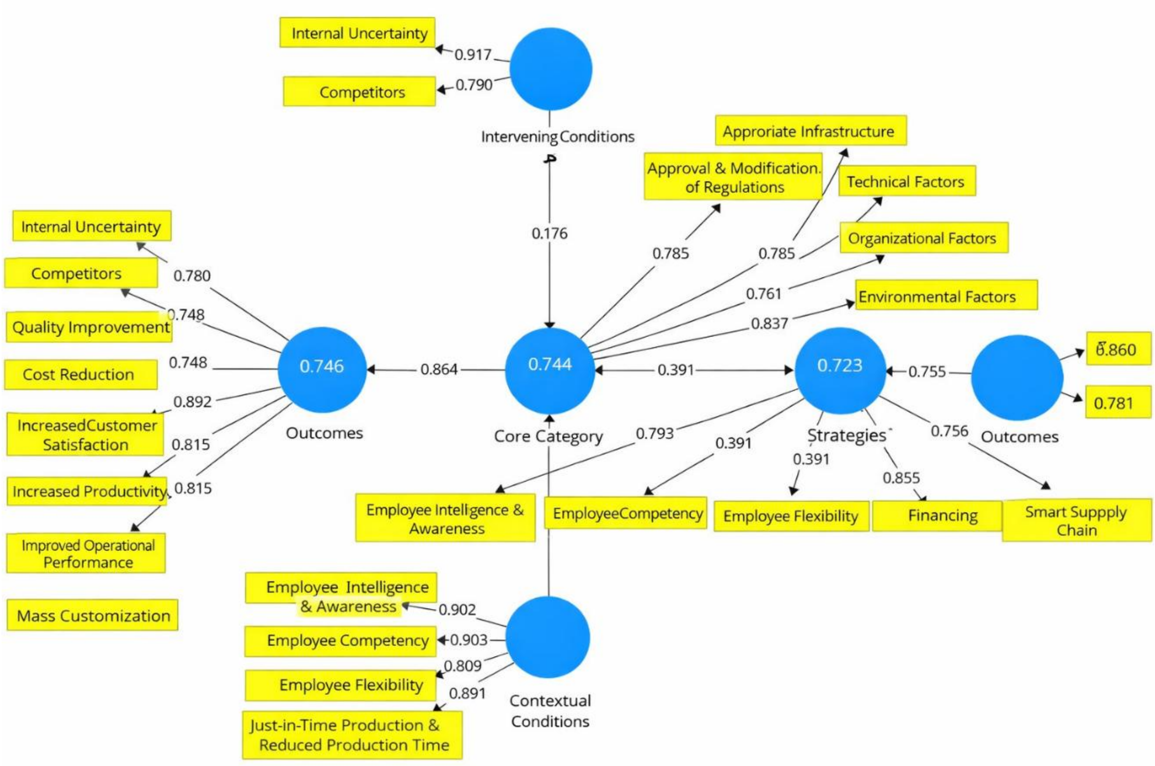
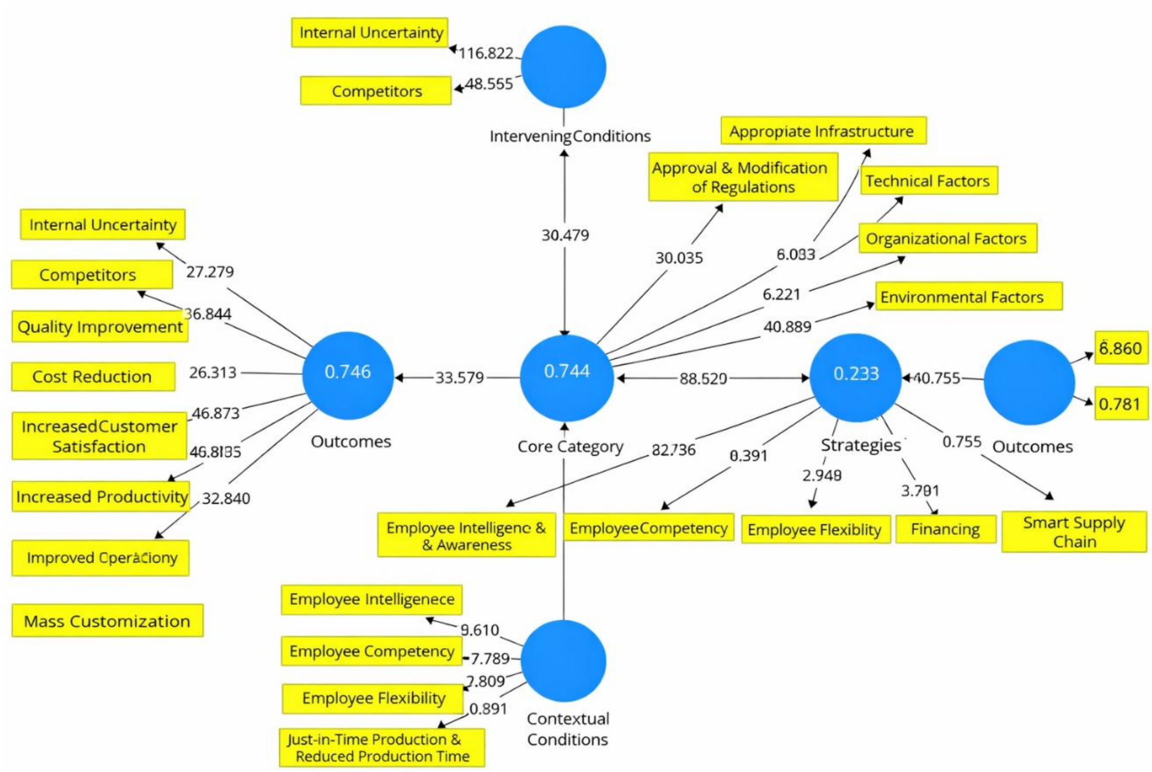


Figure 2

Conceptual model of the research in the coefficients significance mode.



In the following, path analysis is used to examine the nature of the relationships among the process components of lean manufacturing based on Industry 4.0.

Table 5

Path Analysis of the Main Research Model

Paths	Standardized Coefficients	t-values	P-value	Results
Causal conditions → Core category	0.839	47.208	0.003	Significant
Core category → Strategies	0.263	5.020	0.000	Significant
Contextual conditions → Strategies	0.407	8.544	0.000	Significant
Intervening conditions → Strategies	0.274	4.990	0.001	Significant
Strategies → Outcomes	0.755	27.214	0.000	Significant

4. Discussion and Conclusion

The purpose of this study was to develop and validate a process-oriented model for the development of lean production in the context of Industry 4.0 using a grounded theory approach combined with structural equation modeling. The findings provide strong empirical evidence that lean production in Industry 4.0 is not merely a technological upgrade but a systemic transformation shaped by causal, contextual, intervening, strategic, and outcome-related dimensions. The results of the path analysis indicate that causal conditions exert a strong and significant effect on the core category of lean production development, which in turn influences strategic choices and ultimately determines performance outcomes. This confirms the argument that lean–Industry 4.0 integration must be understood as a dynamic process rather than a static configuration of tools and technologies.

The identification of technical, organizational, environmental, and operational factors as causal conditions aligns closely with prior research emphasizing the foundational role of technological readiness, organizational alignment, and external context in Industry 4.0 initiatives (Moeuf et al., 2020; Silvestri et al., 2022). Technical factors such as data infrastructure, system reliability, and smart automation emerged as essential enablers, reinforcing earlier findings that digital technologies act as catalysts for lean practices by enhancing process visibility and real-time control (Ciano et al., 2021; Wang et al., 2021). At the same time, the significance of organizational factors supports studies that highlight the importance of managerial commitment, learning culture, and resistance-free change management in lean–digital transformations (Rossini et al., 2019; Sancha et al., 2020). The inclusion of environmental factors further reflects the contextual sensitivity of Industry 4.0 adoption, particularly in settings characterized by regulatory constraints and limited access to advanced technologies, as noted in prior empirical work (Abbasi Meybodi & Mohibi, 2023; Tortorella et al., 2021).

The core category of the model—lean production development in Industry 4.0—was empirically linked to five key components: lean quality management, smart supply chain, lean process management, smart customer orientation, and smart human resources. This configuration is consistent with the growing consensus that Industry 4.0 expands the scope of lean beyond shop-floor efficiency toward end-to-end value creation (Buer et al., 2018; Kumar et al., 2024). In particular, the strong loadings associated with lean quality management and smart customer orientation support prior findings that digital technologies enhance quality assurance and customer responsiveness through real-time data analytics and feedback mechanisms (Rosin et al., 2020; Vlachos et al., 2023). The prominence of smart human resources further confirms that human-centric capabilities remain central even in highly automated environments, echoing arguments that Industry 4.0 amplifies rather than diminishes the strategic role of skilled and adaptable employees (Hopp, 2018; Valipour Khatir et al., 2022).

The path analysis results demonstrate that the core category significantly influences strategic mechanisms, including appropriate infrastructure, financing, regulatory adjustment, employee empowerment, and downsizing and integration. This finding corroborates studies on lean automation, which argue that strategic alignment is necessary to prevent digital investments from generating complexity and waste (Dombrowski et al., 2017; Kolberg et al., 2017). The importance of infrastructure and financing reflects empirical evidence that insufficient technological and financial resources undermine the effectiveness of

Industry 4.0 initiatives, particularly in small and medium-sized enterprises and emerging economies (Kamble et al., 2023; Moeuf et al., 2020). Similarly, the role of regulatory approval and adjustment aligns with research highlighting the institutional barriers that often slow the adoption of smart manufacturing technologies (Danesh Naroui, 2021; Rossini et al., 2022).

Contextual conditions—specifically employee intelligence and awareness, competency, flexibility, and knowledge management—exhibited a significant effect on strategies, underscoring the mediating role of human and organizational capabilities in translating lean intentions into effective action. This supports the view that Industry 4.0 is as much a socio-technical transformation as it is a technological one (Sancha et al., 2020; Silvestri et al., 2022). Prior studies have shown that without adequate employee skills and learning mechanisms, digital tools may remain underutilized or misaligned with lean objectives (Buer et al., 2018; Kovacs, 2020). The present findings extend this literature by empirically validating the strength of contextual conditions within a comprehensive process model.

Intervening conditions, represented by internal uncertainty and competitive pressure, were also found to significantly influence strategic choices. This result is consistent with contingency-based perspectives suggesting that uncertainty and competition can either accelerate or hinder lean–digital transformation depending on organizational preparedness (Rossini et al., 2019; Tortorella et al., 2021). Competitive pressure may stimulate imitation and rapid technology adoption, while internal uncertainty—such as lack of trust or accountability—can weaken strategic coherence. These findings echo earlier warnings that Industry 4.0 initiatives pursued primarily for competitive signaling, rather than process improvement, may fail to deliver sustainable performance gains (Rosin et al., 2020; Vlachos et al., 2023).

Finally, the strong and significant relationship between strategies and outcomes confirms that well-aligned strategic mechanisms are critical for realizing the benefits of lean production in Industry 4.0. Outcomes such as cost reduction, productivity improvement, just-in-time production, quality enhancement, operational performance, flexibility, mass customization, and customer satisfaction are widely cited in the literature as key advantages of lean–digital integration (Ciano et al., 2021; Kamble et al., 2023). The present study contributes by demonstrating that these outcomes do not emerge directly from technology adoption but are mediated by strategic and organizational choices. This reinforces the argument that Industry 4.0 should be deployed as an enabler of lean value creation rather than as an isolated technological upgrade (Kumar et al., 2024; Rossini et al., 2022).

Overall, the findings support and extend existing research by offering an empirically grounded, process-oriented model that captures the complexity of lean production development in Industry 4.0. By integrating qualitative insights with quantitative validation, the study addresses calls for theory-building approaches capable of explaining causal mechanisms and strategic pathways in lean–digital transformation (Buer et al., 2018; Silvestri et al., 2022). The model provides a coherent explanation of how causal conditions shape core lean components, how contextual and intervening factors influence strategic responses, and how these strategies ultimately translate into performance outcomes.

Despite its contributions, this study has several limitations. First, the empirical context was limited to a specific industrial sector and geographical setting, which may restrict the generalizability of the findings to other industries or national contexts. Second, although the mixed-methods approach enhanced robustness, the quantitative phase relied on self-reported data, which may be subject to response bias. Third, the cross-sectional design captures relationships at a single point in time and does not fully reflect the dynamic evolution of lean–Industry 4.0 integration over longer periods.

Future research could extend this study by applying the proposed model in different industrial sectors and countries to assess its external validity and contextual adaptability. Longitudinal studies would be particularly valuable to examine how lean production development in Industry 4.0 evolves over time and how strategic mechanisms adapt to changing technological and market conditions. Additionally, future studies could integrate objective performance indicators and comparative case analyses to further strengthen causal inference and deepen understanding of sector-specific implementation pathways.

For practitioners, the findings highlight the importance of adopting a holistic, process-oriented approach to lean production development in Industry 4.0 rather than focusing solely on technology acquisition. Managers should prioritize strategic alignment, invest in employee capabilities, and ensure that digital initiatives directly support lean objectives. Policymakers and industry leaders can also use the model as a diagnostic tool to identify gaps in infrastructure, regulation, and human capital that may hinder effective lean–digital transformation.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

Acknowledgments

We would like to express our gratitude to all individuals helped us to do the project.

Declaration of Interest

The authors report no conflict of interest.

Funding

According to the authors, this article has no financial support.

Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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