International Journal of Industrial Engineering and Operational Research (IJIEOR)

Contents lists available at IJIEOR
International Journal of Industrial Engineering and Operational Research
journal homepage: http://ijieor.ir
Volume 8, No. 1, 2026

Integrating Lean Practices and IT Governance Capabilities for Enhancing Smart Manufacturing Performance: An Empirical Framework from the Industrial Engineering Perspective

Zahra Kordian [a], Ebrahim Haj Khan Mirzay Sarraf [b], Ramin Golestaneh [c]

[a,] *Department of Engineering Management, Faculty of Industrial Engineering, University of Science and Culture, Tehran, Iran,*
[b c] *Department of Finance and Economics, Faculty of Humanities, University of Science and Culture, Tehran, Iran*.

ARTICLE INFO

Received: 2026/04/10

Revised: 2026/05/12

Accept: 2026/06/22

Keywords:

Smart Manufacturing, Lean Manufacturing, IT Governance, Industry 4.0, Structural Equation Modeling, Operational Performance, Digital Transformation, Organizational Agility, Overall Equipment Effectiveness.

ABSTRACT

The swift evolution of Industry 4.0 technologies has significantly altered the operational framework of manufacturing companies, compelling them to pursue both process excellence and robust digital governance concurrently. While lean manufacturing has demonstrated effectiveness in removing non-value-adding activities and enhancing operational efficiency, the contribution of information technology (IT) governance in bolstering these advancements is still inadequately examined in the industrial engineering literature. This research aims to fill this void by proposing and empirically validating a comprehensive framework that integrates lean practices with IT governance capabilities to improve smart manufacturing performance. Based on the principles of lean manufacturing, IT governance, and digital transformation, the proposed framework investigates how aligning technological resources with operational goals leads to better manufacturing results. A sequential mixed-methods approach was utilized. Initially, a Delphi panel comprising academic experts and seasoned industry professionals was convened to refine the conceptual dimensions of the framework and ensure content validity. Following this, survey data were gathered from 178 manufacturing firms across various industrial sectors and analyzed using structural equation modeling (SEM) to evaluate the proposed relationships. The empirical results indicate that lean practices have a substantial positive impact on smart manufacturing performance. Additionally, IT governance capabilities partially mediate this relationship by promoting strategic alignment, enhancing decision-making quality, and improving the effective use of digital resources. The findings also highlight top management commitment, cross-functional collaboration, and real-time data analytics capability as essential success factors that facilitate the implementation of the integrated framework. This research enhances the current body of knowledge by connecting two historically distinct fields—industrial engineering and IT governance—while presenting a thorough viewpoint on value generation within smart manufacturing settings. Practically, the suggested framework equips managers with a quantifiable guide for synchronizing technology expenditures with operational enhancement efforts, thus promoting agile, resilient, and data-informed manufacturing systems that can maintain a competitive edge in the digital age.

[a] Corresponding author email address: zkordian@mail.ir (Zahra Kordian).
DOI: https://doi.org/10.22034/ijieor.v8i1.212
Available online 2026/06/23

1. Introduction

The advent of Industry 4.0 has significantly altered the competitive dynamics within manufacturing enterprises. The incorporation of cyber-physical systems, the industrial Internet of Things (IIoT), cloud computing, artificial intelligence, and sophisticated analytics has facilitated the shift from traditional production methods to smart and interconnected manufacturing settings [1], [2]. In these settings, the criteria for manufacturing excellence extend beyond mere productivity and cost efficiency. Companies are now anticipated to exhibit flexibility, resilience, responsiveness, and the ability to make data-informed decisions in order to sustain their competitiveness in fluctuating markets [3].

Despite significant investments in digital technologies by manufacturing firms over the last ten years, the results of these investments frequently do not meet anticipated outcomes. Numerous studies indicate that merely adopting technology does not ensure enhanced operational performance. Instead, organizations must establish suitable governance frameworks that can align digital initiatives with both strategic and operational goals [4], [5]. In the absence of robust governance mechanisms, companies often face disjointed processes, suboptimal resource distribution, and challenges in realizing the value from their technological investments [6].

Lean manufacturing remains a significant operational philosophy in the field of industrial engineering. Originating from the Toyota Production System, lean focuses on the elimination of waste, ongoing improvement, employee engagement, standardization of processes, and the creation of value for customers [7]. Prior empirical research has consistently indicated that the implementation of lean practices leads to decreased inventory levels, shorter lead times, fewer defects, enhanced quality, and improved operational efficiency [8], [9]. Nevertheless, the growing intricacy of smart manufacturing environments has posed challenges to the traditional application of lean principles. Contemporary manufacturing systems produce vast amounts of real-time production data and necessitate close collaboration between operational technologies and information systems [10]. As a result, scholars have increasingly contended that lean manufacturing must progress beyond its conventional limits and incorporate the digital capabilities linked to Industry 4.0 [11]. Recent findings indicate a complementary relationship between lean manufacturing and Industry 4.0 technologies. Researchers in [12] found that the concurrent application of lean practices alongside Industry 4.0 technologies can lead to significant enhancements in operational, environmental, and social performance. Similarly, in [13], through a comprehensive literature review, determined that lean principles and digital technologies mutually reinforce one another and collectively enhance organizational capabilities.

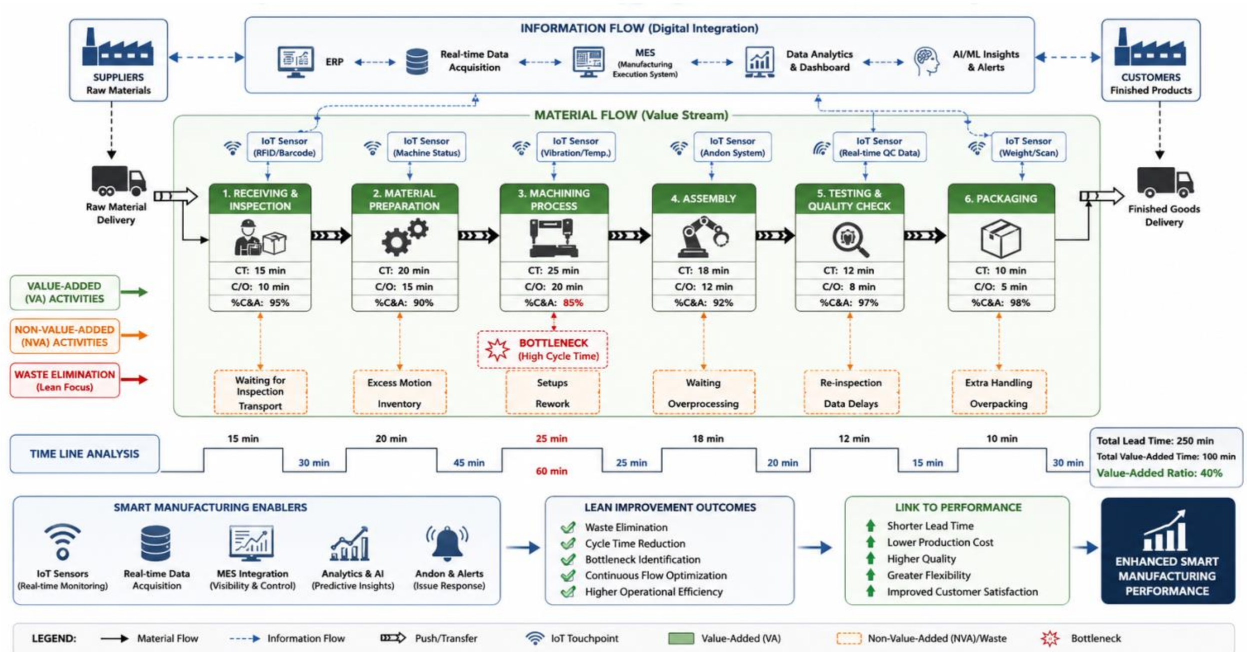

Figure 1. Lean Value Stream Mapping in Smart Manufacturing Context

This figure illustrates a value stream mapping (VSM) structure adapted for smart manufacturing environments. It shows the transformation of raw materials through production stages, highlighting value-added vs. non-value-added activities. Digital touchpoints such as IoT sensors, real-time data acquisition, and MES integration are embedded across the flow to demonstrate how lean waste elimination is enhanced through Industry 4.0 technologies. The diagram emphasizes cycle time reduction, bottleneck identification, and continuous flow optimization, linking operational efficiency improvements directly to lean implementation intensity.

Notwithstanding these advancements, the significance of Information Technology (IT) governance in promoting this integration is still inadequately examined. IT governance encompasses the frameworks, procedures, and relational dynamics that guarantee information technology investments align with organizational goals and create business value [14]. Robust IT governance empowers organizations to enhance the quality of decision-making, bolster accountability, optimize resource distribution, and mitigate technological risks [15].

From a business value standpoint, the capabilities of IT governance have become vital organizational assets. [4] illustrated that companies with more robust IT governance process capabilities demonstrate enhanced IT performance, which in turn leads to better business results. Their research underscores the significance of IT planning, infrastructure modernization, service delivery, monitoring practices, and governance mechanisms in realizing improvements in organizational performance. In a similar vein, scholars in the manufacturing sector have pointed out that data quality, transparency, and information governance are fundamental prerequisites for the success of smart manufacturing initiatives [16]. Without clearly defined governance frameworks, manufacturing firms may find it challenging to convert production data into actionable insights that can facilitate operational excellence. Despite the increasing volume of research on lean manufacturing, Industry 4.0, and IT governance, these fields have predominantly developed in isolation. Current studies mainly focus on operational enhancement initiatives and digital transformation efforts independently, thus neglecting the potential synergies that could exist between them [11], [13]. As a result, there is a scarcity of empirical evidence regarding how IT governance capabilities can bolster the effectiveness of lean practices and improve smart manufacturing performance.

This research aims to fill a significant gap by proposing and empirically validating a comprehensive framework that connects lean manufacturing practices, IT governance capabilities, and smart manufacturing performance from the viewpoint of industrial engineering. In particular, the study investigates whether IT governance serves as an enabling capability that allows lean initiatives to yield enhanced operational advantages in digitally enabled production settings. The current study makes three key contributions to the existing literature. Firstly, it connects two previously isolated research domains by merging principles of industrial engineering with theories of IT governance. Secondly, it empirically explores the mediating effect of IT governance capabilities on the relationship between lean implementation and manufacturing performance. Lastly, it offers practitioners a practical guide for aligning digital investments with ongoing improvement efforts to cultivate agile, resilient, and intelligent manufacturing systems. In this context, the study aims to address the following research questions:

RQ1. In what ways do lean manufacturing practices affect smart manufacturing performance?

RQ2. To what degree do IT governance capabilities enhance performance in smart manufacturing contexts?

RQ3. Is there a mediating effect of IT governance on the relationship between lean practices and smart manufacturing performance?

RQ4. What organizational factors promote the effective integration of lean initiatives and IT governance mechanisms within manufacturing organizations?

2. Literature Review and Hypotheses Development

2.1 Lean Manufacturing and Smart Manufacturing Performance

Lean manufacturing has been widely acknowledged as a strategic method for enhancing operational performance by eliminating non-value-added activities, fostering continuous improvement, and augmenting customer value [7], [8]. Prior research has consistently shown that lean practices lead to increased productivity, shorter cycle times, reduced inventory levels, and improved product quality [8], [9]. With the rise of smart manufacturing, scholars have started to explore the effectiveness of traditional lean principles within digitally enabled production settings. Evidence indicates that lean practices continue to be vital in Industry 4.0 environments by establishing standardized processes and creating stable operational foundations essential for digital transformation [10], [11]. Article [12] indicated that organizations that combine lean initiatives with digital technologies achieve better operational results compared to those that implement either strategy in isolation. Likewise, [17] discovered that lean capabilities have a positive impact on operational performance and can mediate the relationship between Industry 4.0 technologies and organizational outcomes [17]. A recent meta-analysis further validated that the synergy between lean practices and Industry 4.0 significantly enhances firm performance [18]. In light of this, the following hypothesis is proposed: H1: Lean manufacturing practices have a positive and significant effect on smart manufacturing performance.

2.2 Lean Manufacturing and IT Governance Capabilities

While lean manufacturing has historically been linked to production systems, its effective execution increasingly relies on efficient information flows, digital coordination, and collaborative decision-making [13]. Lean organizations necessitate prompt and dependable information to bolster continuous improvement efforts and identify waste. IT governance offers frameworks through which organizations delineate decision-making authority, establish accountability, and align technological investments with strategic goals [14], [15]. Companies that embrace lean principles frequently enhance their governance frameworks to boost transparency and promote organizational learning. Research suggests that initiatives aimed at operational excellence motivate organizations to formalize governance practices and enhance information management processes [4], [19]. As a result, the implementation of lean practices may catalyze the enhancement of IT governance capabilities. Thus: H2: Lean manufacturing practices have a positive impact on IT governance capabilities.

2.3 IT Governance Capabilities and Smart Manufacturing Performance

IT governance has become a crucial organizational capability in the digital age. Effective governance allows companies to manage their technological resources effectively, mitigate IT-related risks, and enhance the value derived from digital investments [14], [15]. Article [4] provided empirical evidence that the capability of IT governance processes significantly boosts IT performance, which in turn enhances business performance. Their research, which included 881 organizations, underscored the significance of IT planning, infrastructure modernization, service delivery, and monitoring systems. In a similar vein, researchers in [5] contended that well-developed governance structures foster improved strategic alignment and organizational efficiency. In the context of smart manufacturing, governance mechanisms facilitate real-time decision-making, ensure data quality, and promote coordination among various stakeholders [16]. As a result, organizations with robust IT governance capabilities are anticipated to achieve better operational results. Therefore: H3: IT governance capabilities have a positive impact on smart manufacturing performance.

2.4 The Mediating Role of IT Governance Capabilities

The literature on the business value of information technology indicates that organizational capabilities frequently act as intermediaries in the connection between managerial practices and performance results [4], [20]. Simply implementing lean initiatives does not ensure exceptional outcomes unless organizations have the appropriate governance structures in place to effectively manage digital resources. Recent research highlights that the advantages gained from digital transformation are contingent upon complementary organizational capabilities [21], [22]. Governance mechanisms enhance communication between operational and technological divisions, optimize resource distribution, and guarantee that lean goals are consistently aligned with technological priorities. Consequently, IT governance capabilities may serve as a facilitating mechanism through which lean initiatives lead to enhanced manufacturing results. Thus: H4: IT governance capabilities mediate the relationship between lean manufacturing practices and smart manufacturing performance.

2.5 Critical Organizational Enablers

The successful execution of lean and digital initiatives is significantly influenced by the conditions within the organization. A commitment from leadership has been consistently recognized as essential for achieving transformation success [12], [23]. Support from top management guarantees sufficient resource allocation and cultivates an organizational culture that is favorable to change. Additionally, cross-functional collaboration between industrial engineering and IT departments is crucial for the integration of operational and technological initiatives [24]. Moreover, the capability for real-time analytics improves the organization's responsiveness and facilitates evidence-based decision-making [25]. In light of these insights, the following hypotheses are proposed: H5: The support from top management has a positive effect on IT governance capabilities. H6: Cross-functional collaboration has a positive effect on IT governance capabilities. H7: The capability for real-time data analytics positively impacts smart manufacturing performance. Figure 2 depicts the conceptual framework established in this research. The model suggests direct relationships between lean practices, IT governance capabilities, and smart manufacturing performance, while also considering the mediating role of IT governance and the influence of key organizational enablers.

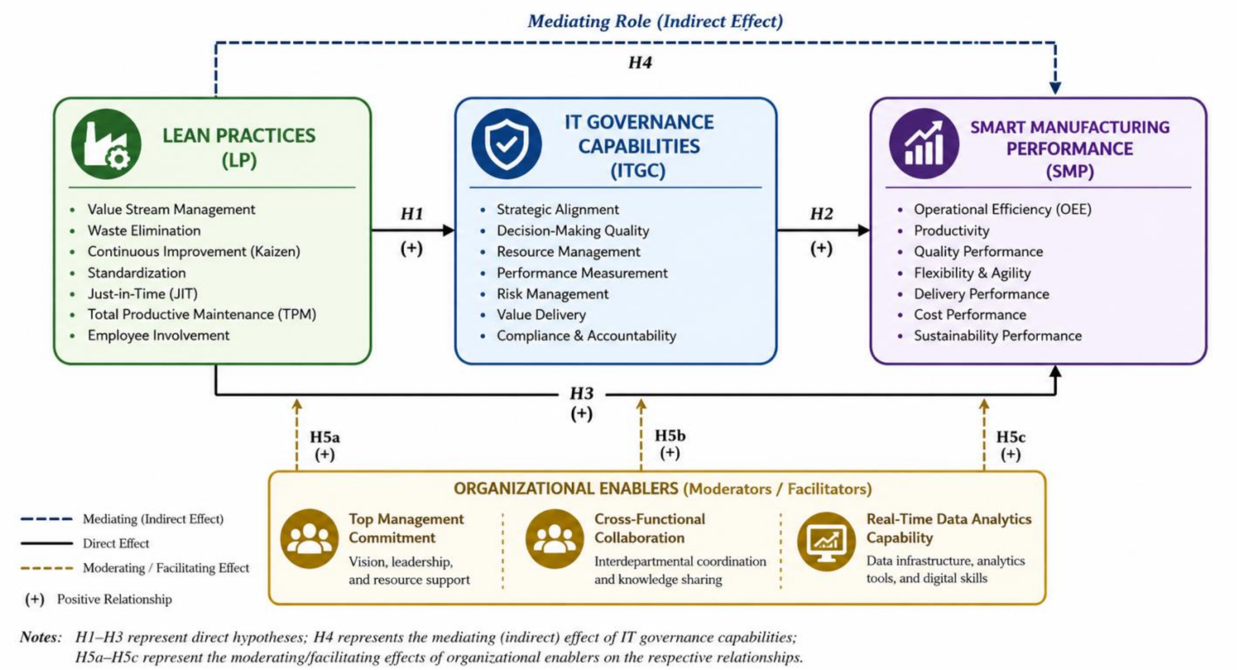

Figure 2. depicts the conceptual framework established in this research.

3. Research Methodology

3.1 Research Design

This research employed a sequential mixed-methods approach to create and validate a comprehensive framework that connects lean manufacturing practices, IT governance capabilities, and smart manufacturing performance. The application of mixed methods allowed the researchers to leverage both qualitative insights and quantitative validation. The qualitative component concentrated on enhancing the conceptual model and confirming content validity, while the quantitative component empirically evaluated the proposed hypotheses through structural equation modeling (SEM). The research process was divided into four distinct stages. Initially, a thorough literature review was conducted to pinpoint the primary constructs and the potential relationships among them. Subsequently, a Delphi study was carried out with experts from both academia and industry to confirm the relevance and clarity of the identified dimensions. In the third stage, a survey instrument was created and disseminated among manufacturing firms. Finally, the data collected were analyzed using SEM to evaluate both the measurement and structural models.

3.2 Delphi Study

A two-round Delphi technique was employed to establish content validity and refine the initial research framework. The Delphi panel consisted of 15 experts selected through purposive sampling. The panel included:

Six academic experts specializing in industrial engineering, operations management, and digital transformation;

Five senior manufacturing managers with more than ten years of experience in lean implementation;

Four IT executives responsible for governance and digital initiatives.

During the first round, experts evaluated the relevance of each construct and measurement item using a five-point scale. Suggestions regarding wording, redundancy, and construct definitions were incorporated into the revised questionnaire. In the second round, consensus levels exceeded 80%, indicating acceptable agreement among panel members.

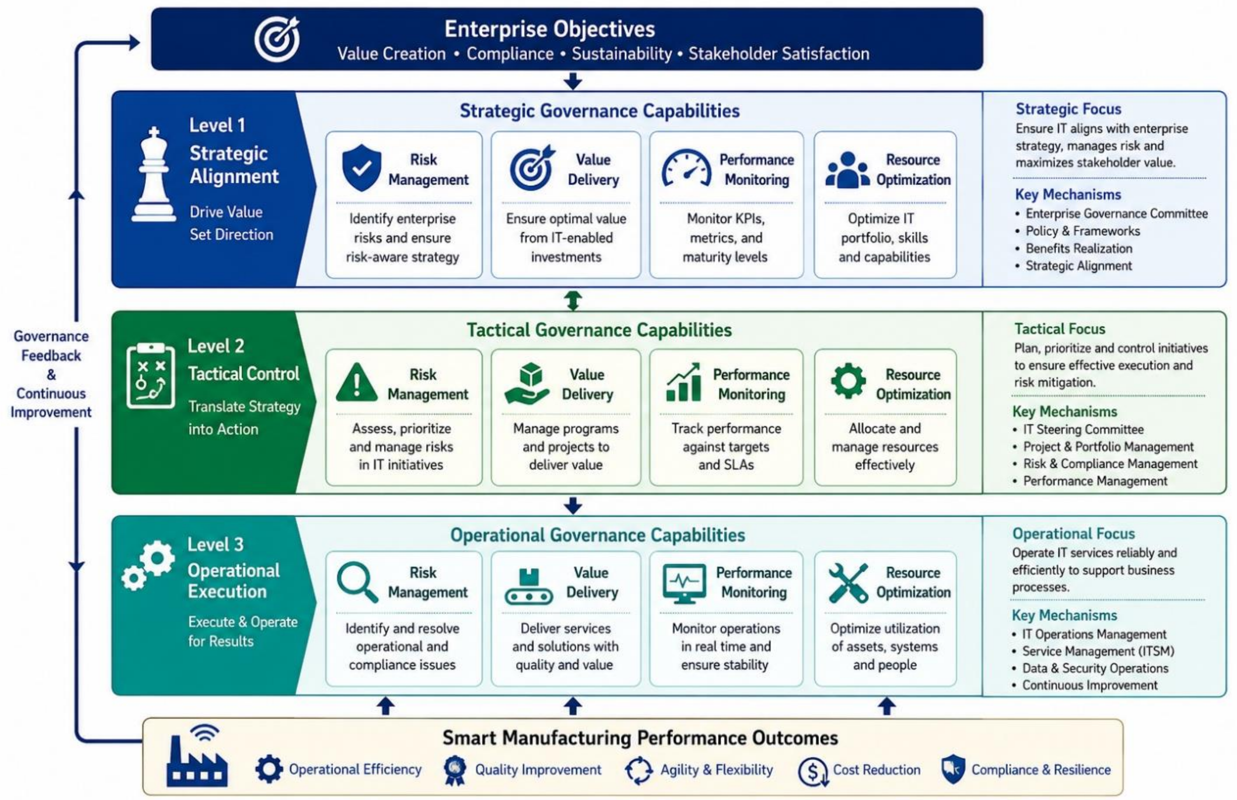

Figure 3. IT Governance Capability Architecture (COBIT-Inspired Model)

This illustration depicts a multi-tiered IT governance capability framework influenced by COBIT principles. It organizes governance into three distinct hierarchical levels: strategic alignment, tactical control, and operational execution. Each tier incorporates essential capabilities such as risk management, value delivery, performance monitoring, and resource optimization. The framework emphasizes the role of governance mechanisms in aligning digital manufacturing investments with organizational objectives, thus enhancing decision-making quality and ensuring compliance with regulatory and operational standards in smart manufacturing systems.

3.3 Population and Sampling

The target population consisted of manufacturing companies that had executed at least one lean initiative and had engaged in digital transformation efforts over the past three years. A purposive sampling approach was utilized to guarantee that participants had adequate knowledge concerning both operational enhancement and information technology practices. Data were gathered from managers in roles related to: • Production and operations management; • Industrial engineering departments; • Information technology units; • Continuous improvement teams; • Digital transformation offices. A total of 250 questionnaires were distributed in both electronic and printed formats. After removing incomplete responses, 178 valid questionnaires were kept for analysis, resulting in a response rate of 71.2%. In accordance with the guidelines provided by Hair et al. [26], the sample size was deemed sufficient for covariance-based structural equation modeling.

3.4 Measurement Instrument

The survey questionnaire was divided into two distinct sections. The initial section gathered demographic data concerning the respondents and the characteristics of their organizations, which included the type of industry, the size of the firm, the duration of lean implementation, and the level of digital maturity. The subsequent section evaluated the latent constructs outlined in the conceptual framework. All measurement items were derived from previously validated research and were assessed utilizing a five-point Likert scale, which ranged from 1 ("strongly disagree") to 5 ("strongly agree"). The constructs assessed included: Lean Manufacturing Practices (LMP) This was measured through indicators associated with: • Continuous improvement; • Waste elimination; • Standardized work; • Pull production; • Employee involvement. The measurement items were adapted from the works of Shah and Ward [8] and Netland and Powell [9]. IT Governance Capabilities (ITGC) This was measured using indicators that captured: • Strategic alignment; • IT decision-making processes; • Performance monitoring; • Resource management; • Accountability mechanisms. The items were adapted from the studies of De Haes and Van Grembergen [5] and Joshi et al. [4]. Smart Manufacturing Performance (SMP) was operationalized using several key indicators, including overall equipment effectiveness (OEE), lead-time reduction, operational flexibility, productivity improvement, and quality enhancement, as adapted from the research conducted in [25]. Top Management Support (TMS) was measured by assessing the degree to which senior leadership demonstrates commitment, allocates resources, and provides guidance for transformation initiatives. Cross-Functional Collaboration (CFC) was evaluated through the level of cooperation and communication between the industrial engineering and IT departments. Finally, Real-Time Data Analytics Capability (RDAC) was measured by examining the firm's ability to collect, analyze, and effectively utilize real-time operational data to inform decision-making. These dimensions collectively contribute to a comprehensive understanding of the factors driving smart manufacturing success.

3.5 Reliability and Validity Assessment

The psychometric characteristics of the measurement tool were rigorously evaluated through a series of established procedures. Internal consistency reliability was assessed using Cronbach's alpha and composite reliability (CR), with acceptable thresholds set at values exceeding 0.70. Convergent validity was examined through a comprehensive analysis involving standardized factor loadings (greater than 0.70), average variance extracted (AVE exceeding 0.50), and composite reliability (CR above 0.70). Additionally, discriminant validity was appraised by employing the

Fornell–Larcker criterion in conjunction with the heterotrait–monotrait ratio (HTMT), where HTMT values below 0.85 indicated sufficient discriminant validity. These assessments collectively contribute to the overall validity and reliability of the measurement tool, ensuring its effectiveness in the context of the study.

3.6 Structural Equation Modeling

The hypotheses put forward were evaluated through covariance-based structural equation modeling (CB-SEM) as executed in AMOS 28. The analytical approach comprised two phases. Initially, confirmatory factor analysis (CFA) was performed to authenticate the measurement model. Subsequently, the structural model was estimated to investigate the proposed relationships among constructs. The fit of the model was assessed utilizing various goodness-of-fit indices, which included: $\chi^2/df < 3.00$; • Comparative Fit Index (CFI) > 0.90; • Tucker–Lewis Index (TLI) > 0.90; • Goodness-of-Fit Index (GFI) > 0.90; • Root Mean Square Error of Approximation (RMSEA) < 0.08; • Standardized Root Mean Square Residual (SRMR) < 0.08. The mediating role of IT governance capabilities was evaluated through the bootstrap resampling technique, employing 5,000 bootstrap samples and 95% confidence intervals.

3.7 Ethical Considerations

Participation in the study was voluntary. Respondents were informed about the objectives of the research and assured that all information would remain confidential and be used exclusively for academic purposes. No personally identifiable information was collected, and organizational data were analyzed in aggregated form.

4. Results and Data Analysis

4.1 Respondent Profile

A total of 178 valid responses were collected from manufacturing organizations. Table 1 summarizes the demographic characteristics of the respondents.

Table 1 Demographic Characteristics of Respondents (n = 178)

Characteristic	Category	Frequency	Percentage (%)
Position	Operations Manager	54	30.3
	Industrial Engineer	41	23.0
	IT Manager	36	20.2
	Continuous Improvement Manager	28	15.7
	Other Senior Managers	19	10.8
Firm Size	< 100 Employees	39	21.9
	100–250 Employees	52	29.2
	251–500 Employees	48	27.0
	> 500 Employees	39	21.9
Lean Implementation Experience	< 3 Years	37	20.8
	3–5 Years	65	36.5
	> 5 Years	76	42.7

The results indicate that the majority of respondents occupied managerial or engineering positions directly involved in operational excellence and digital transformation initiatives. Furthermore, more than 79% of participating organizations had implemented lean practices for at least three years, suggesting adequate organizational experience with process improvement programs.

4.2 Measurement Model Assessment

Reliability Analysis

Reliability was assessed using Cronbach's Alpha (α) and Composite Reliability (CR).

Table 2 Reliability and Convergent Validity Assessment

Construct	Items	Cronbach's α	CR	AVE
Lean Manufacturing Practices (LMP)	5	0.901	0.917	0.689
IT Governance Capabilities (ITGC)	5	0.893	0.908	0.664
Smart Manufacturing Performance (SMP)	5	0.914	0.928	0.721
Top Management Support (TMS)	4	0.879	0.895	0.682
Cross-Functional Collaboration (CFC)	4	0.862	0.884	0.656
Real-Time Data Analytics Capability (RDAC)	4	0.887	0.901	0.694

All Cronbach's Alpha values exceeded the recommended threshold of 0.70 [26]. Similarly, composite reliability values ranged from 0.884 to 0.928, confirming satisfactory internal consistency. The average variance extracted (AVE) values were above the recommended threshold of 0.50, indicating acceptable convergent validity.

Confirmatory Factor Analysis

The measurement model was assessed using CFA. The standardized factor loadings ranged from 0.721 to 0.912 and were statistically significant at $p < 0.001$. The overall measurement model demonstrated a satisfactory fit: $\chi^2/df = 1.93$, CFI = 0.948, TLI = 0.941, GFI = 0.916, RMSEA = 0.062, SRMR = 0.047 These values satisfy the recommended criteria suggested by Hair et al. [26].

4.3 Discriminant Validity

The Fornell–Larcker criterion was employed to assess discriminant validity.

Table 3 Fornell–Larcker Criterion

Construct	LMP	ITGC	SMP	TMS	CFC	RDAC
LMP	0.830					
ITGC	0.592	0.815				
SMP	0.648	0.703	0.849			
TMS	0.481	0.644	0.522	0.826		
CFC	0.432	0.611	0.486	0.544	0.810	
RDAC	0.518	0.584	0.682	0.503	0.472	0.833

The square root of AVE for each construct exceeded the corresponding inter-construct correlations, confirming discriminant validity. Additionally, all HTMT ratios were below 0.85, providing further evidence of discriminant validity.

4.4 Structural Model Evaluation

Following the validation of the measurement model, the structural model was estimated to test the proposed hypotheses. The structural model demonstrated acceptable goodness-of-fit: $\chi^2/df = 2.08$, CFI = 0.942, TLI = 0.936, GFI = 0.908, RMSEA = 0.067, SRMR = 0.051 These results indicate that the proposed framework adequately represents the observed data.

4.5 Hypothesis Testing

Table 4 Structural Path Results

Hypothesis	Relationship	β	t-value	p-value	Result
H1	LMP → SMP	0.328	4.912	<0.001	Supported
H2	LMP → ITGC	0.547	8.226	<0.001	Supported
H3	ITGC → SMP	0.416	6.748	<0.001	Supported
H5	TMS → ITGC	0.283	4.167	<0.001	Supported
H6	CFC → ITGC	0.241	3.882	<0.001	Supported
H7	RDAC → SMP	0.367	5.291	<0.001	Supported

The results demonstrate that lean manufacturing practices significantly influence smart manufacturing performance ($\beta = 0.328$, $p < 0.001$), supporting H1. Lean manufacturing also exhibited a strong positive effect on IT governance capabilities ($\beta = 0.547$, $p < 0.001$), confirming H2. Likewise, IT governance capabilities significantly enhanced smart manufacturing performance ($\beta = 0.416$, $p < 0.001$), providing support for H3. The findings further reveal that top management support and cross-functional collaboration positively contribute to the development of IT governance capabilities. Real-time data analytics capability also exerted a substantial positive influence on manufacturing performance.

4.6 Mediation Analysis

The mediating role of IT governance capabilities was examined using bootstrap analysis with 5,000 resamples.

Table 5 Mediation Analysis Results

Path	Indirect Effect	95% CI Lower	95% CI Upper	Result
LMP → ITGC → SMP	0.228	0.146	0.337	Significant

The confidence interval did not include zero, indicating a statistically significant mediation effect. Since both the direct effect ($\beta = 0.328$) and indirect effect ($\beta = 0.228$) remained significant, IT governance capabilities partially mediate the relationship between lean manufacturing and smart manufacturing performance. Therefore, H4 is supported.

4.7 Explanatory Power of the Model

The coefficient of determination (R^2) was examined to assess the predictive capability of the proposed framework.

Table 6 Coefficient of Determination

Endogenous Variable	R^2
IT Governance Capabilities	0.61
Smart Manufacturing Performance	0.69

The results indicate that lean manufacturing, top management support, and cross-functional collaboration jointly explain 61% of the variance in IT governance capabilities. Furthermore, lean manufacturing, IT governance capabilities, and real-time analytics capability explain approximately 69% of the variance in smart manufacturing performance, suggesting strong explanatory power.

4.8 Summary of Findings

Overall, the empirical findings provide robust support for the proposed framework. Lean manufacturing practices directly improve manufacturing performance while simultaneously strengthening IT governance capabilities. The results further demonstrate that IT governance acts as a critical organizational mechanism that amplifies the performance benefits of lean initiatives. Among the examined antecedents, lean manufacturing exhibited the strongest influence on IT governance capability development, whereas IT governance and real-time analytics capability emerged as major determinants of smart manufacturing performance. These findings highlight the importance of aligning operational excellence initiatives with governance and digital capabilities in Industry 4.0 environments.

5. Discussion and Implications

5.1 Discussion of Findings

The main aim of this research was to explore the combined impact of lean manufacturing practices and IT governance capabilities on smart manufacturing performance from the viewpoint of industrial engineering. The empirical results lend considerable support to the proposed conceptual framework and yield several significant insights. Initially, the findings validated that lean manufacturing practices have a positive effect on smart manufacturing performance. This outcome strengthens the assertion that lean principles continue to hold substantial relevance, even in technologically sophisticated production settings. Despite the growing integration of Industry 4.0 technologies, organizations still reap the advantages of core lean disciplines such as waste reduction, ongoing improvement, process standardization, and employee engagement. This outcome aligns with earlier research indicating that lean practices boost operational efficiency, enhance quality performance, and shorten lead times [8], [12], [17]. The results imply that digital technologies should complement rather than supplant lean thinking; indeed, lean provides the necessary organizational discipline to fully leverage the advantages of smart manufacturing initiatives. Furthermore, lean manufacturing practices were shown to significantly enhance IT governance capabilities. This finding broadens the existing literature by illustrating that the implementation of lean not only influences operational results but also aids in the cultivation of managerial and governance skills. Organizations that focus on continuous improvement typically formalize their decision-making processes, clarify roles and responsibilities, and establish accountability frameworks that bolster effective IT governance. Lastly, the beneficial impact of IT governance capabilities on smart manufacturing performance underscores the strategic significance of governance structures in digitally enabled contexts. Effective governance guarantees that technological investments are in harmony with operational priorities and organizational goals. Organizations with advanced governance capabilities are more adept at coordinating digital initiatives, managing risks, efficiently allocating resources, and transforming technological assets into business value. Furthermore, the mediation analysis indicated that IT governance capabilities partially mediate the connection between lean manufacturing practices and smart manufacturing performance. This result implies that the performance improvements linked to lean initiatives are enhanced when organizations have governance mechanisms that can align operational goals with digital resources. In essence, while lean initiatives can enhance manufacturing results on their own, their effectiveness is significantly increased when underpinned by strong IT governance frameworks. This observation constitutes one of the most important contributions of the current study. Lastly, support from top management, cross-functional collaboration, and the capability for real-time data analytics were identified as essential organizational enablers. These results highlight that the transformation to smart manufacturing goes beyond mere technological implementation and necessitates organizational commitment, interdepartmental collaboration, and analytical proficiency.

5.2 Theoretical Implications

The current research adds to the existing body of knowledge in multiple ways. Firstly, it connects two research areas that have largely developed in isolation: lean manufacturing and IT governance. Prior investigations have mainly focused on these fields separately, emphasizing either operational excellence or digital governance. By merging these viewpoints, this study offers a more thorough understanding of performance enhancement in smart manufacturing environments. Secondly, this research broadens the discourse on the business value of IT by framing IT governance capabilities as a mediating organizational mechanism, rather than simply an independent predictor of performance. This viewpoint provides a deeper insight into how governance capabilities create value in industrial contexts. Thirdly, from the perspective of industrial engineering, the suggested framework promotes systems thinking by acknowledging that manufacturing performance arises from the interactions among individuals, processes, technologies, and governance frameworks. This comprehensive viewpoint is closely aligned with the interdisciplinary essence of industrial engineering. Lastly, the recognition of essential organizational enablers enriches contingency-based approaches to digital transformation. The results suggest that the effectiveness of lean-digital integration is contingent upon organizational conditions that promote collaboration, learning, and strategic alignment.

5.3 Managerial Implications

The results of this research offer numerous practical implications for managers in the manufacturing sector. First, it is crucial for managers to refrain from perceiving lean manufacturing and digital transformation as distinct initiatives that compete for the same organizational resources. Rather, these initiatives ought to be conceptualized and executed as complementary strategies. Second, any investments made in Industry 4.0 technologies should be paired with the implementation of formal IT governance frameworks. Organizations need to delineate decision-making rights, clarify roles and responsibilities, establish monitoring systems, and create accountability structures to ensure that technological investments yield measurable benefits. Third, it is imperative for senior leadership to actively endorse transformation initiatives. The commitment of top management is vital for securing necessary resources, communicating strategic priorities, and mitigating resistance to organizational change. Fourth, companies should promote collaboration between their industrial engineering and IT departments. Cross-functional teams enhance knowledge sharing and ensure that operational needs are adequately represented in digital solutions. Fifth, organizations must bolster their capabilities in real-time analytics. The capacity to convert production data into actionable insights facilitates predictive decision-making, increases responsiveness, and enhances operational performance. In summary, these managerial strategies can aid firms in cultivating agile and resilient manufacturing systems that are capable of adapting to swiftly evolving competitive landscapes.

5.4 Comparison with Previous Studies

Several conclusions drawn from this research support earlier empirical findings. The positive correlation between lean manufacturing and operational performance aligns with the studies conducted by Shah and Ward [8], Netland and Powell [9], and Yilmaz et al. [12]. In a similar vein, the identified impact of IT governance capabilities on organizational performance corresponds with the results presented by Joshi et al. [4] and De Haes and Van Grembergen [5]. Nonetheless, this current study builds upon previous research by empirically illustrating the mediating function of IT governance capabilities. While past studies acknowledged the significance of governance and digital maturity, only a limited number have explored how governance mechanisms can enhance the effectiveness of lean initiatives in smart manufacturing contexts. Consequently, the proposed framework provides new empirical insights and delivers a more cohesive understanding of value creation within Industry 4.0 environments.

6. Conclusion, Limitations, and Future Research Directions

6.1 Conclusion

The shift towards Industry 4.0 has necessitated that manufacturing firms reevaluate their approaches to developing and managing operational excellence alongside digital capabilities. In this regard, the current study aimed to explore the interaction between lean manufacturing practices and IT governance capabilities in enhancing smart manufacturing performance from the perspective of industrial engineering. Building on the tenets of lean manufacturing, IT governance, and smart manufacturing, this research proposed and empirically tested an integrated framework that elucidates how operational and digital capabilities collectively enhance organizational performance. Employing a sequential mixed-methods strategy that included expert validation via the Delphi technique and quantitative analysis through structural equation modeling, the study examined the interrelations among lean manufacturing practices, IT governance capabilities, and smart manufacturing performance. The results indicated that lean manufacturing practices remain pivotal in advancing organizational outcomes, even in production environments that are heavily digitized. Companies that exhibit higher levels of continuous improvement, waste reduction, process standardization, and employee engagement achieved superior operational performance. Moreover, the findings suggested that the implementation of lean practices significantly fosters the development of IT governance capabilities. Organizations that prioritize operational excellence are likely to create more structured decision-making frameworks, clearer accountability systems, and enhanced coordination processes, all of which support the effective governance of technological resources. Another significant discovery was the direct positive influence of IT governance capabilities on the performance of smart manufacturing. Organizations with well-established governance frameworks were more adept at aligning technology investments with their operational goals, optimizing the use of digital resources, and converting technological initiatives into quantifiable business value. Crucially, the research revealed that IT governance capabilities partially mediate the connection between lean manufacturing practices and smart manufacturing performance. This insight indicates that governance mechanisms serve as organizational facilitators that enhance the advantages of lean initiatives within smart manufacturing contexts. Furthermore, support from top management, cross-functional collaboration, and the capability for real-time data analytics emerged as critical elements that promote successful transformation. These organizational capabilities aid in the integration of industrial engineering practices with digital technologies, thereby enhancing agility, resilience, and responsiveness. In summary, the findings underscore that achieving a sustainable competitive advantage in the era of Industry 4.0 cannot rely solely on investments in cutting-edge technologies. Instead, organizations must concurrently develop operational discipline, governance maturity, and collaborative capabilities to fully leverage the value derived from digital transformation efforts.

6.2 Theoretical Contributions

This research offers multiple theoretical contributions. Firstly, it combines lean manufacturing with IT governance into a cohesive framework, thus connecting two areas of literature that have historically developed separately.

Secondly, it enhances the business value of IT perspective by pinpointing IT governance capabilities as a mediating factor through which operational practices affect manufacturing results. Thirdly, it propels industrial engineering research forward by employing a systems-oriented approach that acknowledges the interrelatedness of processes, technologies, information, and organizational structures. Lastly, it provides empirical support to the burgeoning smart manufacturing literature by illustrating how complementary organizational capabilities influence performance outcomes.

6.3 Practical Contributions

From a managerial perspective, the suggested framework provides a pragmatic guide for organizations aiming for digital transformation. Managers should: • Combine lean initiatives with digital transformation efforts instead of executing them separately;• Create formal IT governance structures to guarantee alignment between technological investments and operational goals;• Foster collaboration among industrial engineering, operations, and IT divisions;• Enhance leadership engagement and allocate sufficient resources for transformation projects;• Build real-time analytics capabilities to facilitate evidence-based decision-making and ongoing improvement. By implementing these strategies, manufacturing companies can boost productivity, adaptability, and responsiveness while improving their capacity to manage environmental uncertainties.

6.4 Research Limitations

Notwithstanding its valuable contributions, the current study presents several limitations. The quantitative phase was based on cross-sectional data gathered at a singular moment in time. As a result, any causal relationships must be interpreted with caution. Second, the research was exclusively centered on manufacturing firms. Thus, the applicability of the findings to service organizations or other industrial settings remains uncertain. Third, the reliance on self-reported survey measures may lead to common method bias, even with the procedural safeguards implemented during data collection and statistical analysis. Fourth, while the sample encompassed various manufacturing sectors, the differences among industries were not specifically analyzed. Characteristics unique to each sector may affect the success of lean and governance initiatives. Lastly, the study utilized a perceptual approach to measuring performance. Incorporating objective operational indicators could yield a more thorough evaluation of organizational performance. Numerous avenues are available for subsequent research. To begin with, longitudinal studies ought to be undertaken to investigate the progression of lean practices and IT governance capabilities over time, as well as their impact on organizational outcomes during various phases of digital transformation. Additionally, forthcoming research could seek to validate the suggested framework through the use of objective performance metrics, such as actual OEE values, defect rates, inventory turnover, and financial indicators. Moreover, comparative analyses across different countries and industrial sectors may yield richer insights into the contextual elements that influence lean–digital integration. Furthermore, scholars might explore further mediating and moderating factors, including organizational culture, digital maturity, employee skills, and innovation capacity. In addition, future investigations could utilize sophisticated analytical methods, such as multi-group SEM, fuzzy-set qualitative comparative analysis (fsQCA), machine learning, or system dynamics modeling, to reveal more intricate relationships among the constructs. Lastly, as manufacturing systems continue to advance, it is imperative for future research to examine the ramifications of emerging technologies—such as generative artificial intelligence, digital twins, autonomous decision systems, and edge computing—on the governance and management of smart manufacturing ecosystems.

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