

INTEGRATION OF ARTIFICIAL INTELLIGENCE WITH LEAN SYSTEMS IN THE CONTEXT OF INDUSTRY 5.0: A SYSTEMATIC REVIEW AND CONCEPTUAL MODEL

Nikolina Lulevska

University “St. Kliment Ohridski” – Bitola, Faculty of Technical Sciences – Bitola, N. Macedonia,
nikolina.lulevska@uklo.edu.mk

ORCID ID: 0009-0009-5821-3205

Elizabeta Hristovska

University “St. Kliment Ohridski” – Bitola, Faculty of Technical Sciences – Bitola, N. Macedonia,
elizabeta.hristovska@uklo.edu.mk

ORCID ID: 0009-0007-5580-9738

Abstract: Modern manufacturing systems face growing complexity, dynamic market demands, and the need for sustainable, flexible development. In this context, Industry 5.0 represents an approach that emphasizes integrating advanced technologies with a human-centered perspective in manufacturing systems. Artificial intelligence enables the analysis of large volumes of data, process optimization, and improved decision-making, while lean systems focus on eliminating waste and increasing value. This paper analyzes the integration of artificial intelligence with lean systems within the Industry 5.0 framework, drawing on relevant scientific literature. The results indicate that this integration enables the development of proactive and predictive manufacturing systems that improve efficiency, productivity, and quality. Furthermore, the paper proposes a conceptual framework that explains the relationship among artificial intelligence, lean systems, and the principles of Industry 5.0, contributing to the systematization of existing knowledge and the identification of research gaps to support future empirical research and practical application in modern industrial systems.

Keywords: artificial intelligence, industrial engineering, process optimization, lean systems, Industry 5.0.

1. INTRODUCTION

Global market changes, the introduction of new technologies in industry, rising consumer demands, and intensified competition and market constraints require a new, more efficient approach to managing manufacturing systems. In this dynamic context, organizations face pressure to develop fast, flexible, and sustainable solutions to improve their performance.

In the 21st century, industrial engineering has undergone a significant transformation driven by rapid advances in digital technologies and artificial intelligence (AI). These changes are often associated with the Fourth Industrial Revolution (Industry 4.0), characterized by digital connectivity, automation, and intelligent, data-driven decision-making (Tashkinov, 2024). Although Industry 4.0 has enabled significant advances in the efficiency and automation of manufacturing systems, it has also introduced new challenges, including increased system complexity, greater flexibility requirements, and a redefinition of the human role in industrial processes. This evolution, which began with mechanization through steam-powered machines and has progressed to modern digital and intelligent systems, has drastically transformed production methods. In this context, the emergence of Industry 5.0 signals a new era of industrial expansion. This new industrial revolution emphasizes collaboration between humans and advanced technologies to develop manufacturing systems that are more flexible, sustainable, and adaptive.

Artificial intelligence has emerged as a key technology supporting this transition through data analysis, process optimization, and improved decision-making, particularly when combined with the lean systems approach (Shahin et al., 2024). The lean concept was developed to maximize efficiency by systematically eliminating waste, enhancing customer value, and optimizing resource use. Its further evolution reflects a response to a fluctuating, competitive business environment (Sundar et al., 2014).

Although lean principles significantly improve operational efficiency, they alone are insufficient to fully address the challenges of the digital era, especially in highly variable environments and when real-time system adaptation is required. In this regard, integrating artificial intelligence into lean systems offers significant benefits, including:

- improved prediction of defects and process errors,
- real-time optimization of production flows,
- increased system adaptability and flexibility,
- as well as more efficient data-driven decision-making.

In recent years, AI and lean have increasingly been studied as separate approaches to improving the performance of manufacturing systems. However, their integration has not yet been systematically explored,

leaving a significant gap in the scientific literature. This gap is a key motivation for this research and underscores its scientific relevance and originality.

Based on this, the following research question is posed:

How does integrating artificial intelligence with lean systems affect the performance of manufacturing systems within the Industry 5.0 framework?

This paper aims to analyze and systematize the integration of AI and lean systems in the context of Industry 5.0 by reviewing relevant scientific literature to identify key trends, research gaps, and future development directions.

2. THEORETICAL BACKGROUND AND LITERATURE REVIEW

Artificial intelligence in industrial engineering

Industrial engineering has undergone a significant transformation in recent decades, driven by advances in digital technologies and the growing need to optimize complex manufacturing systems. Within this context, AI has emerged as a key enabling technology for enhancing the efficiency, productivity, and quality of industrial processes (Al Bashar & Khan, 2017; Bhambri & Rani, 2023).

AI is rapidly expanding across various fields, significantly influencing business operations, organizational performance, and quality management. Its application enhances decision-making through advanced data processing, model development, and result interpretation (Jan et al., 2023; Mateo & Redchuk, 2024; Rifqi et al., 2021). AI is generally defined as the capability of machines to simulate human cognitive functions through data processing, learning, and adaptive decision-making (Jan et al., 2023), and as “the ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings” (Encyclopaedia Britannica, n.d.).

Early contributions by researchers such as Herbert A. Simon highlighted the potential of intelligent systems to learn from data and identify optimal solutions without direct human intervention (Carnegie Mellon University, n.d.). This marked a logical direction for the further development of artificial intelligence and its application to lean systems.

Contemporary research shows that AI enables a shift from reactive to proactive and predictive management, particularly in quality control, logistics, process management, and maintenance. As shown in Table 1, AI-based approaches improve accuracy, processing speed, and resource utilization, but their implementation requires quality data, adequate infrastructure, and qualified personnel.

Table 1. Application of artificial intelligence in industrial engineering compared to traditional approaches

Area	Traditional Approach	AI-Based Approach	Advantages of AI Implementation
Quality Management	Manual inspection and statistical methods	Machine learning and computer vision for automatic defect detection	Increased accuracy, faster inspection, and reduction of human errors
Statistical Process Control (SPC)	Control charts and retrospective analysis	Predictive models and real-time anomaly detection	Early detection of deviations and improved process stability
Lean Manufacturing	Manual process and waste assessment	AI-driven data analysis and predictive optimization	Improved waste identification and increased efficiency
Process Management	Heuristic methods and expert-based decision-making	Optimization algorithms and intelligent scheduling	Optimal resource utilization and reduced cycle time
Equipment Maintenance	Periodic and reactive maintenance	Machine learning-based predictive maintenance	Reduced downtime and maintenance costs
Logistics and Inventory Management	Historical data and simple forecasting models	Advanced AI-based forecasting models	Improved forecasting accuracy and inventory optimization

Source: Author’s own elaboration based on the literature (Al Bashar & Khan, 2017)

Lean systems in the context of Industry 4.0 and Industry 5.0

Lean systems in Industry 4.0

Lean systems improve manufacturing efficiency by eliminating waste, optimizing processes, and focusing on customer value (Sundar et al., 2014).

With Industry 4.0, lean systems are enhanced through technologies such as IoT, Big Data, cloud systems, and artificial intelligence. These technologies enable real-time monitoring, analysis, and optimization of manufacturing processes, leading to the development of “Digital Lean” (Ayoubi et al., 2023; Kumar et al., 2022). IoT sensors, for example, allow continuous monitoring of machines, while Big Data supports the identification of process inefficiencies.

Studies show that integrating lean principles with Industry 4.0 technologies can improve productivity, reduce costs, and increase energy efficiency (Rengarajan, 2025). Software tools such as Jira also support better organization and monitoring of work processes, with practices from the IT sector being applicable to mechanical engineering (Avramovska et al., 2024).

However, traditional lean systems face limitations in dynamic and complex manufacturing environments, creating a need for further integration with advanced digital technologies.

Lean systems in Industry 5.0

Lean systems focus on eliminating waste, continuous improvement, and customer value through production process optimization. However, increasing complexity, rapid technological change, and demand for customization require lean systems to evolve beyond traditional approaches.

Within Industry 5.0, lean systems are enhanced through advanced technologies and a human-centric approach that emphasizes human–technology collaboration, sustainability, flexibility, and adaptability (Breque et al., 2021; Rajkumar et al., 2024). The integration of digital technologies, particularly artificial intelligence, enables the transition from static lean practices to dynamic and intelligent systems capable of real-time analysis and adaptation.

This integration contributes to the development of “Human-Centric Lean,” which combines efficiency and productivity with employee well-being, creativity, and participation in decision-making (Breque et al., 2021; Rajkumar et al., 2024; Roveda, 2024). AI and digital tools further enhance lean practices such as value stream mapping, quality management, and continuous improvement through automated analysis and predictive management.

Research shows that Lean–Industry 5.0 integration improves human–technology collaboration, production flexibility, and responsiveness to individualized market demands (Alves et al., 2023; Fani et al., 2024). Nevertheless, successful implementation requires organizational transformation, technological integration, and the development of digital and interdisciplinary employee skills.

Artificial Intelligence in Industry 5.0

The role of artificial intelligence in Industry 5.0

The development of industrial systems has evolved through several industrial revolutions, including Industry 1.0, characterized by mechanization and steam power, Industry 2.0, marked by mass production and electrification, Industry 3.0, defined by automation and digital technologies, and Industry 4.0, which integrates cyber-physical systems, IoT, and artificial intelligence (Groumpos, 2021). But, artificial intelligence plays a key role in realizing Industry 5.0 by enabling the intelligent integration of data, processes, and decisions across manufacturing systems. By applying machine learning, predictive analytics, and intelligent algorithms, AI enables adaptive process management and personalized production (Breque et al., 2021; Rajkumar et al., 2024; Roveda, 2024).

One of the most significant features of Industry 5.0 is the collaboration between humans and machines, with AI systems supporting operators by delivering relevant information and real-time recommendations. This approach not only increases efficiency but also improves safety and working conditions.

In addition, the European Commission highlights human-centricity, sustainability, and resilience as key pillars of Industry 5.0 (Breque et al., 2021), with AI playing a central role in advancing these pillars.

However, the application of AI in Industry 5.0 poses challenges, including ethical issues, data security, and the need for new workforce skills, underscoring the need for further research.

Literature synthesis and basis for the conceptual model

The analysis of the relevant scientific literature indicates that artificial intelligence, lean systems, and the concept of Industry 5.0 are interrelated and complementary approaches to developing modern production systems. Although each of these concepts is the subject of significant research, their integration remains insufficiently systematized in the existing literature.

Artificial intelligence enables intelligent data processing, predictive analytics, and adaptive process management, all of which directly advance lean principles. Conversely, lean systems provide an organizational and process framework for eliminating waste and optimizing the value chain, thereby creating a foundation for more efficient implementation of AI technologies.

In the context of Industry 5.0, this integration takes on an additional dimension by emphasizing a human-centric approach and the sustainability and resilience of systems. The literature indicates that the synergy between AI and lean systems enables the development of intelligent, flexible, and adaptive production systems in which humans and technology work together.

However, significant research gaps have also been identified. First, there is a lack of integrated models that explain the interconnections among AI, lean systems, and Industry 5.0 principles. Second, much of the existing research focuses on individual aspects of this integration rather than on a holistic approach. Third, there is a lack of conceptual frameworks that systematically link technological, organizational, and human factors into a single model. Based on these observations, there is a need to develop an integrated conceptual model that unifies the key elements identified in the literature. Hence, this paper proposes a conceptual model that illustrates the

relationships among artificial intelligence, lean systems, and Industry 5.0 principles, defining their mutual interactions and their impact on production performance.

The proposed model is a theoretical synthesis of existing scientific knowledge and aims to provide a foundation for future empirical research and guidelines for practical application in modern industrial systems.

3. METHODOLOGY

This research is based on a systematic review of the relevant scientific literature to examine the integration of artificial intelligence and lean systems within the Industry 5.0 framework. To this end, a structured methodological approach was applied, including a literature search strategy, selection criteria, and a method for analyzing and synthesizing the selected scientific papers.

Search strategy

The literature search was conducted in Google Scholar, ScienceDirect, and IEEE Xplore databases. To identify relevant scientific papers, keyword combinations and logical operators (AND, OR) were used, including:

- “lean manufacturing” AND “artificial intelligence” AND “Industry 5.0.”
- “lean systems” AND “artificial intelligence” AND “smart manufacturing.”
- (“lean manufacturing” OR “lean system”) AND (“artificial intelligence” OR “machine learning”) AND “Industry 5.0”.

The search was limited to scientific papers published between 2020 and 2025 to capture the most up-to-date research on artificial intelligence, lean systems, and Industry 5.0.

Inclusion and exclusion criteria

To ensure the relevance and scientific quality of the sources analyzed, inclusion and exclusion criteria for the scientific papers were established.

Inclusion criteria:

- scientific papers published in peer-reviewed journals and conference proceedings,
- papers written in English,
- papers related to the fields of industrial engineering, manufacturing, quality management, and management,
- papers analyzing the application of artificial intelligence, lean systems, or their integration.

Exclusion criteria:

- papers without an available full text,
- papers with limited relevance to the research topic,
- duplicate publications,
- publications of a non-peer-reviewed, non-scholarly nature.

Paper selection process

In the initial phase of the research, a total of 4435 scientific papers were identified through searches of selected academic databases. After removing duplicates and applying the defined inclusion and exclusion criteria, the number of papers was reduced to 20 relevant sources for more detailed analysis.

The paper selection process was carried out in several consecutive stages:

- Review of titles and abstracts
- Preliminary selection of relevant papers
- Detailed analysis of the full text
- Final selection of papers for analysis

From the selected papers, the most representative studies were systematized and presented in Table 2 to identify key trends, approaches, and applications of artificial intelligence in lean systems within the context of Industry 5.0. Due to space limitations, Table 2 presents the five most representative studies from the twenty papers included in the final analysis.

Table 2. Overview of selected papers

No.	Title	Authors	Source / Year	Key Focus
1	The Synergy of Lean Principles and Artificial Intelligence: Towards Smart and Sustainable Operations	Mingyuan Lin, Minyan Xia	EIIT Conference Proceedings (2025)	AI-enhanced Lean for Industry 5.0, focusing on human-machine collaboration and sustainability.
2	Exploring the Integration of Artificial Intelligence into Lean Six Sigma Methodologies: A Roadmap for Enhancing Manufacturing Efficiency and Quality	N. C. Dascălu, L.-C. Coca, E. Loghin, M. Pislaru	International Conference on Business Excellence (2025)	AI-augmented DMAIC and the transition from Industry 4.0 to Industry 5.0.

3	Lean Principles Integration with Digital Technologies: A Synergistic Approach to Modern Manufacturing	Charles C. Okpala, Chukwudi E. Udu, Emmanuel C. Chukwumunya	International Journal of Industrial and Production Engineering (2024)	Examines integration of AI, IoT, and digital twins as extensions of Lean practices for Industry 5.0 manufacturing systems.
4	Integrating AI with Lean Manufacturing in the Context of Industry 4.0/5.0: Current Trends and Applications	Aze-Eddine Boursali, Hichem Haddou Benderbal, Mehdi Souier	IFIP Advances in Information and Communication Technology (2024)	AI applications in predictive maintenance and production optimization.
5	Integration of Lean Six Sigma, Artificial Intelligence, and Digital Twin Technologies for Smart Manufacturing Systems	Md Foyzal Hossain	Review of Applied Science and Technology (2025)	AI and digital twins for Lean Six Sigma and smart manufacturing.

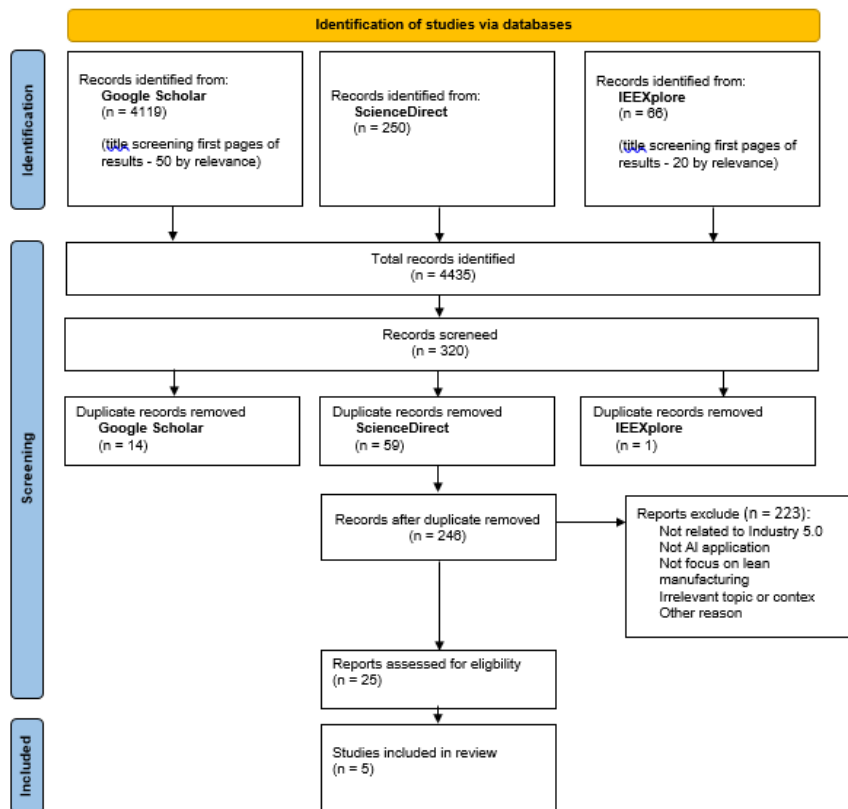
Source: Author's compilation based on the selected literature

Literature analysis method

The analysis of the selected scientific papers was conducted using a qualitative approach, with a focus on identifying and analyzing: key concepts and definitions, applications of artificial intelligence in lean systems, integration tools and technologies, benefits and limitations, and research gaps.

The analysis results were organized into thematic categories to provide a structured, comprehensive understanding of the study area. Furthermore, drawing on a synthesis of relevant literature, a conceptual model was developed to explain the relationships between artificial intelligence, lean systems, and Industry 5.0 principles.

Fig. 1. Flow diagram of literature screening and inclusion (PRISMA 2020)



Source: Authors' own elaboration based on the PRISMA 2020 statement

4. RESULTS AND DISCUSSION OF THE LITERATURE REVIEW

This section synthesizes key findings from the literature, with a particular focus on how artificial intelligence enhances lean systems in the context of Industry 5.0. The results are organized into three interrelated thematic

areas that encompass the technological, methodological, and application dimensions of integrating artificial intelligence into lean systems.

Integration of Lean systems in Industry 4.0 and Industry 5.0

The literature analysis indicates that lean systems have evolved through integration with Industry 4.0 technologies, including the Internet of Things (IoT), Big Data analytics, and cyber-physical systems, enabling greater transparency and real-time process optimization. Within Industry 5.0, this integration emphasizes human–technology collaboration and expands lean principles to include sustainability, flexibility, and human-centeredness. Thus, lean systems are evolving from traditional approaches toward adaptive and intelligent systems in dynamic, digitally connected environments.

Tools and technologies for integrating artificial intelligence with lean systems

The literature identifies several key AI technologies with direct applications in lean systems. The most important of these include machine learning, predictive analytics, big data processing, and intelligent decision support systems.

These tools enhance traditional lean practices, including value stream mapping, quality control, and process management. The application of AI within the DMAIC cycle is particularly significant, enabling automated data analysis and real-time detection of deviations.

In addition, AI enables the transition from reactive to predictive and adaptive systems, thereby leading to reduced process variability and improving operational stability.

Applications and effects of artificial intelligence in lean manufacturing

The literature review indicates that applying artificial intelligence in lean manufacturing significantly affects the operational performance of industrial systems. The most commonly reported effects include improved quality, fewer defects, optimized resource use, and increased productivity.

The application of AI in predictive maintenance is particularly significant, enabling early detection of potential defects through real-time data analysis and reducing unplanned downtime. In addition, AI systems improve inventory management and logistics by applying advanced prognostic models and optimizing supply chains.

However, the literature indicates that despite the significant benefits, implementing AI also has limitations, including the need for high-quality data, technological infrastructure, and appropriately trained personnel. These factors represent key challenges for broader industrial implementation.

5. CONCEPTUAL MODEL FOR INTEGRATION OF ARTIFICIAL INTELLIGENCE AND LEAN SYSTEMS IN INDUSTRY 5.0

The conceptual model in Figure 2 illustrates the relationships among AI, lean systems, and the principles of Industry 5.0. Within the model, a key mechanism is the development of AI–Lean integration capability, which mediates the relationship between technological solutions and organizational performance.

This integration capability enables the effective implementation and operational integration of AI and lean practices across manufacturing and managerial processes. As a result, process efficiency, production quality, system flexibility, and waste reduction improve, directly enhancing overall manufacturing performance in the context of Industry 5.0.

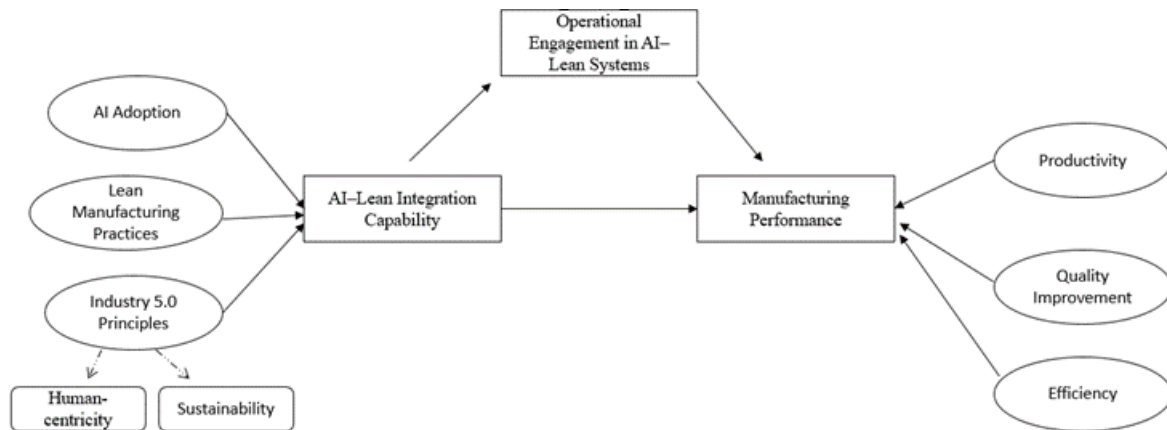
The proposed model is conceptual and has not been empirically validated, but rather a conceptual framework developed through a systematic analysis and synthesis of relevant scientific literature. Its purpose is to identify, structure, and explain the interrelationships among key factors that influence the successful integration of AI and lean approaches in modern manufacturing systems.

Connection with the PRISMA Diagram

The conceptual model is derived directly from the systematic literature selection process shown in the PRISMA diagram (Figure 1). Across the identification, screening, eligibility assessment, and final inclusion stages, scientific papers relevant to the integration of AI, lean systems, and the principles of Industry 5.0 were selected.

In this way, the PRISMA diagram ensures methodological transparency and reproducibility of the literature selection process. At the same time, the conceptual model (Figure 2) presents the results of the analytical synthesis and theoretical integration of the findings.

Fig. 2. Conceptual model for integrating AI and Lean in Industry 5.0



Source: Authors' own elaboration based on the systematic analysis and synthesis of the selected literature.

Figure 2 presents an integrated framework that links artificial intelligence and Lean systems by developing an AI–Lean integration capability, a key mechanism for transforming data, processes, and organizational learning toward Industry 5.0. The model emphasizes interactions among technological capabilities, human factors, and organizational processes to achieve sustainable, high-performance manufacturing systems.

Recommendations for the integration of AI and Lean in Industry 5.0

To successfully implement integrated AI–lean systems in the context of Industry 5.0, the following guidelines are recommended:

- Strategic integration of AI and Lean approaches into the organizational structure and management,
- Data-driven decision-making, advanced analytics, and machine learning,
- Strengthening the organization's technological and digital capacities,
- Continuous development of employee knowledge, skills, and competencies,
- Phased, controlled implementation of AI solutions to reduce risk and increase adaptability,
- Alignment with the human-centric principles of Industry 5.0 and human-machine collaboration,
- Systematic optimization of processes and waste minimization across all stages of production.

6. LIMITATIONS OF THE STUDY

Although this study offers relevant theoretical insights and a conceptual framework, it has several limitations that should be taken into account when interpreting the results.

First, the research is based on a literature review and the development of a conceptual model without empirical validation, which may limit the applicability of the findings in real-world industrial settings.

Second, despite using a systematic approach (PRISMA), the analysis relies on selected scientific sources, potentially leaving some relevant studies, new technologies, or industrial practices uncovered.

Additionally, the dynamic nature of areas such as artificial intelligence and Industry 5.0 implies rapid technological and methodological evolution, which may render some of the literature analyzed less relevant.

Future research could empirically validate the proposed conceptual model through case studies or experimental analyses in real-world industrial settings. Additionally, expanding the database and integrating quantitative methods would enable more in-depth analysis of AI's impact on Lean systems in real production environments.

7. RESEARCH CONTRIBUTION

This study makes several valuable contributions to industrial engineering:

- Theoretical contribution: The research advances existing knowledge by integrating artificial intelligence, lean systems, and Industry 5.0 into a unified conceptual model that highlights their interrelationships in modern manufacturing systems.
- Contribution to conceptual model design: A clear understanding of how AI technologies advance Lean philosophy through predictive analytics, real-time optimization, and data-driven decision-making within the human-centric systems of Industry 5.0 is provided.
- Methodological contribution: Applying the PRISMA approach ensures systematicity, transparency, and reproducibility in selecting the literature, thereby strengthening the scientific validity of the conceptual model.
- Basis for future research: The study lays the groundwork for further empirical analyses, with a focus on practical application, quantitative validation, and the development of operational models that integrate artificial intelligence and lean systems in real-world industrial settings.

8. CONCLUSION

This study examines the integration of artificial intelligence and lean systems within the context of Industry 5.0. The analysis indicates that the integration of AI and lean approaches enables more efficient optimization of production processes, improves data-driven decision-making, and enhances productivity, quality, and operational efficiency.

The findings highlight the importance of human–AI collaboration, technological capabilities, and operational integration as key factors for improving production performance and for transforming traditional production systems into adaptive, human-centric systems in Industry 5.0.

Although the study is theoretical, the proposed conceptual model provides a solid foundation for future empirical research and practical applications in industrial settings.

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