International Journal of Production Management and Engineering

https://doi.org/10.4995/ijpme.2024.21473
Received: 2024-04-03 Accepted: 2024-06-29

Understanding the relationship, trends, and integration challenges between lean manufacturing and industry 4.0. A literature review

Tariq Benslimane *[a1], Rajaa Benabbou [a2], Salma Mouatassim [a3], Jamal Benhra [a4]

[a] Advanced Laboratory in Industrial Engineering and Logistics (LARILE) National School of Electrical and Mechanical Engineering, Hassan II University Casablanca 20190, Morocco.

[a1] tariq.benslimane-etu@etu.univh2c.ma, [a2] r.benabbou@ensem.ac.ma, [a3] a.mouatassim@ensem.ac.ma, [a4] jamalbenhra@gmail.com

Abstract:

This research investigates the synergistic relationship between Lean Manufacturing and Industry 4.0, crucial paradigms in modern industry, through a literature review of 60 scientific articles published from January 2013 to November 2023. The study reveals a tripartite relationship: Industry 4.0 technologies amplify Lean Manufacturing's efficiency; Lean Manufacturing principles facilitate Industry 4.0 adoption; and their interaction fosters mutual enhancement, indicating a dynamic interplay. The results show three main trends: combining Industry 4.0 technologies, especially the Internet of Things, with Lean Manufacturing principles to make things more efficient and productive; highlighting the important role of Lean Manufacturing and Industry 4.0 in tackling sustainability issues and encouraging eco-friendly practices; and combining Lean principles with Industry 4.0 as a step toward Industry 5.0. Challenges include the need for a cultural transformation to align Lean's simplicity with Industry 4.0's complexity, resolve compatibility issues between legacy systems and new technologies, enhance data management and cybersecurity, address skill deficiencies through staff training, and ensure supplier and partner alignment. This research enriches academic and industrial discourse by presenting a novel outlook on the convergence of lean manufacturing and Industry 4.0, highlighting its significance for future works.

Key words:

Lean manufacturing, industry 4.0, Literature review, digitalization, smart manufacturing.

1. Introduction

Lean Manufacturing (LM) and Industry 4.0 (I4.0) play pivotal roles in bolstering manufacturing resilience during challenging times like the COVID-19 pandemic, the conflict in Ukraine, and semiconductor shortages in the automotive sector (Ardolino et al., 2022). Lean principles, focused on waste reduction and process optimization, enable manufacturers to adapt swiftly to disruptions, ensuring efficient resource allocation and reduced costs (Chiarini & Kumar, 2021).

Meanwhile, Industry 4.0's integration of advanced technologies such as automation, Internet of Things (IoT) , and data analytics enhances real-time visibility and predictive maintenance capabilities, minimizing supply chain disruptions and increasing production efficiency (Zhan, 2022). Together, Lean Manufacturing and Industry 4.0 provide the agility and strategic tools necessary for the manufacturing industry to mitigate risks and thrive amidst uncertainty (Rossini et al., 2019).

The correlation between I4.0 and LM is a subject of significant academic research and inquiry, as academics and practitioners seek to assess and elucidate the intricate interplay between these two transformative concepts in the manufacturing domain. While it is widely recognized that I4.0 technologies, including data analytics, IoT, and artificial intelligence (AI), can synergistically boost

To cite this article: Benslimane, T., Benabbou, R., Mouatassim, S., Benhra, J. (2024). Understanding the relationship, trends, and integration challenges between lean manufacturing and industry 4.0. A literature review. *International Journal of Production Management and Engineering, 12*(2), 195-209. https://doi.org/10.4995/ijpme.2024.21473

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

Lean principles by offering real-time data, predictive analytics, and automation capabilities, academic authors are delving deeper to systematically evaluate the extent and nuances of this symbiotic relationship (Rossini et al., 2019; Sony, 2018) . They are actively developing integration frameworks to guide organizations in harmonizing the best practices of both approaches, resulting in optimized production processes and improved enterprise performance. Through empirical studies and practical examples, researchers are shedding light on how I4.0 might enhance LM processes, fostering a holistic and data-driven approach to operational excellence in diverse industrial settings (Rossini et al., 2023).

On the other hand, LM serves as a critical catalyst for the seamless integration of Industry 4.0, promoting a culture of efficiency, waste reduction, and continuous improvement within organizations. By optimizing existing processes and instilling a data-driven mindset, Lean principles lay the groundwork for Industry 4.0's digital transformations (Rossini et al., 2023). This cultural alignment empowers employees to embrace advanced technologies, and Lean's focus on streamlined workflows and just-in-time production harmonizes naturally with Industry 4.0's demand-driven and data-driven manufacturing paradigms. The result is a synergistic relationship where LM enhances the readiness and effectiveness of I4.0 implementations, ultimately, this leads to improved operational efficiency, decreased costs, and enhanced competitiveness in the contemporary manufacturing industry (Buer et al., 2021).

Recent literature has extensively explored the relationship between I4.0 and LM, as well as the trends and obstacles associated with integrating these two concepts. Researchers have examined these subjects separately, identifying how I4.0 technologies can enhance lean practices and the challenges of integrating them. However, there is a notable gap in the literature regarding a comprehensive examination that addresses all three aspects—relationship, trends, and obstacles—in a single study. The main objective of our work is to fill this gap by conducting a literature review to answer the following research questions:

RQ 1: How can we characterize the relationship between LM and I4.0?

RQ 2: What are the main trends of the integration between LM and I4.0 and the obstacles to this integration?

Within this context, the purpose of this article is to analyze the relationship between LM and I4.0 , along with the current trends and challenges related to combining LM and I4.0. The following sections of this work are organized as follows. Section 2 provides a detailed explanation of the methodology that was used, including a review of relevant literature. The outcomes of the study are discussed in Sections 3. The paper concludes in Section 4 and presents future research directions.

2. Methodology: Literature Review

A Literature Review (LR) was utilized as the research methodology for this investigation. A LR is a methodical and thorough process used to collect, assess, and integrate current academics works that are pertinent to a certain study subject (Fink, 2005). This approach entails a systematic and extensive search procedure to uncover relevant research from credible sources, followed by a rigorous evaluation of their quality and a comprehensive synthesis of their results. Its objective is to offer a thorough and impartial summary of the existing knowledge in the selected study field (Kitchenham & Charters, 2007).

Throughout our LR, we followed the technique and principles set forth by Kitchenham (2004) and Kitchenham and Charters (2007), guaranteeing the methodological rigor and dependability of these study among the academic community. The followed steps are elucidated below:

- Define the research questions : This stage seeks to precisely identify the research topic or objectives of the research investigation.
- Develop a Research Protocol: This phase aims to establish a comprehensive review protocol that delineates the extent of the review, encompassing criteria for inclusion and exclusion, search methodology, plan for extracting data, and standards for evaluating quality.
- Conduct a Comprehensive Search: The objective of this phase is to identify relevant databases, libraries, and other sources to search for studies. Construct a well-structured search strategy using keywords, Boolean operators, and controlled vocabulary terms. Execute the search systematically to retrieve relevant publications.
- Data Extraction, Quality assessment and Data Synthesis: The objective of this phase is to extract relevant data from the selected studies,

 Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

evaluate the quality of the selected studies, and synthesize the findings from the selected studies by summarizing and organizing the data to identify common themes, patterns, and trends.

- Report and Interpret Results: This step aims to prepare a comprehensive report of the LR, including the research question, search methodology, study selection process, data extraction, quality assessment, and synthesized findings. It interprets the results in the context of the research question.
- Conclusion and Implications: The purpose of this step is to derive conclusions from the synthesis material and analyze the implications of the findings of the LR.
- Address Limitations: This step aims to discuss the limitations of the review, including potential biases, sources of uncertainty, and the challenges encountered during the review process.

2.1. Define the research questions (RQs)

The article's primary objective is to conduct a comprehensive systematic literature review aimed at addressing a set of pivotal questions that revolve around the intricate relationship between LM and I4.0:

RQ 1 : How can we caracerize the relationship between LM and I4.0?

RQ 2 : What are the main trends of the integration between LM and I4.0 and the obstacles to this integration?

Building upon existing studies that predominantly explore the technological aspects of I4.0 impacting LM, a deeper delve into this convergence is aspired to be achieved. Specifically, how the relationship between LM and I4.0 is characterized is sought to be elucidated. Whether I4.0 technologies are acted upon as enhancers and supporters of Lean techniques and principles, and conversely, whether a significant role is played by Lean techniques in facilitating the implementation of Industry 4.0 technologies is aimed to be investigated. Moreover, whether LM and I4.0 engage in a reciprocal relationship of reinforcement and synergy with each other is also aimed to be explored. Additionally, the prevailing trends in the integration of LM and I4.0 will be identified, shedding light on both the advancements and the obstacles that hinder this integration. By synthesizing the existing body of knowledge on these vital questions, valuable insights into the ongoing dialogue surrounding these two paradigms are intended to be contributed, thereby aiding in the formulation of informed strategies and furthering the understanding of their coexistence.

2.2. Develop a research protocol

To effectively address the research questions, the article carefully designed a rigorously structured research procedure to provide guidance for the process of selecting studies. The procedure established a defined time period for inclusion, covering research completed between January 2013 and November 2023, to ensure that the article included the most up-to-date and relevant literature related to the investigation. The emphasis was solely on journal articles and extensive review articles, acknowledging their stringent academic criteria and thorough analysis. In order to ensure the review's integrity and comprehensiveness, the publication intentionally omitted papers that did not have full-text access, as having access to the entire body of research is essential for a comprehensive analysis. Moreover, the scope of the study was restricted to research conducted in English, in accordance with international research standards. Finally, a deliberate decision was made to not include grey literature, in order to ensure that the review only included the most thoroughly evaluated and academic sources, providing a strong and dependable basis for the study investigation.

2.3. Conduct a comprehensive search

To perform a thorough comprehensive research, the LR utilized two well-known databases, Scopus and Web of Science (WoS) are renowned for their extensive repositories of academics literature across various disciplines. The search query used is: ("Lean Manufacturing" OR "Smart Lean" OR "Lean Production") AND ("Industry 4.0" OR "Digitalisation" OR "Digitalization" OR "Digital Transformation" OR "Internet of Things" OR "IoT" OR "Big Data" OR "Cloud" OR "Robotic" OR "Smart Manufacturing" OR "Augmented Reality" OR "Artificial Intelligence" OR "Smart Production" OR "Smart Factory"). The search criteria guaranteed that the LR covers a wide range of literature on the convergence of LM and I4.0, including related concepts and technological breakthroughs.

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

2.4. Data extraction, quality assessement and Data synthetis

In this crucial step of the LR process, data extraction and quality assessment were conducted adhering to the predefined inclusion and exclusion criteria. Initially, the search yielded a comprehensive pool of 746 articles relevant to the research inquiry. To refine the selection to the most pertinent studies, inclusion and exclusion criteria were applied, which resulted in a significant reduction to 139 articles that met our initial screening requirements. Figure 1 exhibits the PRISMA method scheme, illustrating all the steps carried out until reach the final articles.

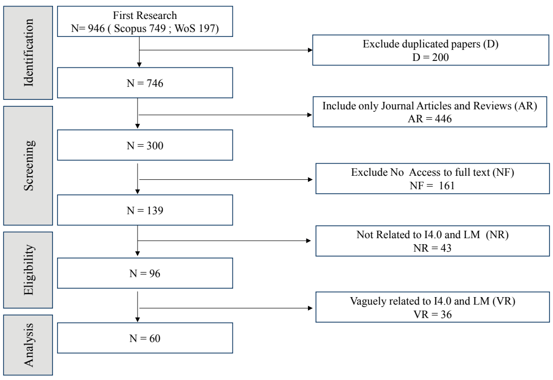

Figure 1. LR Data extraction and quality assessment step, adapted from PRISMA by Liberati et al. (2009)

The 60 selected articles were categorized into four distinct groups. These categories, namely Case Study, Framework, Literature Review, and Survey or interviews, were instrumental in organizing the pertinent literature based on their research methodologies and contributions. Table 1 summurizes the selected papers with their categories.

The categorization of the 60 selected studies investigating the interaction between LM and I4.0 has resulted a balanced distribution across four distinct categories. Notably, 28% of the studies fall into the Case Study category, providing rich insights into real-world applications and practical implications of these paradigms in various industrial settings. Literature Review articles, comprising 30% of the total, have been instrumental in consolidating and synthesizing existing knowledge, offering a comprehensive understanding of the subject matter. Framework-oriented studies, accounting for 25% of the total, have contributed valuable theoretical constructs and models to enhance our conceptualization of the relationship between LM and I4.0. Lastly, the Survey or Interviews category, representing 17% of the selected studies, has extended our insights through empirical data collection and analysis. This well-balanced categorization ensures a comprehensive and multifaceted examination of the literature, enriching our systematic review and enabling to draw well-rounded conclusions about the research questions. Figure 2, shows the methodology distribution of the selected papers.

An analysis of the trend in paper publications over time offers useful insights into the increasing interest and importance of the correlation between LM and I4.0. The interest in the relationship between LM and I4.0 started to gather considerable momentum in 2019 and has continued to thrive in the following

Table 1. Selected papers with their categories.

Categorie	References
Literature review	Moraes et al., 2023; Rossini et al., 2023; Schumacher et al., 2022; Ghouat et al., 2022; Buer et al., 2021; Salvadorinho & Teixeira, 2021; Miqueo et al., 2020; Rifqi et al., 2021; Valamede & Akkari, 2020; Ejsmont et al., 2020; Sony, 2020; Fortuny-Santos et al., 2020; Núñez-Merino et al., 2020; Rosin et al., 2020; Pekarčíková et al., 2019; Varela et al., 2019
Case study	Rahardjo et al., 2023; Arana-Landín et al., 2023; Ooi et al., 2023; Maware & Parsley, 2023; Guha et al., 2023; Tripathi et al., 2022a; Tripathi et al., 2022b; Zhan, 2022; Ghaithan et al., 2021; Chiarini & Kumar, 2021; Ito et al., 2020; Li, 2019; Zhang et al., 2019
Framework	Ahmed et al., 2023; Skalli et al., 2023; Medyński et al., 2023; Tripathi et al., 2022b; Pozzi et al., 2022; Ciliberto et al., 2021; Tripathi et al., 2021a; Tripathi et al., 2021b; Peças et al., 2021; Jiménez et al., 2021; Liao & Wang, 2021; Ramadan et al., 2020; Tortorella et al., 2020; Sony, 2018.
Survey or Interviews	Oliveira-Dias et al., 2023; Bokhorst et al., 2022; Sartal et al., 2022; Nedelko, 2021; Buer et al., 2021; Saxby, 2020; Tortorella et al., 2019; Rossini et al., 2019; Tortorella & Fettermann, 2017; Anosike et al., 2021

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

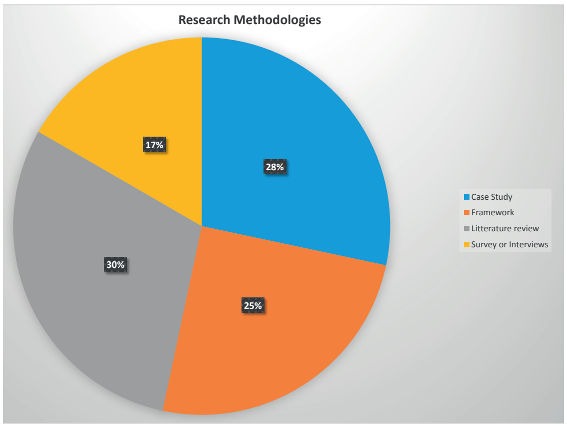

Figure 2. Papers methodology distribution.

years. In 2019, there was a notable surge in academic participation, as demonstrated by the publication of seven papers on this issue. In 2020, this trend continued to grow in popularity, with twelve papers dedicated to examining the dynamic interaction between different paradigms. In 2021, this trend remained consistent with 2020, with 13 papers focused on this topic. In 2022, nine papers were published, and it is expected that in 2023, 12 more papers will be added to this ongoing discussion. Figure 3 shows the evolution of the number of papers per year.

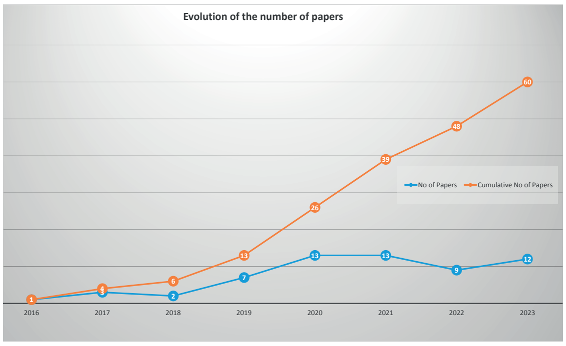

Figure 3. Evolution of the number of papers per year.

In summary, to conduct the LR, 60 articles were selected, representing a well-balanced distribution across categories, including Case Study, Literature Review, Framework, and Survey or Interviews. Furthermore, the data analysis revealed a compelling evolution and trend, with a significant uptick in publications beginning in 2019, highlighting the growing relevance of these paradigms in contemporary industrial discourse.

3. Results

In this section, findings from the LR are presented, aimed at elucidating the nuanced relationship between LM and I4.0, as well as identifying the prevailing trends and challenges associated with their integration.

3.1. Relationship between LM and I4.0

To evaluate the relationship between LM and I40, we classified the publications into three main categories. The initial category comprises papers that explicitly articulate the beneficial influence of I40 technology on the execution of lean procedures. The second category comprises papers that explicitly assert that lean manufacturing facilitates and amplifies the adoption of Industry 4.0 technologies. The last category comprises publications that emphasize the reciprocal reinforcement and synergy between lean manufacturing and I4.0 technology. Out of the 60 articles analyzed, 41 were found to be focused on examining the relationship between LM and I40 through. Out of the 41 articles analyzed, 26 demonstrated that Industry 4.0 technologies improve and facilitate the application of lean principles. Additionally, five articles indicated that LM enhances and supports the implementation of I4.0. Furthermore, nine articles argued that LM and I4.0 emphasize the reciprocal reinforcement and synergy between lean manufacturing and I4.0 technologies. Figure 4 provides a concise overview of this distribution.

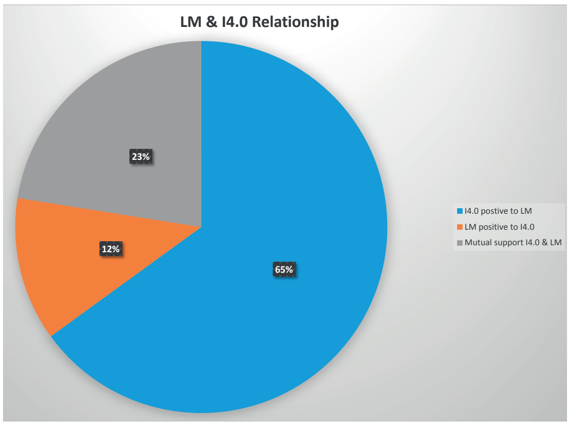

Figure 4. Categorization of articles about relationship between LM & I4.0.

In this subsection, our primary focus will be on an in-depth examination of the first segment of the selected papers. This segment aims to critically analyze and

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

synthesize the arguments presented in these works, elucidating how the integration of advanced Industry 4.0 technologies enhances, supports, and potentially transforms traditional Lean methodologies.

Research by Moraes et al. (2023) highlights the central role of technology in improving performance and quality in industrial processes. It mentions that technology integration with traditional practices leads to the creation of new approaches and tools, such as Digital Lean Manufacturing (DLM), which enhances connectivity and information sharing in manufacturing processes. Administrative Process Automation, including Robotic Process Automation (RPA), is also emphasized for its potential to eliminate operational risks and improve resource management.

Furthermore, Moraes et al. (2023) argued that the relationship between LM and I4.0 should encompass not just technological factors but should also consider environmental,social, and business sustainability. This emphasizes the necessity for additional investigation to comprehend the influence of Lean 4.0 on the progressing notion of Society 5.0, wherein employees assume a fundamental position in the industrial process.

On the other hand, Oliveira-Dias et al. (2023) conducted a study to examines how I4.0 technologies (such as Cyber-Physical Systems, Big Data Analytics, and IoT) influence Lean and Agile supply chain (SC) strategies and their impact on operational performance. Conducted with data from 256 manufacturing firms in Spain, the findings support a model where Industry 4.0 technologies enable Lean supply chain, which in turn positively affects Agile supply chain. This relationship ultimately leads to improved operational performance. Additionally, the study suggests that Agile supply chain has a stronger direct impact on performance compared to Lean supply chain, although Lean practices contribute to enhancing Agile capabilities.

Research by Sartal et al. (2022) investigates the relationship between two lean pillar management practices, which are Just-in-Time (JIT) and autonomation (Jidoka), and tree I4.0 technologies, which are vertical and horizontal data integration (VHDI), advanced robotics (AR), and additive manufacturing (AM). It uses a qualitative analysis of data from 568 European manufacturing plants and identifies different causal paths linking LM and I4.0 technologies, emphasizing the importance of the VHDI. The results suggest that a combination of I4.0 technologies, including VHDI, advanced robotics, and additive manufacturing, can significantly improve plant performance. The findings highlight that I4.0 technologies do not have the same level of synergy with LM, giving the example of advanced robotics, which has a low level of synergy with LM practices.

Similar to the previous authors, Skalli et al. (2023), Medyński et al. (2023), and Ghouat et al. (2022) studied the impact of Industry 4.0 technologies on some specific lean techniques like Six Sigma, Muda, and Total Productive Maintenance. It finds a strong positive impact of I4.0 technologies on LM practices, as Industry 4.0 technologies enhance the principles of lean manufacturing by improving information flow through the interconnection of machines, objects, and people. Real-time data analysis in cyber-physical production systems leads to better decision-making.

In contrast with the authors above, Pozzi et al. (2022), Anosike et al. (2021), and Zhang et al. (2019) studied the impact of specific technologies like IoT and Data Science (DS) tools on lean manufacturing. Anosike et al. (2021) argued that, among IoT technologies, radio-frequency identification (RFID) has the most significant impact on Just-in-Time (JIT) manufacturing and Autonomation. RFID technology facilitates data gathering for inventory control and lead-time management in JIT. Additionally, in the context of automation, RFID's real-time data gathering capabilities play a crucial role in detecting defects within processes and preventing operational interruptions. Table 2 summarizes the study by Anosike et al. (2021) related to the significant impact matrix of IoT technologies on main Lean practices. This study is based on a large worldwide survey of many manufacturing domains.

Table 2. Significant impact matrix of IoT technologies on main Lean practices.

Lean practice / IoT technology	RFID	Wireless Network Sensors (WSN)	Middleware
JIT	x	x	
Value Stream Mapping (VSM)			x
Jidoka	x	x	x
Kaizen			
TPM		x	x

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

RFID technology was particularly impactful onJIT and Autonomation. For JIT, RFID technology enables efficient inventory control and lead-time management by offering up-to-date information on product locations and attributes, aligning with findings from Moraes et al. (2023). RFID also enhanced traceability on the shop floor, reducing waiting times and delays, as supported by Pozzi et al. (2022). For Autonomation, RFID's real-time data gathering was crucial for detecting defects in processes, as discussed by Sartal et al. (2022). WSN had the most impact on Autonomation through interconnectivity and information gathering, followed by TPM and JIT. WSN enabled reduced machine breakdowns, better identification of defects, and improved lead times, similarly impacting JIT and TPM in terms of inventory control Medyński et al. (2023).

Middleware technology showed similar improvements across VSM, Autonomation, and TPM. It facilitated decision-making and communication for VSM, enhancing decision-makers' visibility and offering a more holistic view of operations, as argued by Skalli et al. (2023).

Furthermore, Zhang et al. (2019) showed that Iot ensures synchronized production and raw material plans, synchronized finished product warehousing, and synchronized production and Work-In-rogress (WIP) monitoring. These features improve production efficiency and workflow by reducing stock shortages, optimizing inventory, and enhancing process flow. In addition, Pozzi et al. (2022) demonstrated the utilization of DS technology to enhance conventional Kanban systems and discover product families that share similar routing and task content. On the other hand, Data Science is used to examine the connection between condition parameters and the probability of defaults in order to enhance and optimize TPM.

On the other hand, Rosin et al. (2020) conducted a literature review to explore and clarify the connections between Industry 4.0's principles and tools and those of the Lean management approach. It specifically focuses on how Industry 4.0 technologies enhance the implementation of Lean principles, taking into account the varying levels of technological capabilities. It reveals that Just-in-Time, Foundations, and Jidoka are the most enhanced Lean categories through Industry 4.0, with a notable emphasis on principles like continuous flow and visual management. Conversely, areas such as Waste Reduction, People, and Teamwork, along with specific principles like Genshi Genbutsu and ringi decision-making, remain less impacted. The study also points out the underrepresentation of softer Lean principles, which focus on employee communication and creativity, in the current scope of Industry 4.0 advancements. Technologies like the IoT, simulation, and autonomous robots are predominantly employed, yet there is a lack of focus on cybersecurity and cloud technologies. The research highlights a significant concentration on the monitoring capability level, suggesting the novelty of I4.0 applications. It also observes varied applications across different company sizes and notes the disparity in the depth of these applications, ranging from theoretical to practical implementations. The analysis concludes that while Industry 4.0 technologies have positively impacted certain Lean principles, they do not fully encompass the Lean management approach, particularly in areas requiring employee innovation.

In summary, the analysis of the first category of articles highlights the positive effects of Industry 4.0 technologies such as IoT and Data Science on Lean Manufacturing arguing that I4.0 technologies enables many benefices for lean practices such as real time data gathering, information sharing and predictive maintenance. However, the technique of studying the impact of I4.0 technology lacks precision. In fact, multiple authors acknowledge that the IoT facilitates the instantaneous data gathering and the real time monitoring of industrial processes. Nevertheless, achieving this goal necessitates the integration of multiple I4.0 technologies into a comprehensive framework, such as Reference Architecture model for Industry 4.0 (RAMI 4.0) or IBM reference architecture for Industry 4.0 (IBM 4.0) (Canas et al., 2022). Real-time retrieval and storage of IoT data necessitates the utilization of a Big Data platform like the Hadoop Framework or other cloud-based Big Data technologies such as Google Analytics or Amazon web services (AWS) (Gröger, 2018). This also holds true for the implementation of a predictive maintenance scenario. Furthermore, the authors have neglected to emphasize the crucial role of Cybersecurity, a vital technology that ensures the secure execution of all stated activities, safeguarding them from potential Cyberattacks intrusions. For instance, Figure 5 shows the RAMI 4.0 architecture.

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

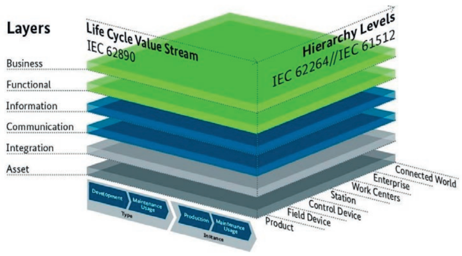

Figure 5. RAMI 4.0 Architecture (Canas et al., 2022).

In this section, we will examine the second category, which focuses on the beneficial impact of LM on the integration of I4.0 technologies. Table 3 summarizes the articles analyzed.

Table 3: Papers LM positive to I4.0.

Category	References
Literature review	Miqueo et al., 2020; Sony, 2020; Fortuny-Santos et al., 2020;
Survey or interviews	Saxby, 2020; Rossini et al., 2019; Tortorella & Fettermann, 2017

The research conducted by Miqueo et al. (2022) emphasizes that the implementation of Industry 4.0 is anticipated to bring a digital waste. They propose that research efforts should be directed towards developing new methodologies rooted in Lean practices to effectively eradicate this waste. On the other hand, According to Sony (2020), I4.0 and Lean can be seamlessly integrated to enhance production management, as they are not mutually exclusive. They complement each other, supporting the creation of better products and processes. I4.0 can incorporate lean concepts, facilitating horizontal, vertical, and end-to-end integration. Additionally, Six Sigma, with its focus on eliminating defects and reducing variation, can be highly beneficial for In4.0 due to its data-driven methodology. Six Sigma can effectively analyze the vast amounts of data generated by I4.0 to control variations. In order to achieve this integration, physical facilities must have embedded sensors, processors, and actuators that enable control and monitoring through Cyber-Physical Systems (CPS). Incorporating Lean Six Sigma principles into the CPS architecture design can strategically benefit organizations in the I4.0 landscape.

Similar to the previous authors, Rossini et al. (2019) argued that companies in emerging economies are more inclined to effectively use I4.0 technologies when they have already achieved a relatively advanced level of Lean maturity. This observation is based on the findings of a survey conducted of 108 European manufacturers that had adopted Lean principles. The survey done by Rossini et al. (2019) yielded the following findings:

- Lean Maturity and Efficiency: Companies with advanced Lean maturity levels have likely already streamlined their processes, reduced waste, and optimized their operations. This high level of efficiency can serve as a solid foundation for adopting I4.0 technologies. Lean principles encourage a focus on continuous improvement and a culture of eliminating inefficiencies, which aligns with the goals of I4.0.
- Process Improvements: Lean practices inherently drive process improvements. When companies have already implemented Lean successfully, they are more experienced in identifying bottlenecks, enhancing productivity, and maintaining quality standards. These skills and capabilities are valuable when integrating I4.0 technologies, which often involve automation, data-driven decision-making and real-time process monitoring.
- Cultural Alignment: Lean principles emphasize employee involvement and a culture of continuous improvement. In emerging economies, where there may be resistance to technological changes or a lack of familiarity with advanced technologies, a Lean culture can facilitate a smoother transition to I4.0. Employees who are accustomed to Lean practices are more likely to embrace new technologies and adapt to changes in the workplace.
- Cost Efficiency: Implementing I4.0 technologies can require significant investments in hardware, software, and training. Companies with advanced Lean maturity are often more adept at managing costs efficiently. They can allocate resources effectively and make informed decisions about which I4.0 solutions to implement, ensuring a better return on investment.

The result of the study by Rossini et al. (2019) is aligned with the result of Tortorella and Fettermann (2017), who conducted a survey within 110 Brazilian companies about the concurrent implementation of LM and I4.0 and their impact on enterprise performance. Tortorella and Fettermann (2017) indicate that enterprises in emerging countries, which have had significant improvements in performance and have widely implemented LM, also tend to adopt I4.0 technology concurrently.

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

In conclusion, the link between advanced LM and successful I4.0 implementation in emerging economies suggests that companies should prioritize Lean practices as they embark on their I4.0 journeys. Lean principles can help organizations build a strong foundation for the efficient adoption and integration of I4.0 technologies, ultimately leading to improved competitiveness and operational excellence.

In summary, there is a lack of study on this topic. Rossini et al. (2019) research has elucidated various facets of the influence of LM on the adoption of I4.0, which can be the basis for future research and case studies.

In the following section, we will examine the final category of papers that propose a synergistic connection between LM and I4.0, where each concept strengthens and supports the other. Table 4 summarize, the articles analyzed.

Table 4. Papers LM Mutual reinforcement and support to I4.0.

Category	References
Literature review	Rossini et al., 2023; Salvadorinho & Teixeira, 2021; Buer et al., 2021; Ejsmont et al., 2020; Núñez-Merino et al., 2020
Case Study	Ooi et al., 2023; Tripathi et al., 2022a; Chiarini & Kumar, 2021
Survey or interviews	Sartal et al., 2022; Anosike et al., 2021

In this section, the authors propose a similar result to that of the previous sections, supported by a more thorough analysis of the reciprocal amplification. Buer et al. (2021) conducted a survey within 212 Norwegian manufacturing companies. The study found that simultaneous utilization of LM and industrial digitalization had a synergistic impact on operational performance, surpassing the benefits of implementing each individually.

This research aligns with the concept of complementary resources, where LM and plant digitalization fulfill the requirements of being non-identical, positively correlated, and producing synergistic effects on performance. The study also emphasizes the resource-based view, indicating that a basic LM system without digital solutions may not yield a substantial competitive edge in terms of operational efficiency. It suggests that combining both domains is essential for optimal results.

Regarding the implementation sequence, while some studies propose a “lean first” approach (Anosike et al., 2021), this research does not identify a specific order for implementation, emphasizing the importance of a stable and streamlined production system as a foundation for digitalization.

Furthermore, Chiarini and Kumar (2021) conducted interviews with ten managers from ten Italians manufacturing companies which implemented lean six sigma for at least five years and came to similar result as Buer et al. (2021) stating that the integration of LM practices and I4.0 resulted in increased productivity and decreased waste and costs. However, Chiarini and Kumar (2021) research came to important results about the requirements to achieve the vertical and end-to-end integration, all the companies unanimously agreed that achieving integration across various process levels, customers, and suppliers is best achieved through digital rather than hardware changes. They provided examples of how they have been redesigning modules of their ERP, specifically Manufacturing Execution System/ Supervisory Control and Data Acquisition (MES/ SCADA) and Master Data Management, to facilitate integration. They also mentioned modifying MES Requirements Planning (MRP) and scheduling software to automate data acquisition, such as workstation stoppages and cycle times, although this was challenging with third-party software. Some respondents modified PDM/PLM to provide real-time information to machines and warehouses, ensuring up-to-date design information. A few have experimented with smart sensors embedded in finished products for data collection, primarily for companies selling end-user products. End-to-end integration was crucial for the seamless coordination of orders and scheduling, necessitating the sharing of databases and software with customers and suppliers. Furthermore, respondents highlighted the difficulty of implementing a big data platform that could store all the real-time data coming from sensors and other software and that could achieve real-time performance and cost monitoring, which is aligned with our analysis of the first category of papers.

On the other hand, Rossini el al. (2023) conducted a systematic literature review about the relationship between lean supply chain management (LSCM) and I4.0 and came up with a framework. This framework contributes to the understanding of the interplay between LM and I4.0 and aligns with existing research indicating a positive correlation between

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

the two paradigms. It underscores the synergistic perspective of these paradigms and is supported by recent literature demonstrating the adaptation of specific I4.0 technologies with lean techniques. In summary, Lean drives I4.0 at the strategic level by streamlining the process, while I4.0 enhances lean practices at the operational level by facilitating data flow and providing advanced tools for workers. This Framewok is illustrated in Figure 6.

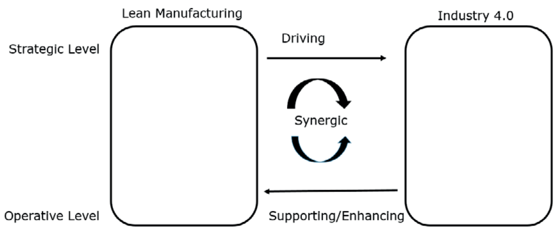

Figure 6. LM and I4.0 integration framework by Rossini et al. (2023).

Similar to Rossini et al. (2023), Núñez-Merino et al., 2020 conducted a systematic literature review about the relationship between LSCM and I4.0. The findings highlight the synergistic and complementary effects of I4.0 technologies and strategies on performance. This study demonstrates that the combined impact of I4.0 technologies and LSCM significantly enhances supply chain flexibility, aligning with LM objectives. This finding supports previous research highlighting how IoT application in LSCM optimizes supply, manufacturing, and delivery processes concurrently. Moreover, I4.0 aids in managing and minimizing supply chain risks.

3.2. Integration between LM and I4.0: Trends and obstacles

This section focuses on conducting a thorough examination of the trends and obstacles related to the integration of LM with I4.0. This study aims to analyze the additionally literature supplied in table 4 to get valuable insights into the integration between LM and I4.0. It will focus on identifying the positive trends and significant challenges found in this integration.

After a thorough analysis of the literature, three primary trends have been identified as noteworthy. The first and most prevalent trend is the integration of I4.0 technologies, particularly IoT (Zhang et al., 2019; Ito et al., 2020; Sartal et al., 2022; Ahmed et al., 2023) with LM principles. This integration aims to enable various use cases that significantly increase enterprise productivity and performance. The second trend focuses on the integration between LM and I4.0, specifically addressing sustainability challenges (Arana-Landín et al., 2023; Ciliberto et al., 2021; Tripathi et al., 2022b). These paradigms play a crucial role in addressing critical sustainability issues, highlighting their potential to drive responsible and eco-friendly industrial practices. A third important trend has emerged, highlighting the integration of Lean principles and I4.0 as a means to anticipate Industry 5.0 (Moraes et al., 2023; Zhan, 2022). The first trend concerning the integration between LM and IoT has been extensively discussed in the preceding section. Therefore, the focus of the subsequent discussion will be directed towards the exploration of the two other trends related to sustainability and the anticipation of Industry 5.0.

Arana-Landín et al. (2023) argued that the integration of LM and I4.0 with a sustainability focus has spurred noteworthy trends. Firms are increasingly embracing circular economy principles, striving to reduce waste, reuse materials, and recycle products in their operations to align with sustainability goals. Additionally, sustainability-oriented innovation, including eco-innovation and eco-design, is gaining prominence, fostering the development of environmentally friendly technologies, processes, and product designs. This integration also witnesses a surge in the adoption of Life Cycle Assessment (LCA) tools, aiding in the comprehensive evaluation of product environmental impacts across their lifecycle, facilitating informed decisions for sustainability enhancements and resource optimization.

Furthermore, the research conducted by Ciliberto et al. (2021) emphasizes the concept of Reverse Logistic (RL), which is essential to reaching sustainable production that allows the opposite flow of goods from the customer to the manufacturer in order to avoid waste, enable recycling, and promote environmental sustainability. It is not efficient without the combination of I4.0 technologies that will allow digitalized supply chain processes, the principles of LM and the principles of Circular Economy (CE).

On the other hand, Tripathi et al. (2022b) argued that implementing I4.0 technologies in complex manufacturing environments plays a crucial role in optimizing processes and shop floor management.

 Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

These technologies, including IoT, AI, digitalization, and asset tracking systems, significantly boost productivity and operational excellence. Management teams are increasingly adopting process optimization approaches with I4.0 technologies to address production control challenges. This integration not only enhances overall process efficiency but also provides mental and physical comfort to production teams. As a result, the shop floor management system's efficiency improves, contributing to industrial sustainability by creating a safe and waste-free production environment.

Finally, Moraes et al. (2023) argued that the integration between LM and I4.0 is considered an important aspect of Industry 5.0, which places a strong emphasis on human orientation, resilience, and sustainability. With Lean's central focus on people as integral elements, the integration of Lean principles with I4.0 technologies facilitates the transition to Industry 5.0. This transition aligns with the broader vision of Industry 5.0, promoting a sustainable and balanced society where societal challenges, including environmental considerations, are shared responsibilities among all stakeholders, including industrial companies. As a result, this alignment presents a compelling opportunity to accelerate sustainability, resilience, and human-centered strategies within modern industries.

Following the analysis of the trends in the integration of LM and I4.0, the current focus is on exploring the obstacles associated with this integration. Following the analysis of the trends in the integration of LM and I4.0, the current focus is on exploring the obstacles associated with this integration. To obtain a deeper understanding of these difficulties, we refer to three main sources. First, Sartal et al. (2022) performed a qualitative analysis of 568 European manufacturers. Second, Chiarini and Kumar (2021) interviewed ten Italian manufacturers about this integration. Lastly, Tortorella and Fettermann (2017) surveyed 110 Brazilian companies on the joint implementation of LM and I4.0 and its effects on performance. Organizations encounter various obstacles during the process:

- Cultural and mindset shift: Integrating Lean, which focuses on simplicity, waste reduction, and continuous improvement, with the complex technology and data-driven decision-making of I4.0 requires a fundamental change in organizational culture and attitude. Harmonizing these two approaches can pose difficulties, as it necessitates individuals and executives to adjust their mindset and embrace novel work methodologies.
- Technology integration: The challenges of incorporating I4.0 technology, including IoT sensors, big data analytics, and artificial intelligence, into current Lean processes and equipment are discussed. The imperative to resolve compatibility concerns, facilitate data sharing, and ensure smooth connectivity between outdated systems and emerging technology is emphasized.
- Data management and cybersecurity: The significance of data security, privacy, and integrity is highlighted as I4.0 largely depends on data collecting and processing. Stringent cybersecurity protocols should be established to protect sensitive data and mitigate the risk of cyber threats.
- Skill and talent gap: Adopting I4.0 technologies frequently requires a staff equipped with novel proficiencies such as data analytics, programming, and cybersecurity. Addressing the talent gap among employees may necessitate investment in training and development.
- Cost and return on investment (ROI) considerations: The financial requirements related to the incorporation of Industry 4.0 technologies, such as initial expenses for hardware, software, and training, are highlighted. Thorough assessment of the return on ROI and the creation of a well-defined business case are considered necessary to justify these expenses.
- Supplier and partner collaboration: Many I4.0 initiatives acknowledge the involvement of suppliers and partners. Ensuring that these external stakeholders are aligned with the integration effort and can provide the necessary support is seen as a potential challenge.

4. Conclusion and future work

In conclusion, this article has addressed three key facets in the context of the relationship between LM and I4.0. The first focal point involved elucidating the characterization of the relationship between LM and I4.0. The analysis revealed that a majority of studies underscored the positive impact of I4.0 technologies on LM. This outcome is unsurprising, given the manifold benefits that I4.0 offers, such as

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

data gathering and analytics. The first key finding regarding the interplay between Lean manufacturing and Industry 4.0 suggests that companies already implementing Lean practices can amplify these practices, thereby boosting performance and productivity. However, it's crucial to note that not all Industry 4.0 technologies equally impact Lean practices. Morever, the results of our literature review show that the main emphasis in studying the connection between LM and I4.0 has been on three specific technologies: IoT, Big Data, and Analytics. Extensive research has been conducted on these technologies to determine their effectiveness in improving and facilitating Lean practices and concepts. Nevertheless, there is still a significant lack of research on essential I4.0 technologies, like Cloud Computing, Cybersecurity, Augmented Reality, and Additive Manufacturing. Further investigation can explore these domains to offer a more extensive comprehension of how these supplementary technologies interrelate with and influence LM techniques, so expanding the range and profundity of the current literature.

The second finding relates to businesses that have initially adopted Industry 4.0. In these cases, integrating Lean principles can further enhance this implementation. This integration is achieved primarily through the standardization of processes, which not only eliminates digital waste but also reduces the costs associated with implementing Industry 4.0 technologies.

The third finding addresses companies that have not yet adopted Lean practices and are looking to implement Industry 4.0 technologies. Most studies advocate that having a foundation in Lean principles is beneficial for preparing for Industry 4.0 implementation. Key impediments like the lack of standardization, inadequate IT infrastructure, and high heterogeneity significantly influence the success of Industry 4.0 implementation projects. Conversely, a minority of studies suggest that the necessity and impact of Lean practices in the context of Industry 4.0 may vary depending on the specific circumstances of each enterprise.

Regarding the second point, the article identified three primary trends in the integration between LM and I4.0. The first trend emphasized the integration of I4.0 technologies, particularly IoT, with LM principles to enhance productivity and performance. The second trend focused on sustainability challenges, showcasing the pivotal role played by LM and I4.0 in addressing environmental concerns and promoting eco-friendly industrial practices. The third trend pointed toward the integration of Lean principles and Industry 4.0 as a precursor to Industry 5.0, highlighting the evolving landscape of manufacturing paradigms. This convergence presents a promising area for future research and studies to further elucidate the implications and strategies for effective integration.

Regarding the third aspect, the article examined the difficulties linked to the integration of LM and I4.0. Thorough investigation uncovered these difficulties, which involved multiple aspects. Initially, there was a need for a cultural and mentality transformation to align the simplicity and continuous improvement principles of Lean with the intricate and data-focused nature of Industry 4.0. This necessitated a fundamental shift in the culture of the business. Furthermore, the challenge of integrating technology arose, requiring the resolution of compatibility concerns between legacy systems and emerging Industry 4.0 technologies. Additionally, the rise of data management and cybersecurity has brought about significant attention to the importance of implementing strong data protection procedures. Furthermore, it was imperative to tackle the deficiency in skills and ability, necessitating a commitment to investing in staff training. Moreover, the evaluation of costs and return on investment played a vital role in justifying the implementation of Industry 4.0 technologies. Prudent oversight of supplier and partner engagement is essential to guarantee synchronization with integration endeavors.

Finally, the article acknowledged its limitations, including the unavailability of access to certain studies that could have further enriched and complemented the research. Despite these limitations, the comprehensive analysis presented in this article contributes significantly to our understanding of the complex relationship between LM and I4.0, the prevailing trends in their integration, and the challenges that organizations must navigate in this transformative journey. This knowledge can serve as a valuable resource for researchers, practitioners, and decision-makers in the field of manufacturing and technology.

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

References

Ahmed, A. A. A., Mahalakshmi, A., ArulRajan, K., Alanya-Beltran, J., & Naved, M. (2023). Integrated artificial intelligence effect on crisis management and lean production: structural equation modelling framework. *International Journal of System Assurance Engineering and Management*, *14*(1), 220-227. https://doi.org/10.1007/s13198-022-01679-1

Anosike, A., Alafropatis, K., Garza-Reyes, J. A., Kumar, A., Luthra, S., & Rocha-Lona, L. (2021). Lean manufacturing and internet of things – A synergetic or antagonist relationship?. *Computers in Industry*, *129*. https://doi.org/10.1016/j.compind.2021.103464

Arana-Landín, G., Uriarte-Gallastegi, N., Landeta-Manzano, B., & Laskurain-Iturbe, I. (2023). The Contribution of Lean Management -Industry 4.0 Technologies to Improving Energy Efficiency. *Energies*, *16*(5). https://doi.org/10.3390/en16052124

Ardolino, M., Bacchetti, A., & Ivanov, D. (2022). Analysis of the COVID-19 pandemic's impacts on manufacturing: a systematic literature review and future research agenda. *Operations Management Research*, *15*, 551-566. https://doi.org/10.1007/s12063-021-00225-9

Buer, S. V., Semini, M., Strandhagen, J. O., & Sgarbossa, F. (2021). The complementary effect of lean manufacturing and digitalisation on operational performance. *International Journal of Production Research*, *59*(17), 1976-1992. https://doi.org/10.1080/00207543.2020.1790684

Bokhorst, J. A. C., Knol, W., Slomp J., & Bortolotti, T. (2022). Assessing to what extent smart manufacturing builds on lean principles. *International Journal of Production Economics*, *253*. https://doi.org/10.1016/j.ijpe.2022.108599

Canas, H., Mula, J., Bolarin, F. G., & Paule. R (2022). A conceptual framework for smart production planning and control in Industry 4.0. *Computers & Industrial Engineering Journal*, *173*. https://doi.org/10.1016/j.cie.2022.108659

Chiarini, A., & Kumar, M. (2021). Lean Six Sigma and Industry 4.0 integration for Operational Excellence: evidence from Italian manufacturing companies. *Production Planning and Control*, *32*(13), 1084-1101. https://doi.org/10.1080/09537287.2020.1784485

Ciliberto, C., Szopik-Depczyńska, K., Tarczyńska-Łuniewska, M., Ruggieri, A., & Ioppolo, G. (2021). Enabling the Circular Economy transition: a sustainable lean manufacturing recipe for Industry 4.0. *Business Strategy and the Environment*, *30*(7), 3255-3272. https://doi.org/10.1002/bse.2801

Ejsmont, K., Gladysz, B., Corti, D., Castaño, F., Mohammed, W. M., & Martinez Lastra, J. L. (2020). Towards Lean Industry 4.0–Current trends and future perspectives. *Cogent Business and Management*, *7*(1). https://doi.org/10.1080/23311975.2020.1781995

Fortuny-Santos, J., López, P. R. D. A., Luján-Blanco, I., & Chen, P. K. (2020). Assessing the synergies between lean manufacturing and Industry 4.0. *Direccion y Organizacion*, (71), 71-86. https://doi.org/10.1080/21693277.2020.1774814

Fink, A. (2005). *Conducting research literature reviews: From the Internet to paper* (2nd ed.). Thousand Oaks, CA: Sage.

Ghaithan, A., Khan, M., Mohammed, A., & Hadidi, L. (2021). Impact of industry 4.0 and lean manufacturing on the sustainability performance of plastic and petrochemical organizations in Saudi Arabia. *Sustainability (Switzerland)*, *13*(20). https://doi.org/10.3390/su132011252

Ghouat, M., Benhadou, M., Benhadou, B., & Haddout, A. (2022). Assessment of the Potential Impact of Industry 4.0 Technologies on the Levers of Lean Manufacturing in Manufacturing Industries in Morocco. *International Journal of Emerging Technology and Advanced Engineering*, *12*(7), 78-85. https://doi.org/10.46338/ijetae0722_08

Guha, B., Moore, S., & Huyghe, J. M. (2023). Conceptualizing data-driven closed loop production systems for lean manufacturing of complex biomedical devices—a cyber-physical system approach. *Journal of Engineering and Applied Science*, *70*(1). https://doi.org/10.1186/s44147-023-00222-8

Gröger, C., (2018). Building an Industry 4.0 Analytics Platform. *Springer Link*, *18*, 4-14. https://doi.org/10.1007/s13222-018-0273-1

Ito, T., Abd Rahman, M. S., Mohamad, E., Abd Rahman, A. A., & Salleh, M. R. (2020). Internet of things and simulation approach for decision support system in lean manufacturing. *Journal of Advanced Mechanical Design, Systems and Manufacturing, 14*(2). https://doi.org/10.1299/jamdsm.2020jamdsm0027

Jiménez, M., Espinosa, M. M., Domínguez, M., Romero, M., & Awad, T. (2021). Adaptation of the lean 6S methodology in an industrial environment under sustainability and industry 4.0 criteria. *Sustainability (Switzerland)*, *13*(22). https://doi.org/10.3390/su132212449

Kitchenham, B. (2004), "Procedures for Performing Systematic Reviews". *Keele University Technical Report TR/SE-0401, ISSN:1353-7776*.

Kitchenham, B. and Charters, S. (2007), "Guidelines for performing systematic literature reviews in software engineering". *EBSE Technical Report EBSE-2007-01*.

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

Liao, M. H., & Wang, C. T. (2021). Using enterprise architecture to integrate lean manufacturing, digitalization, and sustainability: A lean enterprise case study in the chemical industry. *Sustainability (Switzerland)*, *13*(9). https://doi.org/10.3390/su13094851

Liberati, A., Altman, D. G., Tetzla, J., Mulrow, C.; Gøtzsche, P. C., Ioannidis, J. P. A., Clarke, M., Devereaux, P. J.;Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. *Plos Med*, *6*, 1-28. https://doi.org/10.1016/j.jclinepi.2009.06.006

Li, L. R. (2019). Lean smart manufacturing in Taiwan-Focusing on the bicycle industry. *Journal of Open Innovation*: Technology, Market, and Complexity, 5(4). https://doi.org/10.3390/joitmc5040079

Maware, C., & Parsley, D. M. (2023). Can Industry 4.0 Assist Lean Manufacturing in Attaining Sustainability over Time? Evidence from the US Organizations. *Sustainability (Switzerland)*, *15*(3). https://doi.org/10.3390/su15031962

Medyński, D., Bonarski, P., Motyka, P., Wysoczański, A., Gnitecka, R., Kolbusz, K., Dąbrowska, M., Burduk, A., Pawelec, Z., & Machado, J. (2023). Digital Standardization of Lean Manufacturing Tools According to Industry 4.0 Concept. *Applied Sciences (Switzerland)*, *13*(10). https://doi.org/10.3390/app13106259

Miqueo, A., Torralba, M., & Yagüe-Fabra, J. A. (2020). Lean manual assembly 4.0: A systematic review. Applied *Sciences (Switzerland)*, *10*(23), 1-37. https://doi.org/10.3390/app10238555

Moraes, A., Carvalho, A. M., & Sampaio, P. (2023). Lean and Industry 4.0: A Review of the Relationship, Its Limitations, and the Path Ahead with Industry 5.0. *Machines*, *11*(4). https://doi.org/10.3390/machines11040443

Nedelko, Z. (2021). What drives the usage of management tools supporting industry 4.0 in organizations?. *Sensors*, *21*(10). https://doi.org/10.3390/s21103512

Núñez-Merino, M., Maqueira-Marín, J. M., Moyano-Fuentes, J., Martínez-Jurado, P. J. (2020).Information and digital technologies of Industry 4.0 and Lean supply chain management: a systematic literature review. *International Journal of Production Research*, *58*, 5034–5061. https://doi.org/10.1080/00207543.2020.1743896

Oliveira-Dias, D. D., Maqueira-Marin, J. M., Moyano-Fuentes, J., Carvalho, H. (2023). Implications of using Industry 4.0 base technologies for lean and agile supply chains and performance. *International Journal of Production Economics*, *262*. https://doi.org/10.1016/j.ijpe.2023.108916

Ooi, Y. H., Ng, T. C., & Cheong, W. C. (2023). Implementing Industry 4.0 and lean practices for business performance in manufacturing: Case of Malaysia. *International Journal of Advanced and Applied Sciences*, *10*(3), 143-156. https://doi.org/10.21833/ijaas.2023.03.019

Peças, P., Encarnação, J., Gambôa, M., Sampayo, M., & Jorge, D. (2021). Pdca 4.0: A new conceptual approach for continuous improvement in the industry 4.0 paradigm. *Applied Sciences (Switzerland)*, *11*(16). https://doi.org/10.3390/app11167671

Pekarčíková, M., Trebuňa, P., & Kliment, M. (2019). Digitalization effects on the usability of lean tools. *Acta Logistica*, *6*(1), 9-13. https://doi.org/10.22306/al.v6i1.112

Pozzi, R., Cannas, V. G., & Ciano, M. P. (2022). Linking data science to lean production: a model to support lean practices. *International Journal of Production Research*, *60*(22), 6866-6887. https://doi.org/10.1080/00207543.2021.1946192

Rahardjo, B., Wang, F. K., M., Yeh, R. H., & Chen, Y. P. (2023). Lean Manufacturing in Industry 4.0: A Smart and Sustainable Manufacturing System. *Machines*, *11*(1). https://doi.org/10.3390/machines11010072

Ramadan, M., Salah, B., Othman, M., & Ayubali, A. A. (2020). Industry 4.0-based real-time scheduling and dispatching in lean manufacturing systems. *Sustainability (Switzerland)*, *12*(6). https://doi.org/10.3390/su12062272

Rifqi, H., Zamma, A., Souda, S. B., & Hansali, M. (2021). Positive Effect of Industry 4.0 on Quality and Operations Management. *International journal of online and biomedical engineering*, *10*(23), 133-147. https://doi.org/10.3991/ijoe.v17i09.24717

Rosin, F., Forget P., Lamouri, S., & Pellerin, R. (2020). Impacts of Industry 4.0 technologies on Lean principles. *International Journal of Production Research*, *58*(6), 1644-1661. https://doi.org/10.1080/00207543.2019.1672902

Rossini, M., Powell, D. J., & Kundu, K. (2023). Lean supply chain management and Industry 4.0: a systematic literature review. *International Journal of Lean Six Sigma*, *14*(2), 253-276. https://doi.org/10.1108/IJLSS-05-2021-0092

Rossini, M., Costa, F., Tortorella, G. L., & Portioli-Staudacher, A. (2019). Evaluation of the relation between lean manufacturing, industry 4.0, and sustainability. *International Journal of Advanced Manufacturing Technology*, *102*(9), 3963-3976. https://doi.org/10.1007/s00170-019-03441-7

Sartal, A., Llach, J., & León-Mateos, F. (2022). Do technologies really affect that much? Exploring the potential of several industry 4.0 technologies in today's lean manufacturing shop floors. *Operational Research*, *22*(5), 6075-6106. https://doi.org/10.1007/s12351-022-00732-y

 Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

Skalli, D., Charkaoui, A., Cherrafi, A., Garza-Reyes, J. A., Antony J., & Shokri, A. (2023). Industry 4.0 and Lean Six Sigma integration in manufacturing: A literature review, an integrated framework and proposed research perspectives. *Quality Management Journal*, *30*(1), 16-40. https://doi.org/10.1080/10686967.2022.2144784

Salvadorinho, J., & Teixeira, L. (2021). Stories told by publications about the relationship between industry 4.0 and lean: Systematic literature review and future research agenda. *Publications*, *9*(3). https://doi.org/10.3390/publications9030029

Saxby, R., Cano-Kourouklis, M., & Viza, E. (2020). An initial assessment of Lean Management methods for Industry 4.0. *TQM Journal*, *32*(4), 587-601. https://doi.org/10.1108/TQM-12-2019-0298

Schumacher, S. R. H, Hall, R., Bildstein, A., & Bauernhansl, T. (2022). Lean Production Systems 4.0: systematic literature review and field study on the digital transformation of lean methods and tools. *International Journal of Production Research*, *61*(24). https://doi.org/10.1080/00207543.2020.1743893

Sony, M. (2018). Industry 4.0 and lean management: a proposed integration model and research propositions. *Production and Manufacturing Research*, *6*(1), 416 -432. https://doi.org/10.1080/21693277.2018.1540949

Sony, M. (2020). Design of cyber physical system architecture for industry 4.0 through lean six sigma: conceptual foundations and research issues. *Production and Manufacturing Research*, *8*(1), 158-181. https://doi.org/10.1080/21693277.2020.1774814

Tripathi, V., Chattopadhyaya, S., Bhadauria, A., Sharma, S., Li, C., Pimenov, D. Y., Giasin, K., Singh, S., & Gautam, G. D. (2021). An agile system to enhance productivity through a modified value stream mapping approach in industry 4.0: A novel approach. *Sustainability (Switzerland)*, *13*(21). https://doi.org/10.3390/su132111997

Tripathi, V., Chattopadhyaya, S., Mukhopadhyay, A. K., Sharma, S., Singh, J., Pimenov, D. Y., & Giasin, K. (2021). An innovative agile model of smart lean–green approach for sustainability enhancement in industry 4.0. *Journal of Open Innovation: Technology, Market, and Complexity*, *7*(4). https://doi.org/10.3390/joitmc7040215

Tripathi, V., Chattopadhyaya, S., Mukhopadhyay, A. K., Saraswat, S., Sharma, S., Li, C., & Rajkumar, S. (2022). Development of a Data-Driven Decision-Making System Using Lean and Smart Manufacturing Concept in Industry 4.0: A Case Study. *Mathematical Problems in Engineering*, 2022. https://doi.org/10.1155/2022/3012215

Tripathi, V., Chattopadhyaya, S., Mukhopadhyay, A. K., Saraswat, S., Sharma, S., Li, C., Li, C., Singh, S., Ul, Hussan, W., Salah, B., Saleem, W., & Mohamed, A. (2022). A Sustainable Productive Method for Enhancing Operational Excellence in Shop Floor Management for Industry 4.0 Using Hybrid Integration of Lean and Smart Manufacturing: An Ingenious Case Study. *Sustainability (Switzerland)*, *14*(12). https://doi.org/10.3390/su14127452

Tortorella, G. L., and Fettermann, D. (2017). Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. *International Journal of Production Research*, *56*(8). https://doi.org/10.1080/00207543.2017.1391420

Tortorella, G. L., Giglio, R., & van Dun, D. H. (2019). Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement. *International Journal of Operations and Production Management*, *39*, 860-886. https://doi.org/10.1108/IJOPM-01-2019-0005

Tortorella, G. L., N. Pradhan, E. Macias, D.A, Trevino Martinez, S., Sawhney, R., and Kumar,.M (2020). Designing Lean Value Streams in the Fourth Industrial Revolution era: Proposition of Technology-Integrated Guidelines. *International Journal of Production Research*, *58*(16). https://doi.org/10.1080/00207543.2020.1743893

Valamede, L. S., & Akkari, A. C. S. (2020). Lean 4.0: A new holistic approach for the integration of lean manufacturing tools and digital technologies. *International Journal of Mathematical, Engineering and Management Sciences*, *5*(5), 854-868. https://doi.org/10.33889/IJMEMS.2020.5.5.066

Varela, L., Araújo, A., Ávila, P., Castro, H., & Putnik, G. (2019). Evaluation of the relation between lean manufacturing, industry 4.0, and sustainability. *Sustainability (Switzerland)*, *11*(5). https://doi.org/10.3390/su11051439

Zhang, K., Qu T., Zhou, D., Thürer, M., Liu, Y., Nie, D., Li, C., & Huang, G. Q. (2019). IoT-enabled dynamic lean control mechanism for typical production systems. *Journal of Ambient Intelligence and Humanized Computing*, *10*(3), 1009-1023. https://doi.org/10.1007/s12652-018-1012-z

Zhan, S. (2022). Exploring synergies between lean construction theory and industry 4.0 technologies in the in the architectural, Engineering and Construction industry: A people, process, technology perspective. *Results in Engineering*, *14*. https://doi.org/10.1016/j.rineng.2022.100405

Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International