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A Focused Study on Integrating Industry 4.0 and Lean Manufacturing

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Abstract

This study represents mainly a compact literature review aiming at investigating research opportunities/needs in context of industrial systems. It explores the connections and integration of Industry 4.0 and Lean Manufacturing with the focus on a system view perspective instead of the focus on specific information technologies. Industry 4.0 offers a set of advanced technologies that can significantly enhance Lean Manufacturing methodologies, particularly in digitalizing Lean tools. By combining these two paradigms, businesses can leverage technological advancements to increase operational efficiency. The study focuses on examining the integration of Industry 4.0 and Lean Manufacturing, emphasizing the importance of a systematic approach. Lean provides a structured methodology that serves as the foundation for applying Industry 4.0 technologies in industrial settings. This research highlights the gaps in current research, demonstrating the need for a framework that combines the strengths of both paradigms. Moreover, this research focuses on developing an initial framework connecting both paradigms. Developing a further detailed framework that addresses the limitations of Industry 4.0 and can be applied in industrial settings would be a subject of interest in future research. This work aims to contribute to a deeper understanding of Industry 4.0, Lean Manufacturing, and the connections between them.

Keywords
Industry 4.0, Lean Manufacturing, Lean Digitalization, Automation-Lean Digitalization Prism, and Cyber Physical Systems.

1. Introduction
Although both Industry 4.0 (I4.0) and Lean Manufacturing (LM) offer distinct benefits, limited research exists on the integration of these paradigms, particularly in the digital transformation of Lean methodologies. This integration is

crucial, as combining the strengths of I4.0 with LM enables organizations to fully leverage digital tools to enhance traditional Lean practices, resulting in a new era of digitalized LM. Investigating the relationship between these two paradigms could lead to more efficient and agile manufacturing systems that can adapt to the continuously changing demands of today's market.

The main challenge lies in the lack of a structured framework that effectively combines I4.0 technologies with Lean Manufacturing principles. Current research lacks a comprehensive understanding of how I4.0 tools can be systematically applied within Lean frameworks to achieve overall increased productivity and efficiency. This study addresses the existing research gaps in I4.0 and LM and evaluates potential connections between these strategies, aiming to establish a further detailed framework that combines their strengths in future research. Such a framework would provide a foundation for organizations seeking to digitally transform Lean practices, offering a structured methodology to enhance operational efficiency in industrial settings.

A system view approach to integrating I4.0 and LM involves understanding the manufacturing process as an interconnected process, where technology, processes, and people work together seamlessly. This approach emphasizes the importance of aligning I4.0 digitalization with Lean principles and tools to optimize efficiency across the entire value chain. By considering the broader system, organizations can avoid isolated technology implementations and instead create an integrated environment that enhances communication, responsiveness, and flexibility. Flexibility in production and logistics refers to the tactical adaptation of structures and processes to changes through the cooperation of personnel, machinery, manufacturing systems, and value creation networks (Bartodziej, 2017). It would be economically unfeasible to expand the requirements (corridors of action) to handle majority of the unforeseen changes. This is where adaptable systems will become critical. Adaptability is more important than flexibility since it indicates a system's ability to adapt to changes apart from the predetermined corridors of action and to respond proactively to changes (Bartodziej, 2017). Processes and systems can be altered and reorganized by simply rebuilding, for instance, a machine to create different goods. This holistic view supports the digital transformation of Lean methodologies, enabling continuous improvement and adaptation to dynamic market demands while ensuring that innovations are applied in ways that reduce complexity and enhance the overall productivity of the system.

I4.0 targets increased flexibility and efficiency in a low-complexity system (Davis et al., 2020). I4.0 aims to provide a high level of connection between all processes and products throughout their lifecycle. One simple definition of I4.0 is a strategic approach and progression toward digitalization. Another definition is a greater level of organization and control over entire value chains throughout the product's lifecycle. A more precise definition, cited in (Bartodziej, 2017), is the technical integration of Cyber Physical Systems (CPS) into production and logistics, as well as the application of the Internet of Things (IoT) and Services in industrial processes. Erboz (2017) mentions a similar definition stating that it is a collective term for technologies used by value chain organizations, with I4.0 components including the IoT, CPS, Internet of Services, and Smart Factory. CPS are the result of the data acquisition of a closed loop of sensor based physical process combined with software based (Cyber) data processing and autonomous actuator process control connected with Internet of Things and Services (Wagner et al., 2017). I4.0 will have an impact on value creation, business models, downstream services, and work organization. The primary consideration of resource allocation in I4.0 must be on workers, so that, through new approaches and the implementation of innovative technologies, they minimize the efforts of individuals while adding value rather than increasing it, generating stress, and diminishing value in the process.

2. Methodology

To adopt a holistic system view and investigate research opportunities, a clear strategy must be established. This involves initially examining I4.0 and LM separately to understand the core principles and methodologies of each. Then, the shared connections between the two paradigms will be explored, focusing on how each can complement and enhance the other. This process will help identify current research gaps and highlight potential areas for future improvements. For I4.0, its design principles, system structure and features will be analyzed to understand its key elements. Additionally, its benefits and limitations will be examined to leverage its strengths while avoiding its limitations. Similarly, the fundamentals of LM will be explored to understand how it can be integrated with I4.0. Finally, the literature review is conducted, which would help in establishing an initial framework connecting both paradigms. The methodology structure of the literature review is illustrated in Figure 1. This figure highlights the two main research areas in the literature review. The first area explores the automation pyramid, traditionally used to represent the structure of automation in industrial settings. With the advancements of I4.0, this pyramid's structure is evolving; rather than a strict layered approach, it is transforming into interconnected entities. Lean principles have the potential to integrate within these entities. Therefore, the potential applications of Lean in the I4.0 pyramid would be investigated. The second area focuses on the existing frameworks, whether focused on integrating Lean with I4.0 through digitalization or assessing the readiness and maturity of enterprises for implementing I4.0 and Lean will be examined. Moreover, frameworks combining Lean and Enterprise Resource Planning (ERP) to support the digitalization of business processes would be discussed. These frameworks form the foundation of this study, as insights gained from them will support the development of a new, unified framework. Also, this figure highlights the subsections under each research area and the primary research papers involved in this study for each subsection. Moreover, the output obtained from each research area is displayed leading to the development of the initial I4.0-Lean framework.

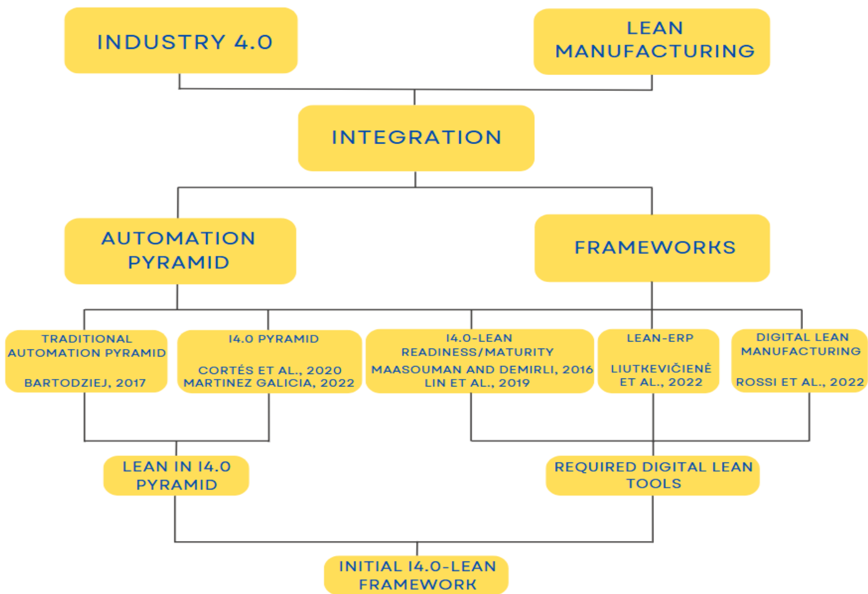

Figure 1. Methodology Structure

3. I4.0-Lean Overview

Interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity are the six design principles of I4.0 (Davis et al., 2020). The ability to operate with interconnected products and systems without requiring further effort from the customer is known as interoperability within a production system (Davis et al., 2020). According to Lucizano et al. (2023), physical, virtual, and human systems can communicate transparently. In the context of interoperability, machines can exchange and analyze data with one another. It enables visualization of production planning and control of processes and products. The creation of a virtual or "digital twin" of an entire value chain enables an end-to-end view of a product life cycle. By allowing designers to identify potential setup or simulation issues, this digital twin helps reduce the time needed for new product planning. Moreover, it does not require physical investment, which is cost-effective (Saturno et al., 2017). Decentralization, or the transfer of decision-making authority to lower hierarchies in the production process, is a key principle which allows a system to self-organize and adjust to changes to enhance productivity.

Reaction time decreases and productivity increases by data collection and real-time processing through ongoing product or process monitoring. Both virtualization and decentralized decision making require real-time capability. Another principle is service orientation, which involves granting people, machines, and software access to information and enabling them to cause real-time changes in the system based on customer preferences. The final principle is modularity, which describes the standardization across product vendors and communication networks to build systems that are highly compatible and require few to no modifications. The term modularity refers to both a fast-responding, interchangeable production system and modular items that enable mass customization after the customer decoupling point. As per the definitions in (Davis et al., 2020), Table 1 summarizes the definition of each principle.

Table 1. I4.0 Principles Definitions

I4.0 Principle	Definition
Interoperability	The ability to operate with interconnected products and systems without requiring further effort from the customer
Virtualization	Virtual or "digital twin" of an entire value chain, enables an end-to-end view of a product life cycle
Decentralization	The transfer of decision-making authority to lower hierarchies in the production process
Real-Time Capability	Real-time processing through ongoing product or process monitoring
Service Orientation	Involves granting people, machines, and software access to information and enabling them to cause real-time changes in the system based on customer preferences
Modularity	Fast-responding, interchangeable production system and modular items that enable mass customization after the customer decoupling point

The availability of all essential information in real time through the connectivity of all instances involved in value creation, as well as the ability to extract the best possible value stream based on the outcome of data, serve as the foundation for the development of I4.0. I4.0 should not be viewed as a closed system, but rather as one critical component of multiple crucial areas. This change involves the shift from isolated IT systems to fully connected systems (CPS) that are less dependent on human involvement (Lucizano et al., 2023). They could optimize the production process by monitoring and adjusting machine settings in real time to minimize waste and downtime (Lucizano et al., 2023). CPS are connected to databases and stored in cloud computing, which enables data acquisition in real time (Mendes et al., 2020).

Bartodziej (2017) specifies three fundamental features of the digital transformation. The first feature is horizontal integration via value networks, which requires the integration of different IT systems used in various phases of manufacturing and business planning processes that involve the transfer of materials, energy, and information both within a company (e.g., inbound logistics, production, outbound logistics, and marketing) and between multiple companies (value networks). The second feature is vertical integration, which require the integration of multiple IT systems at different hierarchical levels within a company (e.g., actuator and sensor, control, production management, manufacturing and execution, and corporate planning levels) to provide an end-to-end solution. The third feature is end-to-end digital integration of engineering across the entire value chain, which involves the use of appropriate IT systems capable of providing end-to-end support for the full value chain, from product development to manufacturing system engineering, production, and services. The definitions of these system features are displayed in Table 2.

Table 2. I4.0 System Features

I4.0 System Feature	Definition
Horizontal Integration	The integration of partners within supply chains such as suppliers, manufacturers, and distributors
Vertical Integration	The integration of multiple IT systems at different hierarchical levels within a company
End-To-End Digital Integration	The use of appropriate IT systems capable of providing end-to-end support for the full value chain, from product development to manufacturing system engineering, production, and services

I4.0 has wide range of benefits: meeting individual customer requirements, flexibility, optimized decision-making, resource productivity and efficiency, creating value opportunities through new services, responding to demographic change in the workplace, work-life balance, and a high-wage economy that is still competitive (Bartodziej, 2017). These changes significantly correspond with possibilities for reducing expenses. The report in (Rossi et al., 2022), conducted in 2019 and in collaboration with the World Economic Forum, emphasized the potential for manufacturers and suppliers that apply I4.0 to earn an additional value of 3.7 trillion dollars in sales by 2025.

I4.0 will assist industries improve their operational efficiency in terms of time, cost, and productivity. Building IoT infrastructure provides shared platforms via cloud systems across all parties in the supply chain, allowing business processes to be optimized (Erboz, 2017). Intelligent systems and the data they generate have a significant impact on a company's performance levels, cost efficiency, and the quality and fault free processes (Erboz, 2017). To summarize, the main benefits of I4.0 are shown in Figure 2.

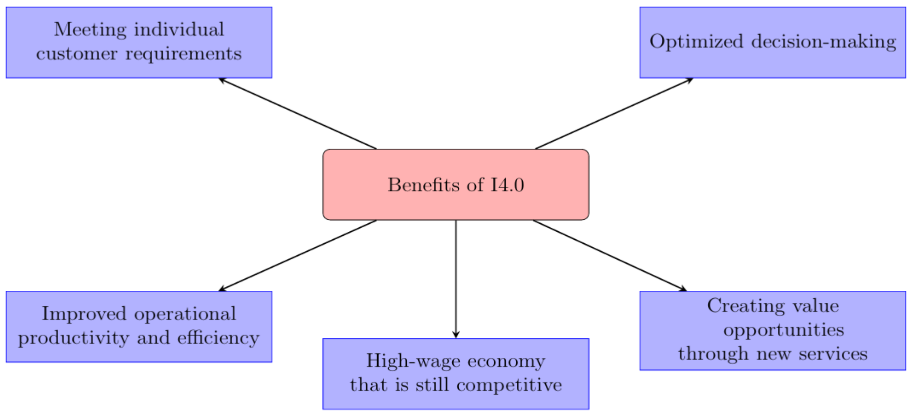

Figure 2. Benefits of I4.0

I4.0 has some constraints, which should be discussed and realized. The current approach to achieving the high level of autonomy required for this revolution is not fully clear. The deployment of I4.0 causes a financial risk to businesses, and the cost of high-tech equipment and IT infrastructure is hindering many, particularly small and medium sized businesses. In the study in (Rossi et al., 2022), five main barriers in I4.0 projects are listed: insufficient resources or lack of knowledge, high implementation costs, difficulty in justifying the investment in the business without a short-term return, prototype projects do not justify the investment, and too many cases to justify implementation. If not properly implemented, digital transformation can become a source of waste and failure; studies suggest that about 70% of digital transformation processes fail due to a lack of strategy and long-term thinking (Rossi et al., 2022).

The inherent problems of decentralization of decisions are complicated, creating design obstacles for humans and algorithms. Transferring data causes significant idle time. For example, in mechanical and engineering factories, just 4% of throughput time is spent on manufacturing, whereas the majority is spent on ordering, procurement, delivery, and other tasks (Davis et al., 2020). Furthermore, technological barriers between segments in a value chain reduce visibility between suppliers, producers, and customers (Davis et al., 2020). The main limitations of I4.0 are displayed in Figure 3.

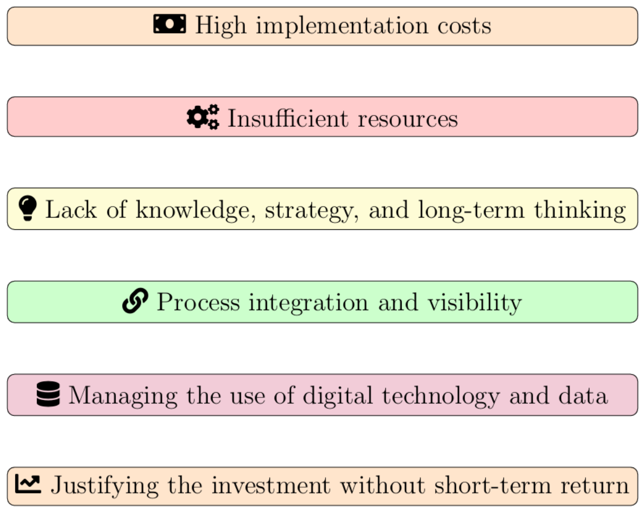

Figure 3. Limitations of I4.0

LM is a Japanese concept which was developed by Toyota. Previously, it was called Toyota Production System (TPS). It was originally designed to minimize cycle times, control outputs, facilitate decision-making processes, save costs, and enhance worker's safety (Chen and Wang, 2022). Lean aims to do more with less, which means aiming for efficient use of resources to improve the planning, control, and management of a manufacturing system. Lean is centered around pull production principle, in which the process starts from customer's requirements and demands. Common characteristics of Lean tools are transparency, ease of use and communication (Chen and Wang, 2022). These characteristics ensure smooth flow of information and data in the enterprise. According to (Chen and Wang, 2022), the success factors of LM are supplier relationship, process and control, human factors, and customer focus.

LM aims to eliminate waste or "Muda". These wastes are activities that add no value to the process and the customer is not willing to pay for. Basically, value-added activities avoid waste and produce exactly what is needed, at the place and time it is needed (Chen and Wang, 2022). These wastes are reduced through organizational practices; however, it does not rely heavily on emerging technologies (Shahin et al., 2020). Lean wastes are defects, overproduction, transportation, waiting, inventory, motion, over-processing, and non-utilized talent. However, with technological advances, the way to creating value to the process has changed. The 8 conventional wastes have been transformed into what is called "digital waste". Rossi et al. (2022) defines digital waste for each of the conventional wastes. These wastes are related to the way of handling, transporting, and storing data.

In Figure 4, the basic idea of LM is illustrated. The 3 main aims of Lean are waste elimination, efficient usage of resources, and smooth end-to-end system flow. These aims are based on pull production system. Lean would be achieved only if lean thinking and culture are spread within the organization. Lean has always empowered employees to be creative and help organizations thrive. This opens new opportunities and areas of improvement.

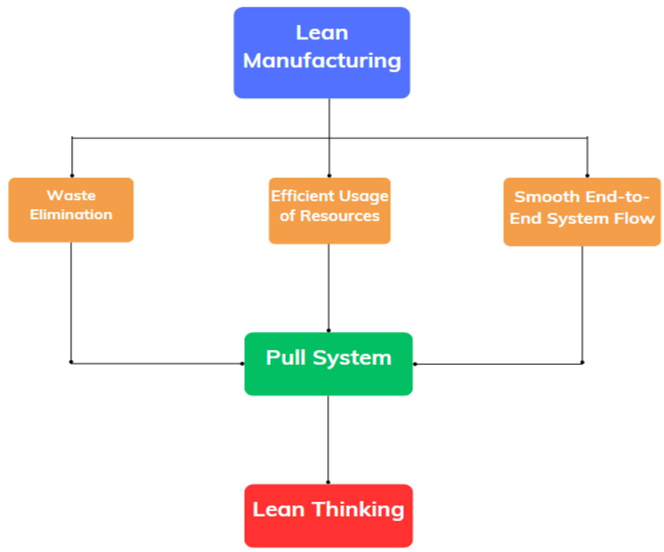

Figure 4. Lean Manufacturing Fundamentals

Horizontal and vertical integration in I4.0 can support and accelerate Lean principles by minimizing human error and improving intercommunications between systems, which leads to productive integration. For businesses, this represents a manufacturing revolution that will enhance productivity and stakeholder value. I4.0's horizontal and vertical integration improves visibility and communication across the value chain, suggesting new business models centered on adding value to all stakeholders (Davis et al., 2020). An optimized production process developed using the pull production system focuses on value-added activities, and data in the value chain should flow seamlessly through connected systems. If all decision makers in an enterprise share its core principles, there is a shift to a bottom-up approach that promotes decentralized problem solving (Davis et al., 2020). Lean's employee and customer focus promotes trust and learning opportunities, resulting in responsible decentralized teams that can serve as the foundation for new standards (Davis et al., 2020). The study mentioned in (Ejsmont and Gladysz, 2020), which conducted a comprehensive literature review on wastes in LM related to I4.0, stated that inventory levels could be improved by 70.2% through using appropriate I4.0 tools. Figure 5 demonstrates the main connections between I4.0 and LM.

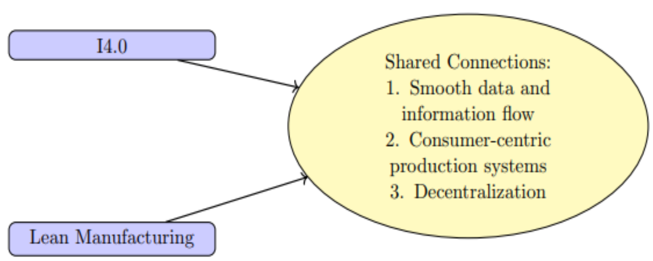

Figure 5. Shared Connections between I4.0 and Lean

I4.0 required users to understand sophisticated information and communication systems, limiting usability and hence not always meeting the original vision (Davis et al., 2020). Both Lean and I4.0 promote process improvement and enhanced efficiency, but do not consider one another in their implementation (Davis et al., 2020). With the advancements of I4.0, various issues related to inefficient digitalization become more apparent in enterprises. To address these issues, the lean mindset must be used in digital environments. However, before Lean can begin to address digitalization issues, its tools must be digitalized to understand I4.0 dynamics and become more effective (Rossi et al., 2022). There is a lack of literature on how Lean 4.0 works, what its key tools that are influenced by technological innovations, how Lean 4.0 can be applied in industry, and how the digital aspect of Lean affects the reduction in performance waste produced by I4.0 implementations, also known as digital waste (Rossi et al., 2022).

As I4.0 generates data on a continuous basis, which is stored in the cloud and processed by Big Data, there is a lot of waste in data storage that Lean 4.0 can help decrease. However, I4.0 has varying technical levels, and it is possible that it has more technologies than it requires or that its technological capabilities are outdated (Rossi et al., 2022). The article mentioned in (Rossi et al., 2022), highlighted that there is a lack of research on including customers in the control of information sharing in real time. Cortés et al. (2020) acknowledges the gap of evaluating multiple decision-making scenarios at different levels in the business models. Moreover, there is limited knowledge among employees about emerging technologies (Saturno et al., 2017). Without creative people, there is no Lean, and there is no waste control, whether digital or not (Rossi et al., 2022). In Figure 6, 8 main research gaps are shown. They are grouped into 2 main categories: I4.0 Technology Group and Lean Digitalization Group. This grouping was made based on the relevance of the gap to I4.0 digital technologies or Lean digitalization in respect to Lean tools.

Figure 6. Research Gaps

4. Results

Based on the literature review, which was illustrated in Figure 1, including both the automation pyramid and the frameworks connecting I4.0 and Lean, further conclusions and interpretations were reached. An "Automation-Lean Digitalization Prism" as a novel conceptual framework is here developed and introduced. The prism, as shown in Figure 7, is divided into a triangle evolved from the I4.0 pyramid and an additional dimension which is Lean Operational Excellence. The triangle, evolved from I4.0 pyramid, is divided into 3 main horizontal-vertical integration levels: Digital Data Collection, Digital Information Processing, and Digital Operations Management (OM). The required digital Lean tool for each horizontal-vertical integration level serves as the platform or base of the corresponding level. Each horizontal-vertical integration level and its corresponding digital Lean tool are further divided into 4 in-depth levels: conceptualization, preparation, implementation, and improvement. These in-depth levels represent the Lean Operational Excellence dimension.

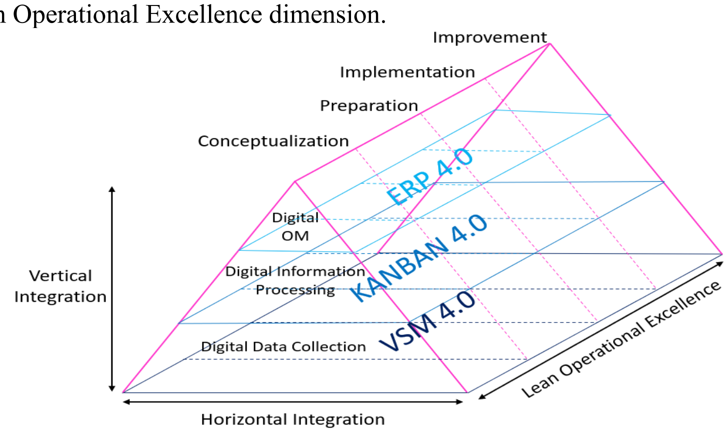

Figure 7. Automation-Lean Digitalization Prism

The bottom horizontal-vertical integration level, which is Digital Data Collection, is responsible for digital representation and mapping of operations through simulation, and data collection through smart sensors and actuators. The required digital Lean tool for this level is Value Stream Map (VSM) 4.0. This Lean tool organizes the overall flow of the value chain and can continuously track workflow inefficiencies and bottlenecks. Therefore, it forms the base of the prism. The second level is Digital Information Processing, which involves information processing through Programmable Logic Controller (PLC) and Supervisory Control and Data Acquisition (SCADA) systems, and inventory control and materials management. The required digital Lean tool for this level is Kanban 4.0. This Lean tool can manage inventory and material levels based on demand fluctuations. The topmost level is Digital Operations Management, which is the head of operational decisions and connection point for all levels together, and responsible for decision-making through real-time data analysis and visualization. The required digital Lean tool for this level is ERP 4.0, which can automatically update stocks, reduce stock counting errors, and inform workers in real time about the minimum demands for each station. Other digital Lean tools could be used with the required digital Lean tools in different levels as supporting tools such as Jidoka 4.0 and Poka Yoke 4.0. The horizontal-vertical integration levels, their primary functions, and required digital Lean tool are summarized in Table 3.

Table 3. Horizontal-Vertical Integration Levels

Horizontal-Vertical Integration Levels	**Primary Functions**	**Required Digital Lean Tool**
Digital Data Collection	- Digital representation and mapping of operations through simulation - Data collection through smart sensors and actuators	VSM 4.0
Digital Information Processing	- Information processing through PLC and SCADA systems - Inventory control and materials management	Kanban 4.0
Digital Operations Management	- Head of operational decisions and connection point for all levels - Decision-making through real-time data analysis and visualization	ERP 4.0

In table 4, the in-depth levels of I4.0-Lean maturity of the horizontal-vertical integration levels in enterprises are displayed. The Lean state in each level is defined in (Maasouman and Demirli, 2016) and corresponds to the dimension of Lean Operational Excellence. The I4.0 state, which occurs in parallel with Lean, is adopted from LEAD framework defined in (Lin et al., 2019). The bottom level, which is the conceptualization level, includes a Lean state of spreading Lean related principles among employees, while engaging them to develop innovative solutions. The I4.0 state involves learning related principles and concepts of I4.0. Then, the preparation level, involving a Lean state of training employees to start implementing Lean solutions and I4.0 state of evaluating the current status, identifying gaps, and determining future needs for adopting I4.0. The next level is the implementation level, including Lean implementation and I4.0 state of bridging the gaps by developing a strategic plan and roadmap for the transformation. The top level is the improvement level. In this level, continuous improvement of Lean solutions occurs. Moreover, the outcomes of I4.0 are delivered.

All components of the physical world should have their digital counterpart to comprehend all levels of the manufacturing systems (Cortés et al., 2020). Therefore, the Automation-Lean Digitalization Prism represents the cyber world including the digital components corresponding to the components of the physical world. On the other hand, the physical world is represented by the industrial setup focusing on production and logistics operations. Figure 8 represents the CPS integration between the physical world and their digital counterpart in the cyber world.

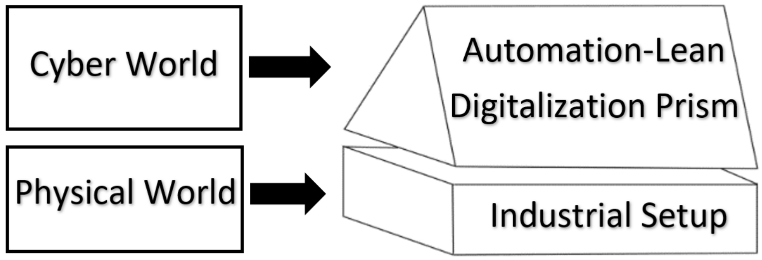

Figure 8. CPS Integration

This study proposes steps for implementing the digital required Lean tools. VSM 4.0 is classified as the required digital Lean tool for the Digital Data Collection Level. The steps for implementing VSM 4.0 are illustrated in Figure 9. It begins by mapping the current state using digital tools such as simulation that will aid in gathering real-time data on workflows, material flow, and information flow. Afterwards, the bottlenecks and inefficiencies are identified using real-time data analysis and visualization. Then, the optimized future state VSM is designed. Finally, the future state VSM is implemented and continuously monitored. Utilizing digital dashboards aids in sustaining the improvements.

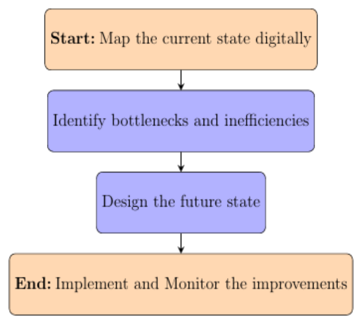

Figure 9. VSM 4.0 Implementation

Kanban 4.0 is regarded as the required digital Lean tool for the Digital Information Processing Level. In Figure 10, the steps for implementing Kanban 4.0 are introduced. The first step involves setting clear Work-In-Progress (WIP) limits to identify minimum stock levels and replenishment levels for each stage in the production line to control inventory and materials. The second step involves replacing physical Kanban cards with digital ones that use IoT sensors, Radio Frequency Identification (RFID) tags, or barcodes to track inventory and materials movement in real time. The third step involves integrating Kanban with ERP and real-time data analytics to automatically update stocks and perform real-time analysis of the system's performance. Finally, bottlenecks and inefficiencies are identified to continuously monitor and improve the system's performance.

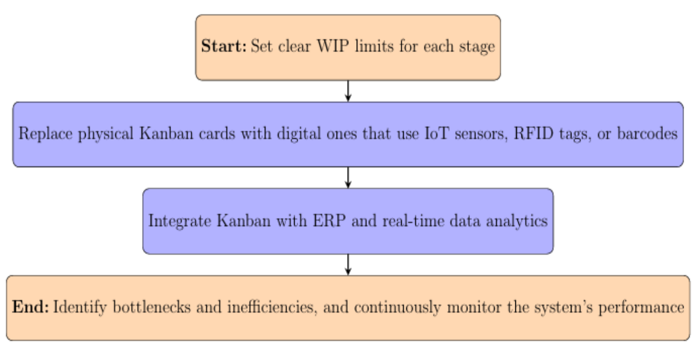

Figure 10. Kanban 4.0 Implementation

Digital Operations Management Level considers ERP 4.0 as the required digital Lean tool. The framework, which is proposed by (Liutkevičienė et al., 2022), serves as the basis for implementing digitally supported Lean-ERP system (ERP 4.0). It is divided into two main phases: setting the strategy and preparing for ERP and Lean capabilities, and managing improvement projects, which operates in repeating cycles. Figure 11 illustrates the steps proposed for implementing ERP 4.0. In the first step, setting the strategy for Lean and ERP includes identifying the maturity of Lean and ERP, aligning efforts with company's strategic priorities, and planning the improvement initiatives. The second stage involves determining Key Performance Indicators (KPIs) and targets for the improvement initiatives to monitor the progress. Then, executing digital ERP system requires training the employees, automating the repetitive tasks, and integrating operations. Finally, ERP capabilities are sustained and enhanced through repetitive cycles which involve monitoring performance and making adjustments if needed.

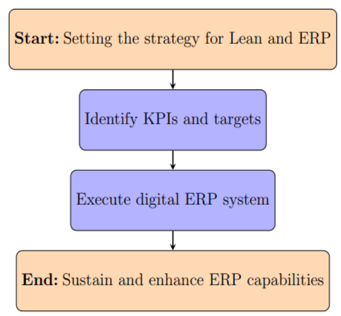

Figure 11. ERP 4.0 Implementation

5. Conclusion

In conclusion, this study focused on examining I4.0 and LM, and the shared connections between them. Moreover, the current research gaps were highlighted, representing challenges in both paradigms that should be addressed through further including case studies and the practical implementation of solutions. These gaps were grouped based on the relevance of the gap to I4.0 digital technologies or Lean digitalization, particularly in relation to Lean tools. Afterwards, a literature review was conducted, leading to developing and introducing an initial framework combining both paradigms and exploiting their strengths.

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