Department of Industrial Engineering & Maintenance

Interdependencies of Lean Manufacturing and Industry 4.0

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Abstract: This paper delves into the relationship between lean manufacturing principles and Industry 4.0, emphasizing their mutual impact on operational efficiencies and performance. While lean manufacturing plays a vital role in waste reduction and continuous improvement within production systems, Industry 4.0 represents a shift towards digital transformation and automation, driving smart manufacturing. The integration of these two paradigms offers opportunities for synergistic enhancement in operational effectiveness. Through a literature review, this paper explores three perspectives: the role of lean as an enabler for Industry 4.0 implementation, how Industry 4.0 advances lean manufacturing practices, and the correlation between these two paradigms. The term "Lean 4.0" describes the integration of lean principles with innovative Industry 4.0 tools, promising optimization of operations and adaptation to the demands of the digital age for organizations.

Key-Words: Lean Manufacturing, Industry 4.0, Cyber-Physical system, Lean 4.0

Contents

1. Introduction

The global marketplace has undergone remarkable transformations, driven by shifting consumer behaviors and the rapid pace of digital technologies. These changes have had profound effects across various sectors, particularly in manufacturing companies, resulting in shorter life cycles for products and a reduction in the lead time. [1]

Over the past few decades, the adoption of "lean management" has yielded positive outcomes across numerous industries [2]. This concept is grounded in the fundamental notion of removing all non-value-added activities within the factory, offering various tools and techniques to achieve this goal. These activities are commonly known as waste, including overproduction, inventory, overprocessing, defects, waiting time, transportation, unnecessary movements, and inadequate employee training [3]. Despite the proven effectiveness of lean tools across various sectors, implementing lean production in the face of dynamic market demands appears to be increasingly challenging and inefficient, leading to conflicts with the intended design of the concept [4]. Indeed, the shorter life cycles of products necessitate continuous updates in production processes, which can cause lean initiatives to diminish over time due to inadequate regular oversight and attention [1] [5]. Moreover, lean set instructions are not always followed by workers due to the absence of real time visibility, which improves the execution of these instructions [6]. As a result, there is a lack of systematic theory on the real time control framework that underlies lean manufacturing techniques [7] [8]. Therefore, manufacturers have had to adapt swiftly, embracing innovative practices that allow them to solve these types of issues efficiently and effectively by adopting the new concept of “industry 4.0 “. By 2011, the industrial landscape took a significant step forward towards autonomous factories, which are capable of self-management with minimal human intervention, leveraging powerful technologies such as the Internet of Things, Big Data analysis, Vertical and Horizontal Integration, Digital Twins, Cyber-Physical System, Cloud, Augmented Reality, Virtual Reality, Artificial intelligence (AI) and Self-Guided Robots. These technologies form the recently released “Industry 4.0.". Their objective is to enhance transparency within manufacturing facilities by implementing real-time data collection on the shop floor [9]. This initiative also offers increased flexibility in the supply chain and the ability to manage complex production processes and products. Multiple interdependencies exist between lean production and Industry 4.0. Both concepts share a common focus on efficiency, optimization, and meeting industry demands, however, the topic that now has to be addressed is: What are the current viewpoints on fusing Industry 4.0 with lean philosophy? Several authors agree that Lean serves as the foundational and prerequisite approach for implementing Industry 4.0. In additional research, authors explain that the automation and digitization technologies integral to Industry 4.0 appear to be an embodiment and execution of lean principles [9]. However, others affirm that the two concepts may coexist and benefit one another [10]. The inquiry revolves around which perspectives companies find more adaptable and how these perspectives will impact their performance.

The purpose of this paper is to address the three perspectives through an examination of multiple research studies. The article is structured as follows: Section 01, "Background," provides brief definitions of lean management and Industry 4.0, accompanied by illustrations. Section 02 explores the first perspective, "Lean enabling Industry 4.0," while Section 03 discusses the second perspective, "Industry 4.0 advancing lean." Further exploration in this section includes detailed case studies illustrating the combination of Industry 4.0 and lean principles. Section 04 investigates the third perspective, "Positive correlation between lean management and Industry 4.0," by analyzing a rich literature. Section 05, "Discussion," summarizes the key points from the three perspectives. Finally, the concluding section offers insights to conclude the paper.

2. Background

2.1. Lean Manufacturing

In 1970, Toyota Motor Corporation introduced the Toyota Production System, also known as lean production. This approach encompasses a variety of methods and tools designed to systematically eliminate the seven types of waste, known as muda [11]. Lean outlines, the true organizational approach to production, aiming for a concise lead-time, cost-effectiveness, and optimal quality [12].

Waste elimination in the lean production system involves removing all non-value-added activities. This capability is achieved through the implementation of methods and principles such as standardization, the zero-defect principle, flow principle, pull principle, employee orientation, management by objectives, continuous improvement, and the avoidance of waste, as illustrated in Figure 1 [13] [14].

The rigorous practices focus on waste elimination and involve a set of tools, including Just-In-Time, Heijunka, Jidoka, and visual management. However, the effectiveness of these tools depends on the company’s soft practices [15], Just-In-Time emphasizes the need to have the right materials available at the correct time, place, quantity, and quality, making it an integral part of the pull principle. On the other hand, Jidoka, or Autonomation, is a method that involves immediately halting processes when errors occur and resuming operations only after the issues are resolved. Jidoka aligns with the zero-defect principle, ensuring a focus on delivering flawless, outcomes [16].

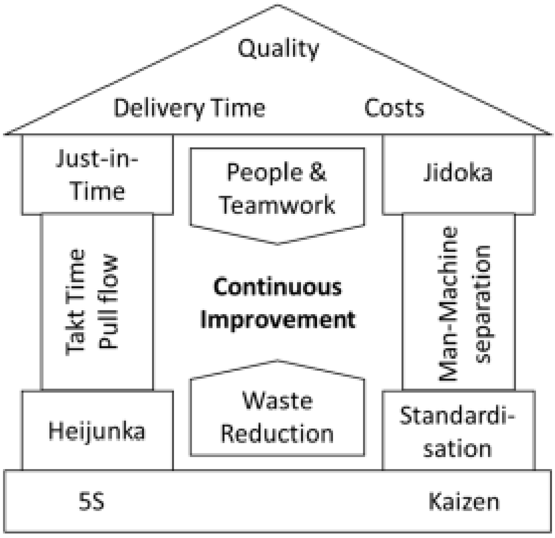

Figure 1: House of Toyota Production System[13] [14]

2.2. Industry 4.0

The progression of industrial revolutions marks significant shifts in manufacturing methodologies and technologies. The first industrial revolution introduced the use of engines in production systems, followed by the second revolution, characterized by the integration of electrically powered mass production. The third industrial revolution leveraged electronics and information technology to automate manufacturing systems. Finally, the fourth industrial revolution, often referred to as Industry 4.0, emphasizes digitalization and the interconnection of people, products, and machines[17].

Industry 4.0 refers to the digital transformation of industrial processes. The transformation focuses on the creation of smart factories using advanced technologies such as cyber-physical systems, the internet of things, cloud computing, artificial intelligence, and machine learning [18] [19]. Industry 4.0 is defined by the integration of products and systems, with a primary focus on advancing automation, flexibility, and customization in products, production methods, and associated business processes. By bridging the physical and virtual realms, Industry 4.0 aims to seamlessly connect real-world operations with digital capabilities [20].

Cyber-Physical Systems (CPS) is a technology designed to ensure seamless connectivity of all components within the production system through the Internet of Things (IoT). This enables efficient tracking and monitoring of the production processes, enhancing visibility and control. Moreover, CPS is characterized by its adaptability, allowing the system to flexibly accommodate changes and evolving requirements[21]. Cyber-Physical Systems (CPS) emerge from a feedback loop involving the acquisition of sensor-driven physical process data, software-driven data processing, and autonomous actuator-based process control. These components are interconnected with the internet, enabling seamless access to data and services [14] [22].

The internet of things refers to an interconnected network of objects embedded with sensors, software, and other technologies that enable the ability to collect and exchange data [23] [24].

Big data plays a pivotal role in Industry 4.0; big data refers to the extremely large amount of data [25].

Cloud computing is a technology that allows the storage of large amounts of data. Therefore, it facilitates the execution of decision-making [26] [25]. The structure of industry 4.0 elements is indicated in Figure 2 [27].

3. Lean enables Industry 4.0

As previously stated, the objective of this paper is to explore the correlation between lean manufacturing and Industry 4.0, examining the mutual influence they exert on each other. According to S. Adam et al [28], lean production is a prerequisite for the successful implementation of Industry 4.0.

Uwe Dombrowskiet et al. [27] highlighted that successful implementation of Industry 4.0 necessitates a well-established and efficient process prior to automation. The author notes that the incorporation of horizontal and vertical networking through Industry 4.0 facilitates enhanced integration of customers and suppliers into the process. Horizontal networking involves collaboration at the same level in the supply chain. While vertical networking integrates various stages of the supply chain, linking suppliers, manufacturers, and customers.

A. Davies et al. [29] asserted that Lean serves as a facilitator for the incorporation of Industry 4.0, representing a shift aimed at altering the operational performance of the organization. Conversely, Industry 4.0 has the potential to support Lean and Six Sigma capabilities at both the operational and enterprise levels of an organization. This improvement is evident through Cyber-Physical Systems (CPS) networks, such as electronic kanban and production surveillance, where metrics like production rate, downtime, and setup time can be automatically captured. Additionally, concepts like Total Productive Maintenance (TPM), data analysis, and the application of virtual value stream mapping, commonly associated with lean initiatives, can undergo transformation with the integration of virtual reality.

V.L. Bittencourt et al. [30] undertook a study examining the connection between lean principles and Industry 4.0. According to the authors, lean is a crucial approach to the integration of Industry 4.0. Numerous research studies acknowledge a complex interplay involving individuals, machinery, and environmental elements within organizational systems. Each of these interactions is customized and managed in unique ways to meet the specific needs of the customers.

Prinz, C et al. [21] believe that successful implementation of digitization is contingent upon the prior optimization of the organization, especially its processes, in accordance with lean principles. Conversely, it aids in minimizing efficiency losses in a lean-optimized pro-

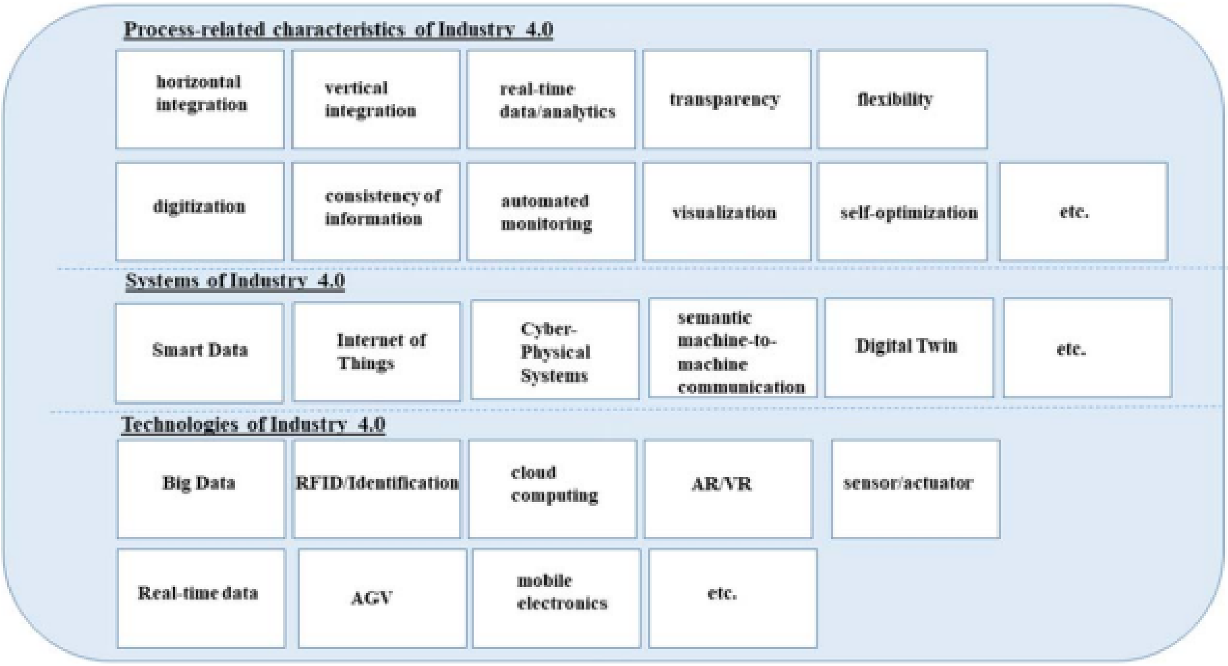

Figure 2: Industry 4.0 technologies, systems, and process-related characteristics[27]

duction system during disruptions and contributes to overall productivity enhancement. However, participants also face challenges and limitations. Moreover, the task involves integrating various Industry 4.0 applications into a comprehensive concept to ensure enduring learning effects among participants.

Abdulnour, S et al [31] detailed a case study on the customized implementation of Industry 4.0 within a mass production setting, following the implementation steps proposed by Gamache [32]. These steps require the prior implementation of lean manufacturing principles and the optimization of production processes before Industry 4.0 adoption. Gamache's [32] digital transformation framework comprises six steps: initial mapping of the value chain to ensure process control and develop a strategic company vision plan, conducting an audit to assess digital performance and identify relevant business practices, prioritizing and planning projects within a digital plan, implementing digital and non-digital business practices categorized in the article, deploying the selected solutions in business processes, and optimizing processes by correcting, streamlining, and implementing the next project on the list. In this study, the focus was on enhancing the production line for ambulance structures, aiming to increase the production rate from five to seven structures per week. Beginning with process mapping, the company utilized its existing ERP system for production management and planning. Additionally, the company adhered to lean principles for executing improvement projects. Identified areas for improvement led to a prioritized list of projects, including standardization work and waste reduction through methodologies like 5S and single-minute exchange of die (SMED). The implementation of lean practices resulted in a production rate increase to six structures per week on the line. Subsequently, a simulation model was developed using Arena software from Rockwell Automation. Simulation results indicated that integrating Industry 4.0 increased the production rate to 6.83 structures per week. This highlights the role of simulation in the decision-making process and suggests its broader utilization by small medium enterprises in Industry 4.0 implementation.

4. Industry 4.0 advances Lean Manufacturing

According to A. Mayret al. [9], various i4.0 technologies can support lean methods and assist in the realization of lean targets. In addition, F. Aljoscha Schmida et al. [33] demonstrated the influence of Industry 4.0 on various levels of lean practices, including objectives, processes, principles, methods, and tools.

M. Pagliosa et al. [17] explained the aforementioned aspects by analyzing multiple publications that enable the authors to create evaluation systems with different criteria, such as: the frequency with which I4.0 technologies and lean production system (LPs) are cited, the execution of I4.0 and LPs at various organizational levels, the findings discovered in the literature, and the sum of the scores for all criteria according to the total score. The synergy level was divided into three categories : high level, medium level and low level. The high level category indicates the presence of important cooperation between LPs tools and I4.0 technologies, which leads to improved operational performance. This is the same situation with Cyber-physical system (CPS) and Value Stream Mapping (VSM). Both of them are interested in the value stream level. The VSM requires a high potential of collecting data so with the integration of CPS, it could cover this limitation and deliver more reliable data that helps in continuous improvement. The medium level describes that the association of technologies and lean methods needs a presided analysis of their characteristics, like simulation and POKE-YOKE. Simulation contributes in the examination of the production process before its implementation to reduce its failures and improve its potential. However, it does not eliminate the mistakes. This is not the case with POKA-YOKE, which is based on avoiding errors. As a result, the association between these two still not certain. Finally, the low level assumes that the relations between the pair LPs and I4.0 technologies require crucial adjustments with deep studies. This is the case of advanced robots and single minute exchange of die (SMED). Their combination can lead to a problem because it could minimize the flexibility of the production line, which affects negatively the order of the family products that exist in the line. In addition to the changeover time, which is the inverse of SMED's essence, this association needs to be developed.

A.Mayr et al. [9] explored this aspect by integrating Total Productive Maintenance (TPM) with Computer Monitoring and Cloud to make the maintenance activity of the sheet metal stamping machine easier. Starting with reducing the downtime, then predicting machine failures and tool destruction, the data collected by the previous system is not displayed. It was solely kept in Access or Excel. This is why the application of the technology of the Computer Monitoring (CM) system allows data to be visualized by transmitting and combining the collected data from sensors to the Siemens cloud to be analyzed. With the help of a graphical user interface, the data will be displayed on mobile devices. This new system has several features, such as informing stakeholders in case of failure by notification, the accessibility of data among the different departments because of cloud privileges, the dynamic planning of maintenance activities.

In another study, M. Marinellie et al. [24] developed surveys regarding the implementation of this concept in industrial settings and distributed them electronically to over 200 companies. The findings indicated that the utilization of cyber-physical systems and predictive algorithms enable optimized maintenance scheduling within the framework of TPM.

A.Mayr et al. [9] also introduced the promising plan of enhancing VSM by integrating the technology of digital twins. For example, the existing software Siemens Simulation helps VSM and suggests new process optimization in the new VSM model, but it remains a limitation that must be improved in the era of digitalization. With the revelation of the digital version that is connected to a real system in real time, the VSM model will be built on reliable data.

In 2022, W de Paula Ferreira et al. [34] treated the combination of VSM with hybrid simulation.

M. Shahin et al. [35] demonstrated that I4.0 technologies could improve Kanban in order to help managers make correct decisions with the use of cloud computing, which is the center of industry 4.0 technologies to create visual tools: cloud Kanban which is a support system decision that generates and controls the usage of enterprise resources, R. Davies et al. [36] indicated the support of a cyber-physical system in the monitoring of e-Kanban by managing automatic orders and controlling store levels.

EC Ogu et al. [37] described the integration of the internet of things and cloud computing in Cognizant computers with lean practices in order to advance the business. This system has a positive impact on the decrease in lead time, inventory levels, and reduction of process waste.

Stäubli Corp., Duncan, SC, invented a new automated quick mold change that allows the mold operations to occur in only a few minutes. This system displaces the mold from the injection machine and replaces it with a preheated one that is ready. It also allows the processors to frequently prepare the next mold in parallel while production goes on, which is the essence of a single-minute exchange of dies. This intelligent mold has a charge table that modifies its height to move the mold according to the data received from the injection machine.

NYG Lai et al. [38] indicated that the Internet of Things contributes to the decrease of the lead time because of its accessibility to real-time data, which helps to minimize the waiting time. Also, the use of augmented reality can eliminate all the waiting times that are considered waste.

Tortorella et al. [39] discussed that big data and maintenance preventive scheduling enhance traceability.

T. Wagner et al. [14] employed a use case involving the development of a cyber-physical Just-In-Time (JIT) delivery solution based on the Industry 4.0 impact matrix. JIT, a concept emphasizing waste reduction and high product quality, is supported by integrating big data, data analytics, and vertical machine-to-machine communication according to the author's impact matrix. The use case aimed to establish a seamless information flow encompassing manufacturing orders, material delivery, material stock, material consumption, and the automatic generation of purchase orders to suppliers. This use case serves as evidence of the development of lean processes through the adoption of Industry 4.0 technology.

4.1. results of combining lean tools with Industry 4.0 technologies

After mapping information from different articles, the possibilities of joining industry 4.0 technologies with Lean Manufacturing tools are summarized in a relationship matrix, which is a conceptual model that allows the identification of the combination results of each pair of LM/I4.0: which technologies could be utilized to support lean tools. Figure 3 [9] indicates multiple synergy points that will be treated briefly.

Lean methods / I4.0 tools	JIT/ JIS	Hei- junka	Kanban	VSM	TPM 1*	TPM 2**	TPM 3***	SMED	VM 5 S	VM Zoning	VM Andon	Poka- yoke
Additive manufacturing (AM)	x					x		x				
Plug and play							x	x				
Automated guided vehicles (AGV)	x		x									
Human-computer interaction (HCI)			x	x	x				x	x	x	x
Virtual representation (e.g. VR, AR)	x				x			x	x	x		x
Intelligent bins	x		x									
Auto-ID	x		x	x	x			x	x	x		x
Digital object memory	x				x			x				x
Digital twin/simulation	x	x	x	x		x	x	x	x			
Cloud computing	x			x	x	x						x
Real-time computing	x	x	x	x	x	x	x	x	x	x	x	x
Big data & data analytics	x	x	x	x		x						x
Machine learning				x	x			x				x

* autonomous maintenance, ** planned maintenance, *** early product and equipment management

Figure 3: combining industry 4.0 technologies and lean methods [9]

4.1.1 Value Stream Mapping 4.0

Value Stream Mapping (VSM) is identified as a significant tool in Lean Manufacturing. It maps the valuable points in the production process to discover the bottlenecks, waiting time, and circulation of flows [40]. By catching the rhythm of the digitalization transition, this tool will transfer to VSM 4.0, empowered with the technologies of industry 4.0. Big data and cloud collect data in real time from all the supply chain [41] and consolidate them to provide an effective system based on. This helps the manager make decisions. By implementing human-computer interaction such as smart phones and tablets, the stakeholders will receive information like process variability and initiate measures remotely. Furthermore, machine learning and data analytics contribute to the design of new value stream. The VSM 4.0 ensures the transparency of value stream level because of real-time data and helps in identifying waste in the production process, which contributes to continuous improvement [9].

4.1.2 Kanban 4.0

Kanban works on maintaining a continuous material flow by generating inventory levels to ensure a persistent supply of resources [9]. In the term of Industry 4.0, new characteristics will be added to these tools by integrating technologies such as big data, which participate in flow material real-time control and smart stock volume monitoring. With the help of digital twin, new Kanban solutions can be planned correctly, respecting the production environment. The simulation guarantees the recognition of reliable Kanban parameters such as lot size, stocks level, and delivery times [42]. Automated guided vehicles (AGV) can update the production lines with needed material at the right time, effectively reducing the need of overstocks [9].

4.1.3 Total Predictive Maintenance 4.0

Total Predictive Maintenance (TPM) is a methodology that integrates all the organizational levels of the company. It ensures the optimization of assets by reducing downtime and eradicating any failures and their causes, plus offering maintenance systems managed by operators and involving them in their daily activities to increase the availability of equipment, which affects positively productivity and quality [43]. The technologies proposed by Industry 4.0 to improve TPM and help the operators more on engaging the correct actions in case of failures are virtual reality and augmented reality, which visualize virtual elements and guide the operators remotely [44]. The communication machine to cloud provides a warning notification in case of failure to the shop floor, based on the analysis of the big data historic that works with complicated algorithms. The defects can be predicted, smart products and computer monitoring allow for loads and damages to be generated while the machine is processing [45] and the technology of additive manufacturing helps in the digital design of product elements [41].

4.1.4 Just in time 4.0

This tool ensures that the items that are delivered to clients meet their needs in terms of pricing, location, quality, and time. In the context of Industry 4.0, multiple technologies could be combined with this tool. The automated guided vehicles (AGV) transfer the items of the flow material automatically with fewer errors, such as the needed supplies, to the work station. The technology digital objects and memory stores [46] each important manufacturing parameter with the help of monitoring the condition of material transportation, the AGV is guided correctly, In addition, this Radio Frequency Identification (RFID) technology can be implemented to track the goods movement in real time and find their location in the supply chain exactly [47]. Big data and data analytics have the potential to analyze the real-time information that comes from the shop floor, which allows the determination of the capabilities and failures of the production system in order to define the crucial rules that keep production ongoing [48] also provide transparency to the value stream [9]; furthermore, predictive maintenance reduces the downtime to ensure the circulation of the continuous material flow [49].

4.1.5 Heijunka 4.0

The aim of this tool is to keep the production rhythm constant by producing only customer orders in order to eliminate the waste of type overproduction [9]. With the injection of data analytics the production scheduling will be stabilized by exploiting historical data and combining it with a deep market study to understand customer behavior [50]. Furthermore, the use of software tools supports data analytics, such as software "AnaPro," which is utilized to level production planning automatically based on product characteristics, inventory levels, and sales history [51].

4.1.6 Poke-Yoke 4.0

This tool describes techniques that allow the operator to make fewer errors. Besides that it helps in detecting anomalies in the production process to eliminate deficient products, which makes its application in factories with a wide range of products useful. The implementation of POKA-YOKE needs a high level of knowledge of the process activities during their execution and their cessation because of failures [52]. The combination of AUTO–ID boosts this tool; for example, the digital object memory helps the identification of the needed parts and the wrong deliveries [10]. The use of smart sensors and machine learning adds a new feature to the machine, which is self-optimization, in order to ensure the optimal quality of the product. The technology RFID is using to reach zero defect in the picking operation [53].

4.1.7 Single Minute Exchange Of Die 4.0

The purpose of using this tool is to reduce setup and changeover time in order to increase the flexibility of the production line with different ranges of products. The Additive Manufacturing technology is the expected solution to reach the minimum set-up time because it works on the processes of a variety of products. However, it's still unsure of how it will affect the cleaning process and temperature adjustments [54].

5. Positive correlation between Lean Manufacturing and Industry 4.0

Mrugalska et al. [10] presented a review of literature about the possibility of matching industry 4.0 and lean manufacturing by providing examples of smart products, machines, and augmented operators in reference to lean production principles, which proved that these two approaches can support each other.
Satoglu et al.[55] indicated that problems caused by mismanagement or disorganization cannot be solved by simply deploying Industry 4.0 technologies. In actuality, lean activities that are effectively completed before automatization should benefit from the application of these technologies. They also confirm how crucial it is to have an efficient information flow before and after putting these technologies into use.
A study by Tortorella et al. [56] found that Industry 4.0 technologies positively impact the relationship between lean concepts and operational performance. This was after analyzing data from 147 Brazilian companies that had implemented both the concepts of lean manufacturing and Industry 4.0. However, process-related technologies had a negative effect on the relationship between low setup time and operational performance. This suggests that Industry 4.0 technologies can either strengthen or weaken the relationship between Lean management practices and operational performance indicators. This provides guidance for managers and practitioners on balancing Industry 4.0 technologies with Lean tools for optimal performance.
Khanchanapong et al. [57] investigated the unique and synergic effects of manufacturing technologies and lean practices on operational performance within the factory by using collected data from 186 manufacturing plants in Thailand. They found that both of these concepts have special effects on a range of operational performance, such as quality, lead time, flexibility, and cost.
Azadeghan et al.[58] established the effects of environmental complexity and dynamism on lean operations by examining these relations using archived surveys and data from 126 manufacturers. The results of this examination proved that environmental complexity positively moderates the effects of lean operations. However, environmental dynamism decreases the benefits of lean operations on performance. Despite the fact that it might not seem immediately related to our subject, researchers are able to determine whether specific Industry 4.0 technologies have the ability to limit or alter the impact of lean techniques on production performance by looking into how these technologies affect environmental complexity.
Riezebos et al. [59] explored the influence of Information Technology (IT) on lean production principles. They found that initially, IT and Lean approaches had similar origins but diverged over time. As Lean manufacturing gained acceptance, these practices converged into hybrid production systems, which incorporate elements from various approaches in a manner consistent with Lean principles. The study primarily focused on centralized IT systems, overlooking distributed structures facilitated by cloud technologies[60]. Cloud-based structures are more compatible with Lean philosophy, emphasizing teamwork and decentralized decision-making. This mitigates many of the contradictions between IT systems and Lean principles, as cloud technologies emphasize collaboration and workforce empowerment.
D. de Oliveira-Dias et al. [61] investigated the interplay between Industry 4.0 (i4.0), lean, and agile supply chain, examining their mutual influences. Be-

ginning with the development of hypotheses, the researcher concludes six key propositions: i4.0 base technologies exert a direct and positive impact on Lean Supply Chain (LSC) implementation; i4.0 base technologies similarly have a direct and positive influence on Agile Supply Chain (ASC) implementation. Furthermore, LSC is found to have a direct and positive impact on ASC in i4.0 environments, while both LSC and ASC contribute positively to the focal firm's operational performance. Additionally, a positive correlation is identified between i4.0 base technologies and the focal firm's operational performance. The survey research conducted involved data collected from 256 manufacturing companies located in Spain. Adopting a dynamic capability perspective, the observed results support a model characterized by direct effects. In this model, Industry 4.0 foundational technologies play a facilitating role in Lean Supply Chain (LSC), leading to subsequent positive influences on Agile Supply Chain (ASC) and ultimately resulting in improved operational performance.

6. Discussion

The review of literature highlights the interconnections between Industry 4.0 and lean manufacturing, emphasizing their reciprocal influence. Several studies corroborate the notion that these two methodologies can coexist harmoniously, exhibiting a positive correlation. Authors such as Dombowski et al.[27] and Adam Sanders et al. affirm that lean production is indispensable for the successful implementation of Industry 4.0, with lean principles serving as enablers for Industry 4.0 adoption. Davies et al. further assert that establishing efficient processes prior to automation is essential for Industry 4.0 implementation. As demonstrated in the case study conducted by Abdulnour et al.[31], which followed the steps outlined by Gamache. This case study underscores the significance of prior implementation of lean manufacturing principles, yielding notable improvements in production outcomes. However, other studies presented a different perspective by highlighting the potential of integrating industry 4.0 with lean practices to enhance operational performance, M. Pagliosa et al. [17] demonstrated that i4.0 technologies can support lean methods. For instance, the integration of cyber-physical system improves VSM data collection capabilities and contributes to continuous improvement efforts. While W de Paula Ferreira et al. [34] and R. Davies et al. [36] discovered that technologies such as digital twins and real time monitoring enhance VSM and Kanban by providing reliable data, which enables decision making and process optimization, to enhance maintenance activities. A. Mayr et al.[9] proposed combining TPM with computer monitoring and cloud technologies by fostering predictive maintenance, reducing downtime, and increasing machine reliability, even though Tortorella et al. [56]suggested that big data and maintenance preventive scheduling enhance traceability. The integration of the Internet of Things (IoT), cloud computing, and augmented reality (AR) contributes to reducing lead time and minimizing waste to improve workflow effectiveness, as discussed by EC Ogu et al. [37] and NYG Lai et al. [38]. A use case involving the creation of a cyber-physical Just-In-Time (JIT) delivery system was given by T. Wagner et al. [14]. Big data analytics and machine-to-machine communication are combined in this system to create a smooth information flow between production processes, which reduces waste and improves product quality.

The correlation between Industry 4.0 and lean management has been discussed in multiple studies. The article [10] established examples of how smart products, machines, and augmented operators align with lean methods, while Stogolu et al. [55] mentioned that deploying industry 4.0 technologies alone may not solve the disorganization and mismanagement problems, Tortorella et al. [56] proved that I4.0 technologies can positively impact the relation between lean management and operational performance, D de Oliveira-Dias et al. [61] proved that with the agile supply chain.

7. Conclusion

This research aims to investigate the dynamic interaction between Industry 4.0 and lean production, which is characterized by a cooperative effort that produces benefits in modern manufacturing. This combination of classic Lean principles and innovative Industry 4.0 tools—like big data analytics and the Internet of Things creates a synergistic effect that led to the creation of the phrase "Lean 4.0." This integration is an example of how cutting-edge technologies and well established procedures may coexist. The review of the literature focuses on three points of view: first, how Industry 4.0 is implemented using Lean principles; second, how Industry 4.0 drives improvements in Lean methodology; and third, how does Industry 4.0 impact lean methods.

The implementation of these concepts within the company has been demonstrated through various use cases to significantly enhance the production system's performance and productivity.

The success of this integration hinges on factors such as organizational size, type of business, and the unique characteristics of the organization in question.

References

[1] M Ramadan and B Salah. Smart lean manufacturing in the context of industry 4.0: a case study. *International Journal of Industrial and Manufacturing Engineering*, 13(3):174–181, 2019.

[2] Mohammad Shahin, F Frank Chen, Hamed Bouzary, and Krishnan Krishnaiyer. Integration of lean practices and industry 4.0 technologies: smart manufacturing for next-generation enter-

prises. *The International Journal of Advanced Manufacturing Technology*, 107:2927–2936, 2020.

[3] Arthur Henrique Gomes Rossi, Giovanna Bueno Marcondes, Joseane Pontes, Paulo Leitao, Fernanda Tavares Treinta, Luis Mauricio Martins De Resende, Elaine Mosconi, and Rui Tadashi Yoshino. Lean tools in the context of industry 4.0: literature review, implementation and trends. *Sustainability*, 14(19):12295, 2022.

[4] Dennis Kolberg, Joshua Knobloch, and Detlef Zühlke. Towards a lean automation interface for workstations. *International journal of production research*, 55(10):2845–2856, 2017.

[5] Torbjørn H Netland. Critical success factors for implementing lean production: the effect of contingencies. *International Journal of Production Research*, 54(8):2433–2448, 2016.

[6] Daniel Metz, Sachin Karadgi, Ulf Müller, and Manfred Grauer. Self-learning monitoring and control of manufacturing processes based on rule induction and event processing. In *4th international conference on information, process, and knowledge management (EKNOW 2012)*, pages 88–92, 2012.

[7] Kai Zhang, Ting Qu, Dajian Zhou, Matthias Thürer, Yang Liu, Duxian Nie, Congdong Li, and George Q Huang. Iot-enabled dynamic lean control mechanism for typical production systems. *Journal of ambient intelligence and humanized computing*, 10:1009–1023, 2019.

[8] Sven-Vegard Buer, Jan Ola Strandhagen, and Felix TS Chan. The link between industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda. *International journal of production research*, 56(8):2924–2940, 2018.

[9] Andreas Mayr, M Weigelt, A. Kühla, S Grimm, A Erll, M Potzel, and J Franke. Lean 4.0-a conceptual conjunction of lean management and industry 4.0. *Procedia Cirp*, 72:622–628, 2018.

[10] Beata Mrugalska and Magdalena K Wyrwicka. Towards lean production in industry 4.0. *Procedia engineering*, 182:466–473, 2017.

[11] Monden Y. Toyota production system. *Boca raton: CRC Press.*, 2012.

[12] T. Ōno. Toyota production system : Beyond largescale production. *Cambridge, Mass., Productivity P .*, 1988.

[13] Taiichi Ohno. Toyota production system: Beyond large-scale production. portland: Productivity, 1988.

[14] Sebastian Thiede Tobias Wagner, Christoph Herrmann. Industry 4.0 impacts on lean production systems. *Procedia CIRP,*, 63:125 – 131, 2017.

[15] Crhistian R. Baldoa Vagner Agostinho Jr.a. Assessment of the impact of industry 4.0 on the skills of lean professionals. 2021.

[16] J.K. Liker. The toyota way: 14 management principles from the world's greatest manufacturer. *McGraw-Hill, New York, xxii*, page 330, 2004.

[17] Guilherme Tortorella Marcos Pagliosa and Joao Carlos Espindola Ferreira. Industry 4.0 and lean manufacturing a systematic literature review and future research directions. *Journal of Manufacturing Technology Management*, 32(3):543–569, 2021.

[18] Mariia Golovianko. Industry 4.0 vs. industry 5.0: Co-existence, transition, or a hybrid. page 102–113., 2023.

[19] H. L. Kagermann. Industry 4.0: With the internet of things on the way to the 4th industrial revolution. *VDI New*, page 2–3., 2011.

[20] S. M. Christian Leyh. Industry 4.0 and lean production – a matching relationship? *Proceedings of the Federated Conference on Computer Science and Information Systems*, page 989–993, 2017.

[21] N. K. Christopher Prinz. Lean meets industry 4.0 - a pratical approach to interlink the method world and cyber-physical world. *Procedia Manufacturing,*, pages 21–26, 2018.

[22] M Broy. engineering cyber-physical systems: challenges and foundations . *Springer*, page 1 – 13, 2013.

[23] A. M. Konanahalli. Drivers and challenges associated with the implementation of big data within uk facilities management sector: an exploratory factor analysis approach. *IEEE Transactions on Engineering Management.*, 2019.

[24] A. A. Marina Marinelli. Lean manufacturing and industry 4.0 combanative application: Practices and perceived benefits. *IFAC PapersOnLine.*, page 288–293, 2021.

[25] H. P. Abhilasha Sharma. Big data and analytics in industry 4.0. *Springer Nature Switzerland*, pages 68–83, 2020.

[26] L. D Xu. Industry 4.0: state of the art and future trends. *International Journal of Production Research*, pages 2941–2962, 2018.

[27] Krenkel P Dombrowski U, Richter T. Interdependencies of industrie 4.0 lean production systems: A use cases analysis. *Procedia Manufacturing*, (11):1061–1068, 2017.

[28] Jens Wulfsberg Adam Sanders, Chola Elangeswaran. Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing. *Journal of Industrial Engineering and Management*, pages 811–833, 2016.

[29] Coole T. Smith A. Davies, R. Review of socio-technical considerations to ensure successful implementation of industry 4.0. *Procedia Manufacturing*, 2017.

[30] C.P. Leão V.L. Bittencourt, A.C. Alves. Lean thinking contributions for industry 4.0 : a systematic literature review. 2019.

[31] Georges Abdulnour Sébastien Gamache Samir Abdulnour, Chantal Baril. Implementation of industry 4.0 principles and tools: Simulation and case study in a manufacturing sme. *Sustainability*, (14), 2022.

[32] S Gamache. Stratégies de mise en oeuvre de l'industrie 4.0 dans les petites et moyennes entreprises manufacturières québécoises. *Ph.D. Thesis, Université du Québec à Trois-Rivières, Trois-Rivières*, 2019.

[33] Andreas Bildstein Thomas Bauernhansl Simon Schumacher, Felix Aljoscha Schmid. Lean production systems 4.0: systematic literature review and field study on the digital transformation of lean methods and tools. *Procedia CIRP*, page 259–264, 2021.

[34] William de Paula Ferreira, Fabiano Armellini, Luis Antonio de Santa-Eulalia, and Vincent Thomasset-Laperrière. Extending the lean value stream mapping to the context of industry 4.0: An agent-based technology approach. *Journal of Manufacturing Systems*, 63:1–14, 2022.

[35] Mohammad Shahin, F Frank Chen, Hamed Bouzary, and Krishnan Krishnaiyer. Integration of lean practices and industry 4.0 technologies: smart manufacturing for next-generation enterprises. *The International Journal of Advanced Manufacturing Technology*, 107:2927–2936, 2020.

[36] Robert Davies, Tim Coole, and Alistair Smith. Review of socio-technical considerations to ensure successful implementation of industry 4.0. *Procedia Manufacturing*, 11:1288–1295, 2017.

[37] Emmanuel C Ogu, Amos Benita, and Edy-Ewoh Uduakobong. Cognisant computing and'lean'practices: interactions with 21st century businesses and implications. *International Journal of Business Information Systems*, 27(2):264–275, 2018.

[38] Nai Yeen Gavin Lai, Kok Hoong Wong, Dunant Halim, Jiawa Lu, and Hooi Siang Kang. Industry 4.0 enhanced lean manufacturing. In *2019 8th international conference on Industrial technology and management (ICITM)*, pages 206–211. IEEE, 2019.

[39] Guilherme Luz Tortorella, Flavio S Fogliatto, Paulo A Cauchick-Miguel, Sherah Kurnia, and Daniel Jurburg. Integration of industry 4.0 technologies into total productive maintenance practices. *International Journal of Production Economics*, 240:108224, 2021.

[40] Arthur Henrique Gomes Rossi, Giovanna Bueno Marcondes, Joseane Pontes, Paulo Leitao, Fernanda Tavares Treinta, Luis Mauricio Martins De Resende, Elaine Mosconi, and Rui Tadashi Yoshino. Lean tools in the context of industry 4.0: literature review, implementation and trends. *Sustainability*, 14(19):12295, 2022.

[41] Luana Sposito Valamede and Alessandra Cristina Santos Akkari. 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):851, 2020.

[42] Dennis Kolberg and Detlef Zühlke. Lean automation enabled by industry 4.0 technologies. *IFAC-PapersOnLine*, 48(3):1870–1875, 2015.

[43] David Mendes, Pedro D Gaspar, Fernando Charrua-Santos, and Helena Navas. Integrating tpm and industry 4.0 to increase the availability of industrial assets: A case study on a conveyor belt. *Processes*, 11(7):1956, 2023.

[44] Samir Benbelkacem, Nadia Zenati-Henda, Fayçal Zerarga, Abdelkader Bellarbi, Mahmoud Belhocine, Salim Malek, and Mohamed Tadjine. Augmented reality platform for collaborative e-maintenance systems. *Augmented Reality-Some Emerging Application Areas, InTech*, pages 211–226, 2011.

[45] Andrew KS Jardine, Daming Lin, and Dragan Banjevic. A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical systems and signal processing*, 20(7):1483–1510, 2006.

[46] S Kaspar and M Schneider. Lean und industrie 4.0 in der intralogistik: Effizienzsteigerung durch kombination der beiden ansätze. *Productivity Management*, 20(5):17–20, 2015.

[47] Hansjörg Künzel. *Erfolgsfaktor lean management 2.0.* Springer, 2016.

[48] Kai Ding and Pingyu Jiang. Rfid-based production data analysis in an iot-enabled smart job-shop. *IEEE/CAA Journal of Automatica Sinica*, 5(1):128–138, 2017.

[49] G Srinivasan and G Ganesh Prasad. The role of intelligent automation, big data and internet of things in manufacturing-a survey. *Imperial Journal of Interdisciplinary Research*, 3(5):934–940, 2017.

[50] Thomas Bauernhansl, Michael Ten Hompel, and Birgit Vogel-Heuser. *Industrie 4.0 in Produktion, Automatisierung und Logistik. Anwendung · Technologien · Migration.* 2014.

[51] Krzysztof Żywicki, Paulina Rewers, and Mariusz Bożek. Data analysis in production levelling methodology. In *Recent Advances in Information Systems and Technologies: Volume 3 5*, pages 460–468. Springer, 2017.

[52] Franz J Brunner. *Japanische Erfolgskonzepte: KAIZEN, KVP, Lean Production Management, Total Productive Maintenance, Shopfloor Management, Toyota Production System, GD3-Lean Development.* Carl Hanser Verlag GmbH Co KG, 2023.

[53] Tobias Rammelmeier, Stefan Galka, and Willibald A Günthner. Fehlervermeidung in der kommissionierung. In *8. Fachkolloquium der Wissenschaftlichen Gesellschaft für Technische Logistik e. V.*, 2012.

[54] Carsten Feldmann and Anneliese Gorj. *3D-druck und lean production.* Springer, 2017.

[55] Sule Satoglu, Alp Ustundag, Emre Cevikcan, and Mehmet Bulent Durmusoglu. Lean transformation integrated with industry 4.0 implementation methodology. In *Industrial Engineering in the Industry 4.0 Era: Selected papers from the Global Joint Conference on Industrial Engineering and Its Application Areas, GJCIE 2017, July 20–21, Vienna, Austria*, pages 97–107. Springer, 2018.

[56] Guilherme Tortorella, Ricardo Giglio, and Desirée H van Dun. Industry 4.0 as a moderator on the relationship between lean and operational performance. In *25th International Annual EurOMA Conference: To Serve, to Produce and to Servitize in the Era of Networks, Big Data and Analytics. Budapest, Hungary: University of Twente*, pages 1–10, 2018.

[57] Teerasak Khanchanapong, Daniel Prajogo, Amrik S Sohal, Brian K Cooper, Andy CL Yeung, and Tai Chiu Edwin Cheng. The unique and complementary effects of manufacturing technologies and lean practices on manufacturing operational performance. *International journal of production economics*, 153:191–203, 2014.

[58] Arash Azadegan, Pankaj C Patel, Abouzar Zangoueinezhad, and Kevin Linderman. The effect of environmental complexity and environmental dynamism on lean practices. *Quality control and applied statistics*, 59(3):215–216, 2014.

[59] Jan Riezebos, Warse Klingenberg, and Christian Hicks. Lean production and information technology: connection or contradiction? *Computers in industry*, 60(4):237–247, 2009.

[60] Hamed Bouzary and F Frank Chen. A hybrid grey wolf optimizer algorithm with evolutionary operators for optimal qos-aware service composition and optimal selection in cloud manufacturing. *The International Journal of Advanced Manufacturing Technology*, 101:2771–2784, 2019.

[61] Diéssica de Oliveira-Dias, Juan Manuel Maqueira-Marin, José Moyano-Fuentes, and Helena Carvalho. Implications of using industry 4.0 base technologies for lean and agile supply chains and performance. *International Journal of Production Economics*, 262:108916, 2023.