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Crafting a Synergistic Convergence: An Integrated approach for Lean and Industry 4.0 Transformation

By Andrea Chiarini **– University of Verona, Department of Business Administration, Via

Cantarane 24, 37129 Verona, Italy – Phone +393358201899 andrea.chiarini@chiarini.it

Maneesh Kumar – Cardiff Business School, Aberconway Building, Colum Road, Cathays, Cardiff,

UK, CF 10 3EU – kumarm8@cardiff.ac.uk

** Corresponding author

Abstract

This paper presents an integrated approach that combines Lean principles with Industry 4.0 (I4.0) technologies, exploring how Lean tools intersect with and adapt to digital advancements. Using an inductive grounded theory methodology, qualitative data were gathered from 22 in-depth interviews with 15 large Italian manufacturing companies that have mature Lean practices. Seven key categories emerged from the analysis. The findings reveal the importance of leadership, raising awareness, and developing employee skills to navigate digital transformation, while addressing concerns during this process. The study highlights how some Lean tools were modified or replaced with I4.0 technologies, enhancing employees' autonomy and predictive capabilities. It also identifies a redefinition of kaizen activities, with opportunities to leverage analytics and AI in continuous improvement initiatives. These insights fill a gap in the literature by offering evidence and practical guidelines for integrating Lean and I4.0. The research further dispels the misconception that Lean merely serves as a starting point for digital transformation, arguing that the sequence of integration depends on the specific context.

Keywords: Lean, Industry 4.0, Integrated approach, Grounded Theory

1. Introduction

Do you remember the '80s song *Video killed the radio star*? Well, radio stars are still with us but surely more digitally broadcasted. The term 'Lean' was coined by researcher Krafcik in 1988 and originated from the Japanese Toyota Production System (TPS) gradually implemented after the Second World War. Lean has evolved from being a methodology for cost reduction and efficiency improvement to becoming a strategy for (co)creating value from the customer's perspective. Lean utilizes practical tools such as Value Stream Mapping (VSM), 5S, Kanban, Total Productive Maintenance (TPM) and Single Minute Exchange of Die (SMED) (Chiarini and Kumar 2021). These tools are employed by Kaizen teams involving all workers and managers, fostering a strong attitude and awareness of Kaizen principles (Manos 2007; Aoki 2008). Waste reduction, respect for the human system, and Kaizen remain essential Lean foundations (Bhamu and Sangwan 2014; Okoro 2024).

Lean underwent a digital transformation, particularly with the launch of Industry 4.0 (I4.0) in 2011 (Kagermann et al. 2011). I4.0 places a strong emphasis on connecting cyber-physical systems (CPS) and smart technologies with customers, machinery, factories, and business processes. The base and front-end technologies included under the I4.0 umbrella are capable of autonomously exchanging information, initiating actions, making decisions, and controlling each other independently (Kagermann et al. 2013; Frank et al. 2019).

I4.0 and Lean share similar objectives, including improving productivity, reducing lead times, and enhancing quality (Chiarini and Kumar 2021; Komkowski et al. 2024). Early research has identified a synergistic relationship between Lean and I4.0 technologies (Kolberg et al. 2016), leading to their integration, often referred to as Lean automation, Lean 4.0 (Kolberg et al. 2016; Metternich et al. 2017), or Digital Lean (Romero et al. 2018). The existing literature has shown that both Lean and I4.0 can improve manufacturing performance, and their integration is expected to produce even greater results, offering a compelling framework for companies to adopt (Chiarini and Kumar 2021; Januszek et al. 2023). However, limited research evidence provides a

practical framework for integrating Lean and I4.0 (Rossini et al. 2022; Rossi et al. 2022; Tissir et al. 2023).

Researchers and practitioners are actively investigating how to integrate Lean tools with I4.0 technologies. They aim to understand the reasons, methods, and contexts that facilitate this integration. A literature review conducted by Tissir et al. (2023) highlighted the absence of a validated framework for the practical integration of Lean and I4.0. Existing frameworks often suffer from several limitations. For example, many do not adequately address the softer aspects of change induced by digitalization, such as the role of leadership and the impact on employees' ability to embrace technological changes (Tissir et al. 2023; van Dun and Kumar 2023; Januszek et al. 2023; Cimini et al. 2023; Komkowski et al. 2024).

Additionally, there is confusion among researchers and practitioners regarding the sequence of implementing Lean and I4.0 technologies, as well as how to adapt Lean tools and principles in conjunction with these technologies. I4.0 presents challenges due to the wide array of technologies involved (Saabye et al. 2022) and its implications for work organization (Cagliano et al. 2019), alongside various socio-technical factors. As a result, the best approach to combine Lean and I4.0 remains unclear. Should we integrate Lean principles and tools, and if so, how? Or should we consider replacing the Lean principles and tools we have been using? In other words, are we at risk of discarding some essential "Lean stars"?

To address the aforementioned research gaps, the researchers propose the following research questions to help develop a holistic understanding of how integration can be achieved: (1) *How do manufacturing companies cope with integrating Lean tools and principles with I4.0 challenges?* (2) *How do Lean tools and principles intersect with and adapt to the advancements of I4.0 and its technologies?* and (3) *How does the proposed integration explain the sequencing of Lean tools and principles with Industry 4.0 technologies?*

To address the three research questions, this paper employs an inductive grounded theory (GT) approach. It involves conducting 22 in-depth interviews with managers from 15 large Italian manufacturing companies that have been implementing Lean practices for several years. Italy is a significant representative of the manufacturing

sector, ranking second in Europe, just behind Germany, in terms of the EU value of sold industrial production (Eurostat 2022). Additionally, in 2016, the Italian government launched a national strategy for digitizing industry, known as Industria 4.0, which was adapted from the German model (Italian Ministry of Economic Development 2017).

2. A Priori Sensitizing Literature

Research connected with theory generation might require sensitizing concepts and not hypotheses; to this end, we reviewed relevant papers to provide a priori theoretical sensitivity (Strauss 1987). The sensitizing concepts were then used as topics for the open-ended questionnaire. The reviewed literature focuses primarily on identifying gaps linked to publications on integrating Lean and Industry 4.0.

2.1 The integration of Lean and Industry 4.0

Earlier forms of automation were often less adaptable, leading Lean scholars to approach it with caution. Taiichi Ohno (2013, p. 76) expressed concerns about automation becoming an engineering gimmick. Monden (2012, p. 236) recommended automation only when it relieved workers from repetitive tasks, allowing more time for meaningful activities. This relationship is embodied in the Toyota principle of Jidoka, or "autonomation," which emphasizes a human touch in automation (Ohno 2013). Notably, Mitsuru Kawai, Toyota's head of manufacturing, revealed in a 2018 interview that he chose to shut down robot lines to improve quality, relying solely on human workers. This highlights the importance of employee involvement in the Lean Industry 4.0 integration process.

The discussion on the fourth industrial revolution includes a comparison between Lean principles and I4.0, first explored by Kolberg et al. (2016). Although the paper did not provide a specific framework, it sparked debate about Lean automation and Lean 4.0. Lean has been globally recognized for decades, making it logical to view I4.0 as an enhancement of Lean. Many authors emphasize how I4.0 can improve Lean methodologies (Bittencourt et al. 2021; Chiarini and Kumar 2021; Tortorella et al. 2019). This approach views LM as a means to create a suitable environment for I4.0 adoption.

Davies et al. (2017) noted that Lean tools help implement I4.0, while I4.0 technologies strengthen Lean tools like kanban, TPM, and VSM. Tortorella and Fetterman (2018) found that Lean-experienced companies are more likely to adopt I4.0 successfully, influenced by socio-economic factors. Tortorella et al. (2019) argued that Lean should precede I4.0 adoption, advocating for Lean's value in blending high-tech applications with simplicity. Prinz et al. (2018) highlighted that I4.0's efficiency relies on prior Lean optimization, emphasizing the need for comprehensive Lean training. Agostini and Filippini (2019) supported this viewpoint, finding a link between organizational practices and I4.0 implementation, particularly with Lean and ERP. They also noted that Lean helps prevent the "digitization of waste" through better process knowledge.

Similarly, Chiarini and Kumar (2021) pointed out that some manufacturing companies mistakenly "automatized the waste" by implementing I4.0 technologies without first addressing waste and variability through Lean practices. Powell et al. (2018) coined the term "digital waste" to describe non-value-adding digital activities in Lean companies arising from new digital technologies. While several authors (Kagermann et al. 2013; Wang et al. 2015; Dalenogare et al. 2018; Chiarini and Kumar 2021) discussed frameworks for integrating I4.0 and Lean Six Sigma, they often overlooked the human aspect of managing digitization changes.

Some experts advocate for a balanced approach, suggesting that Lean can serve as a mediator for I4.0. In this view, the two methodologies can be combined to create a "smart and lean" production system (Rosin et al. 2020). On the other hand, there is a perspective that sees I4.0 as the dominant force, capable of addressing the limitations of Lean by emphasizing the critical importance of speed in data and information processing. Additionally, it has been proposed that the implementation of either Lean or I4.0 can enhance dynamic capabilities, which in turn facilitates the integration of both approaches (Komkowski et al. 2024).

Rossini et al. (2021) identified two approaches to digital transformation: sustaining and disruptive. Lean companies tended towards gradual digital improvements, whereas disruptive organizations sought rapid changes, often neglecting human development. Rossini et al. (2022) proposed a model for Lean-I4.0 integration focused on operational stability and speed to market. Nounou et al. (2022) suggested a Lean-based I4.0

architecture with a three-level decision-making system for real-time production flow decisions. Three literature reviews (Bittencourt et al. 2021; Rossi et al. 2022; Tissir et al. 2023) highlighted the benefits of Lean-I4.0 integration, positioning Lean as a precursor to I4.0 implementation. This ongoing debate has brought to light two key concepts regarding the sequence and methodology of integration.

Rossi et al. (2022) proposed a six-step framework for Lean 4.0 implementation, focusing on adapting Lean tools to digital technologies. However, operationalizing this model is challenging. They highlighted the relationship between Lean tools and Industry I4.0 technologies, suggesting transformations that can be either augmentative or reductive. Tissir et al. (2023) noted that more research is needed to determine the benefits of Lean-I4.0 integration and acknowledged that not all Lean tools, especially those related to teamwork and Kaizen, have been studied in the context of I4.0. To address this gap, we explored how Lean tools can be adapted to stay relevant in the digital age.

Kumar et al. (2023) conducted a literature review that categorized Lean and I4.0 integration studies into three clusters: I4.0 enhancing Lean, generic associations, and conceptual models. However, they did not analyze the similarities or differences among these models or their operational validity. Saraswat et al. (2024) reviewed 92 papers on Lean and I4.0, creating a theoretical framework based on their findings. This framework, structured into four levels, details the combinations of I4.0 technologies and Lean tools, with primary goals focused on improving quality and operational performance. Unfortunately, it overlooks factors such as employee involvement, necessary skills, and leadership.

In contrast, Frank et al. (2024) reviewed five studies and proposed a framework centered on dialectical and paradoxical tensions in Lean and I4.0 integration, highlighting outcomes like improved social performance and enhanced problem-solving and learning capabilities. The integration requires a more systemic view of human factors, moving beyond just physical workload to address issues like mental exhaustion and job satisfaction to foster better collaboration between humans and machines (Meindl et al. 2021). The study by Komkowski et al. (2024) presents a framework for integrating Lean principles with I4.0 through Dynamic Capabilities. It emphasizes the importance of routines, learning practices, and cultural factors for successful integration while

suggesting that governance and execution are less critical initially. Although the study highlights human factors, it does not address the sequence of integrating Lean and I4.0.

Table 1 summarizes the literature on integrating Lean principles with Industry 4.0. Although several conceptual frameworks for the integration of I4.0 in Lean exist, specific details of the design of methods and tools are missing. Notably, no studies provide a comprehensive theoretical model that addresses the softer aspects of change along with the sequence of implementing Lean tools with I4.0 technologies. The most in-depth research comes from Chiarini and Kumar (2021), Rossi et al. (2022), Frank et al. (2024) and, Komkowski et al. (2024). While it is evident that I4.0 impacts Lean tools and principles, the exact effects on specific Lean tools remain unclear. Furthermore, the assertion that implementing I4.0 alongside Lean can yield better results requires more investigation.

Most papers in Table 1 lack a human-centric focus. However, there is a growing discussion about enhancing skills and competencies through digital technologies (Romero et al. 2020; Tortorella et al. 2021; Frank et al. 2024; Komkowski et al. 2024). It is also suggested that managers should embrace a transformational leadership style (van Dun and Kumar 2023). This emphasizes the need for employee involvement in developing the necessary skills and competencies for successful integration.

<<<< Insert Table 1 here >>>>

3. Methodology

The current study employs systematic inductive research, which is suitable, especially when little theoretical understanding exists (Gligor and Autry 2012), as our literature review demonstrated. The inductive pattern is guided by Glaser's grounded theory (GT) methods (2001), allowing the researcher to attain a path of inquiry that is not predetermined. Through the sensitizing concepts from the literature review, we developed an unstructured, open-ended questionnaire to interview 22 managers from 15 different manufacturing companies. The interview focused on the sensitizing concepts from the literature review, specifically the unstructured open-questions such as:

- *How do leaders drive and communicate the integration needs?*
- *How are you involving employees in the integration and what kind of skills and competency are you developing in employees?*
- *In your opinion, is there a specific sequence of implementation (e.g. Lean before I4.0 or vice versa, no particular sequence, etc.)?*
- *What is your approach to achieving integration? And why?*
- *How do I4.0 technologies complement or replace Lean tools and practices?*
- *What adaptations are required in Lean tools and techniques to keep their relevance in the digital era?*

The interviews lasted from 45 minutes to 60 minutes and were audio recorded and then transcribed for analysis. The aim of the study and the questions were shared with managers before the interview to ensure they provided in-depth answers and evidence of integration. We clarified the meaning by discussing the answers with the interviewee to ensure no misunderstandings. In five instances, we rephrased the text to provide greater clarity. Lastly, we sent all the interviewees a summary of the findings to collect further feedback (Miles et al. 2014).

3.1 Sampling and Data Collection

The unit of analysis of this research is a manufacturing company that is implementing Lean and I4.0 in Italy. We chose companies with a high degree of Lean maturity, the identification of which was facilitated by two consultancy firms specialized in Lean applications. With their help, we selected the first potential sample of 67 manufacturing companies. Specifically, all the manufacturing companies have been implementing Lean for at least 10 years and they have launched a relevant digital transformation plan in the last 5 years. We only selected large companies (> 250 employees) to analyse theoretical aspects connected with both technical and softer aspects of digitalization-induced change. Additionally, we deduced that larger companies, with their greater turnovers and financial resources, would have a higher propensity than smaller companies to embrace and implement I4.0 technologies and systems. For instance, they all have complex ERP systems and have heavily invested in automation and digital technologies.

We first phoned the companies with a checklist to understand the level of Lean implementation (beginner, adopter, advanced adopter), the coverage of the I4.0 technologies implemented (limited to some processes and technologies – widespread implementation), and if they are implementing advanced technologies based for instance on artificial intelligence (AI) or simulations. In this way, we ruled out 13 companies out of 67. We tried lastly to cover different kinds of production processes, like assembling processes and machinery-based production, engineering to order, as well as continuous processes. Participants were then chosen based on their Lean and I4.0 knowledge and the possibility of making meaningful contributions and data saturation.

Data collection and theoretical sampling were conducted in parallel. In January 2023, we started with a sample of four companies where Lean has been implemented for almost 20 years and has launched a massive I4.0 implementation at all levels. Using these four companies as a starting point, we created an initial memo to gain a deeper understanding of the direction of our findings and identify the types of additional companies and participants needed to fully develop the categories and concepts (Gligor and Autry 2012). We ended the sampling process after achieving saturation in the 22nd interview. In total, we interviewed 22 managers from 15 companies. All the companies are classified as large and operating in a B2B environment. Table 2 summarizes the company, product types, production system, size, the number of interviewed managers, and their positions within the company. The companies are listed in the order they were sampled. The kind of production process and product made by the company were also coded according to the first column of Table 2 and the legend below.

<<<< Insert Table 2 here >>>>

3.2 Data analysis

To identify core categories and the pattern within the field data, we followed the GT process proposed by Strauss and Corbin (1998) structured with open, axial and selective coding. It is well known how the researcher's biases could affect the analysis and the process of coding. To avoid this, we also employed the MAXQDA 2022 software to code text segments, inductively developing the categories from our data. Starting from

the open coding process, we analysed all the transcribed texts from the interviews, isolated text with no connections to our research questions, and sensitized concepts from the literature review. Typical software like MAXQDA helps the researcher create such connections, first- and second-order codes, and exclude text that is poorly related or not. The last column of Table 3 shows an excerpt of the most representative quotes with such connections. While the fourth column contains the number of quotes that contain first-order concepts. This gave us better support for the development of the final categories. Then we broke down the text into coded units, discrete pieces labelled or first-order concepts. Once we had a set of first-order concepts, we developed a second set, and in the axial coding, we found connections and relationships to develop the categories (Glaser 2001). Lastly, in selective coding, the categories found in the axial coding process were brought together with one overarching category, the core category. The latter is the category which best describes a recurring trend in the previous categories; we named it *Improving Lean through I4.0 integration*.

In the beginning, we identified 145 open codes. We continued giving more uniformity and kept comparing data, reviewing all the codes, and checking whether they had enough data to be sound. We reached 30 open codes or concepts founded in at least 10 quotes, as the fourth column in Table 3 demonstrates. The 30 open codes were grouped into 15 second-order concepts and finally into seven categories/ axial codes.

4. Findings

It is important to note that a substantial amount of data was collected from the interviewees; however, in the last column of Table 3, we have selectively presented the most relevant excerpts, which provided strong indications for coding the textual components.

<<<< Insert Table 3 here >>>>

4.1 Leader as a learning facilitator

The first specific category is the leader as a learning facilitator. Analysis of quotations from companies C03-LB and C05-CC shows that managers believe top management should adopt a new approach instead of sticking to traditional Lean practices. The conventional Lean method, which relies on visual and paper-based tools, may hinder digitalization and automation, as indicated in 20 quotes referencing first-order code (1a). This traditional approach can lead to misconceptions about I4.0 throughout the organization. An interviewee from company C10-CB noted that such misconceptions may cause the company to miss valuable improvement opportunities. Companies C05-CC and C06-LS highlighted the need for leaders to embrace an open learning style to effectively integrate I4.0 with Lean principles. Therefore, company C06-LS sought new production managers with I4.0 expertise and a distinct leadership mindset.

Leaders emphasize the significance of enhanced communication and knowledge dissemination to convey the advantages of integrating Lean principles and I4.0 innovation within processes and supply chains. Notably, C15-XS referred to the notion of "I4.0 literacy and awareness," accurately capturing the essence and significance of comprehensive dissemination and communication. This concept (2a) is stressed in 21 quotes. For instance, the interviewees from companies C02-XS, C05-CC, C06-LS, C14-XB, and C10-CB expressed a clear consensus that for the successful implementation of I4.0 technologies, organizations should train managers and employees at all levels and in every department while maintaining continuous communication regarding the integration efforts. It is intriguing to observe how these companies, representing diverse sectors with varying production processes, exhibit a shared commitment to this phenomenon. A one-size-fits-all approach is inadequate when designing training and skill enhancement programs, as they must be tailored to specific job roles and hierarchical levels, as identified and practiced by senior management in some of the selected case companies.

4.2 Dynamic mapping processes in new scenarios

The majority of interview responses indicate that the initial step toward integration involves a mapping process, typically using traditional VSM. However, conventional Lean

mapping tools have notable challenges. Interviewees acknowledged VSM's static nature, which struggles to adapt to rapid changes. They suggested that incorporating Industry 4.0 (I4.0) technologies could make VSM more dynamic, allowing it to connect with evolving factors like product requirements and supply chain conditions. Interviewees C02-XS, C04-LS, and C06-LS noted that dynamic mapping tools using simulations, virtualizations, and real-time data might improve VSM. C02-XS highlighted the potential integration of VSM with systems like Manufacturing Execution System (MES) or Product Lifecycle Management (PLM), and emphasized the importance of displaying real-time performance indicators such as Overall Equipment Effectiveness (OEE) within the VSM. However, they cautioned that complex mapping actions could lead to increased costs without significant value.

The selected case organizations envision implementing VSM in real-time using simulations and virtualizations. However, this requires workers and the kaizen team to exhibit high adaptability in response to process changes. This dynamism was typically absent in a more traditional Lean environment, resulting in difficulties for employees in keeping up with the rapid pace of changes.

4.3 The sequence of Lean and Industry4.0 implementation

In the discussions regarding the appropriate stages for implementing Lean and I4.0 technologies, the interviewed managers conveyed a lack of rigid sequencing in mind. For example, interviewees in C11-XS and C15-Xs discussed that the implementation process is not strictly about prioritizing Lean before I4.0 or vice versa. Instead, they highlighted the importance of thoroughly analysing and mapping processes first and then selecting the appropriate tools based on the specific situation at hand. According to the managers, the choice of tools should be flexible and tailored to the unique needs of each process. These tools may originate from Lean methodologies, I4.0 technologies, a combination of both, or even from other compatible systems.

C01-CB, C07-XB, and C15-XS stressed the importance of mapping company processes, independent of subsequent improvement actions. Their main objective is to identify opportunities to enhance process efficiency without introducing unnecessary complexity and costs. However, regarding the specific sequence of implementation

stages, none of the participants explicitly stated that Lean activities should necessarily precede I4.0 initiatives.

C07-XB focused on organizational actions, such as eliminating certain activities and modifying job descriptions, while C15-XS declared that there is no predetermined order and that I4.0 technologies alone could be employed as needed.

4.4 Enhanced end-to-end integration

As discussed in the previous theoretical category, the adoption of I4.0 technologies allows companies to navigate the dynamic and unpredictable nature of modern market scenarios by embracing more agile solutions. One key aspect where I4.0 technologies prove valuable is in achieving end-to-end integration with both customers and suppliers. According to managers from C02-XS and C15-XS, customer relationships have evolved over time, with changing orders and technical specifications impacting various aspects such as bills of materials, cycle times, machine parameters, and supplier orders. Consequently, I4.0 technologies are seen as essential for effectively managing customers' evolving needs.

C02-XS specifically lingered over integrating customer relationship management (CRM) and product lifecycle management (PLM) software modules with production processes. By using a shared part of the CRM, customers can modify their requirements, which are then reviewed by the design department for feasibility. The PLM system then automatically translates these requirements into machine parameters and assembly instructions. Operators, equipped with augmented reality (AR) apps on tablets or 3D glasses, have access to instructions and other relevant information. This integration of I4.0 technologies enables a seamless flow of information, ensuring a better understanding and alignment of customer requirements throughout the production process.

Furthermore, I4.0 technologies are also seen as catalysts for enhancing or even replacing certain Lean tools and principles in supply chain management. Managers from C05-CC, C08-XB, and C15-XS highlight how they are leveraging I4.0 technologies to establish higher levels of integration with suppliers, surpassing the limitations of traditional Lean approaches. For example, C08-XB is exploring the use of RFID and smart sensor technologies for the geolocation and visibility of products within the supply chain. C05-

CC has moved away from just-in-time (JIT) and Kanban principles, instead favouring advanced software integration with suppliers and initiatives to improve product visibility.

Prior to the pandemic, all case organizations had successfully implemented a highly efficient Lean Kanban tool, which effectively managed their supplier-led time and ensured a stable supply chain. However, with the disruptions caused by the pandemic, the traditional JIT approach is no longer viable for all products. By leveraging I4.0 technologies, these companies aim to enhance collaboration, improve efficiency, and achieve better synchronization with suppliers.

4.5 Adapting Lean tools and principles

With the emergence of I4.0 technologies, the interviewed managers have begun considering alternative approaches or even replacements for traditional Lean tools and principles in their production systems. A notable example to consider is the use of traditional Kanban cards, which have long been associated with the principle of process synchronization. Companies such as C02-XS and C07-XB are gradually implementing real-time synchronization and communication between machines and assembly stations, realizing that the physical Kanban card is no longer necessary. These companies aim to achieve, leveraging the IoT as a binding element among production technologies, a state of perfect automated process synchronization and a form of automatic JIT execution.

For example, the interviewee from C02-XS revealed that, over time, the traditional Kanban was upgraded to an electronic Kanban, wherein the machine operator would receive communication through a computer whenever the line required additional components. Currently, when the production line completes a batch of a specific product as per the daily schedule, the system automatically initiates a request for new components through the IoT. Simultaneously, an automated guided vehicle is triggered to transport the products to the final warehouse for assembly.

The interviewees focused on the relevance of I4.0 technologies, particularly identification and geolocation, in improving Lean activities. Companies C06-LS, C13-CC, and C14-XB automate instructions for 5S, SMED, and TPM tools using these systems, aiding workers in executing Lean practices. These technologies notably reduce the need for inspections, control, and individual responsibility in maintaining tool implementation.

Simplifying 5S and enabling precise instructions for autonomous maintenance streamlines operations. C14-XB and C13-CC managers believe this can shift inspections and controls from a fixed schedule to a predictive one. Similarly, we found other 17 quotes, for a total of 19, highlighting this concept (11a). Analytics and AI, particularly machine learning, are preferred for achieving this. C14-XB exemplified their shift from checklist-based maintenance to data-driven analytics triggering inspections and replacements.

In C14-XB, a testing phase for AR is currently underway, marking a significant technological advancement. This technology enables them to efficiently monitor the proper placement of tools, instruments, and products within the workspace. With the aid of tablets, they can geolocate machines and receive on-screen instructions for implementing essential Lean tools such as 5S, SMED, and TPM. The implementation of these automated systems has resulted in reduced reliance on individual self-responsibility and routine controls. Consequently, employees can shift their focus towards predictive controls, leveraging the power of AI and analytics, rather than relying solely on preventive or programmed approaches.

There is increasing concern among interviewees regarding the gradual replacement of certain Lean tools with emerging digital technologies. A significant challenge lies in acquiring the necessary skills to effectively utilize these new tools. There is a worry that, in the future, only a small number of engineers and external specialists will be able to participate in kaizen events and contribute to problem-solving initiatives. This situation raises fears about the potential exclusion of the broader workforce from these essential improvement processes. It emphasizes the need to address the skills gap and ensure inclusivity in the adoption of I4.0 technologies.

4.6 Redefining Kaizen Activities and Roles

The insights provided by the managers in Table 3 shed light on the potential applications of simulations and virtualization in Kaizen events, particularly in scenarios that necessitate frequent redesigning of production lines, cells, and material flows. To address this need for adaptability, emerging technologies such as AR, digital twins, and other Industry 4.0 advancements offer promising solutions. A manager from C10-CB

declared that Lean methodologies, although effective for stable situations, tend to be static and ill-suited for environments with frequent changes in product specifications and quantities. In such dynamic circumstances, I4.0 technologies provide the advantage of rapidly and proactively addressing process redesign challenges.

Likewise, the manager from C14-XB highlighted the importance of promptly adjusting production parameters when raw materials change. Ensuring a seamless transition without introducing non-conforming products becomes crucial in maintaining operational efficiency. This necessitates an early design process where Kaizen teams can leverage simulations and virtualizations.

The interviewees also believe that Kaizen events could shift their focus from process corrections to the early design process. A manager from C12-XS discussed with us, for example, how every time they have to reconfigure a U-shaped cell, they launch a specific Kaizen event. However, the majority of the time, they made mistakes in terms of spaces, cycle times, number of operators, etc. Consequently, the cell must be redesigned and calculated several times. With the help of a start-up, they have developed a digital twin software that can simulate in advance whether the cell works well. The software uses AR to virtualize cells and the workers in the real space on the shop floor.

4.7 Continuous Improvement Opportunities supported by Analytics and AI

This final category builds on the findings from the last three categories to show how AI and analytics are driving improvement efforts in organizations. The interviews with 15 organizations revealed that analytics and AI have broad applications beyond kaizen events. C08-XB and C12-XS emphasized their usefulness in identifying root causes and patterns at all levels, from the shop floor to the board of directors.

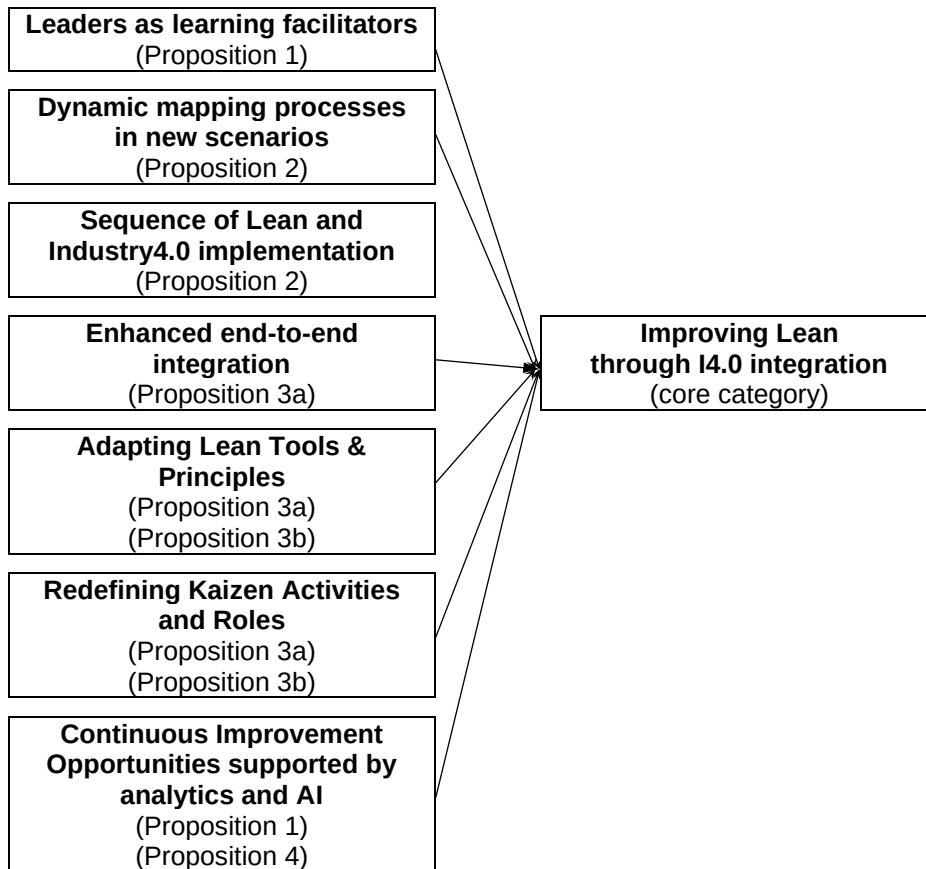
The advent of analytics and AI brings remarkable possibilities and potential challenges. On the one hand, if organizations can create user-friendly and collaborative tools, it has the potential to empower employees with lower to moderate skill levels to excel in their daily Kaizen initiatives (see Table 3, C09-XS and C12-XS examples). By providing accessible and straightforward AI systems, employees can leverage these technologies to enhance their job performance and contribute to continuous improvement efforts.

However, the interviewees also discussed how these analytics should be simple and intuitive. This was found in a total of 20 quotes (14c). Moreover, C09-XS and C14-XB highlighted the problem of introducing AI without instilling fears about the possibility of losing some tasks or even the job. In this case, 18 quotes referred to the coded concept (15a). The interviewees across the sample stated that if companies fail to develop inclusive and comprehensible AI systems, it can lead to increased frustration and inequality among employees. Introducing complex AI technologies without proper training and support can create barriers and exacerbate existing disparities within the workforce. This not only poses a significant problem for the company itself, as opined by selected case samples but also has broader implications for society.

5. Discussion and formulation of propositions

Emerging from the narrative structure of the GT approach (Strauss and Corbin 1998), it seems that our manufacturing companies are following seven specific categories depicted in Figure 1, along with the so-called core category. Each of the seven categories is intricately linked to this core category and led to the formulation of specific propositions.

Figure 1: Categories, propositions, and the core category



We begin our discussion by comparing our approach to previous integrated frameworks. In contrast to more comprehensive frameworks (Chiarini and Kumar 2011; Rossini et al. 2021; Rossini et al. 2022; Rossi et al. 2022; Saraswat et al. 2024; Komkowski et al. 2024), our study introduces key enhancements related to aspects such as leadership and employee involvement, which have been inadequately addressed in the past. Recent findings from a special issue on the integration of Lean and Industry 4.0 (Frank et al. 2024) focused on improving worker performance but again overlooked critical elements like leadership. Furthermore, none of these frameworks explored the future trajectory of Lean tools and principles as they adapt to digital integration.

The category of "leaders as learning facilitators" is essential for successful integration, as highlighted by several managers and literature (Schneider 2018; Januszek

et al. 2023). Leadership style significantly influences Lean implementation success (Seidel et al. 2019; Saabye 2022; Januszek et al. 2023), and this also applies to managing changes from I4.0 (Schneider 2018; Schneider and Sting 2020; van Dun and Kumar 2023). Our findings suggest that to implement I4.0 technology effectively, leaders must shift from traditional Lean practices that focus solely on hard practices (Bhamu and Sangwan 2014). Instead, they should foster the right expectations and attitudes among employees during digitalization changes (van Dun and Kumar 2023; Januszek et al. 2023; Frank et al. 2024). Adopting a transformational leadership style with high emotional intelligence is critical for speeding up digital changes (van Dun and Kumar 2023). Leaders should prioritize training that upskill and reskill employees while improving communication and awareness. Interviewees stressed that without these qualities, integration efforts are likely to fail.

Schneider (2018) emphasized that I4.0 leaders drive necessary technical changes and promote a culture of experimentation. D'Angelo et al. (2024) introduced the concept of digital champions to mobilize skills effectively. Van Dun and Kumar (2023) supported Schneider's insights, showing that successful organizations demonstrated transformational leadership and emotional intelligence, creating a supportive environment for employees to learn and adapt. Moreover, Gibney et al. (2009) found that supportive leader-employee relationships encourage employees to embrace additional roles, such as using I4.0 technologies alongside Lean tools.

Our findings align with the conclusions drawn by Romero et al. (2020), Tortorella et al. (2021) and Cimini et al. (2023), proposing the importance of acquiring new digital competencies across various roles within the organization. Yet, we propose how company (and Leader acting as Learning Facilitator) efforts about training and awareness should be even stronger towards complete dissemination, communication and widespread "I4.0 literacy". In addition, Saabye et al. (2022) also reported that leaders need to act as learning facilitators by going beyond understanding best practices for I4.0 adoption to developing learning-to-learn capabilities amongst employees to enable I4.0 adoption. Learning-to-learn approach was demonstrated by a few organizations in our sample. The integration process can be negatively affected by managers' negative

attitudes and messages towards the potential of I4.0 technologies or excessive emphasis placed on traditional Lean tools. Therefore, we propose this:

Proposition 1: *Successfully navigating the integration of Lean and I4.0 necessitates a distinct leadership style, i.e. a Leader as Learning Facilitator.*

The category "*Dynamic Mapping Processes in New Scenarios*" underscores the necessity of assessing the current situation before integrating Lean practices and Industry 4.0 (I4.0). Implementing Lean and/or I4.0 requires an initial assessment and mapping (Wang et al. 2011; Bhamu and Sangwan 2014; Rafique et al. 2019). We term it "dynamic" because the VSM tool provides only a static view of processes (Nounou et al. 2022). In today's volatile market conditions, relying solely on VSM is insufficient; incorporating simulation, virtualization, and real-time data is vital. This represents a shift from Lean's static assessments. By using I4.0 technologies alongside simulations, VSM can adapt to dynamic processes. Several authors have proposed enhancing VSM through simulation (Marvel and Standridge 2009; Deshkar et al. 2018) and exploring its role as a real-time management tool (Meudt et al. 2017; Valamede and Akkari 2020; de Paula Ferreira et al. 2022). Our research highlights the potential of newer I4.0 technologies, like Augmented Reality (AR) and Artificial Intelligence (AI), in simulations and virtualization.

Mapping processes first allows an understanding of the context and issues linked to the process, which will help managers decide whether to use Lean or I4.0 or simultaneously apply both. This decision-making process forms the sequencing category '*Sequence of Lean and Industry4.0 implementation*'. The majority of integration studies advocate the application of Lean first for eliminating waste and inefficiencies, followed by the implementation of Industry 4.0 technologies (Prinz et al. 2018; Powell et al. 2018; Agostini and Filippini 2019; Tortorella et al. 2019; Chiarini and Kumar 2021; Bittencourt et al. 2021; Saabye et al. 2022). However, our study challenges this conventional wisdom and presents compelling evidence to suggest that a comprehensive evaluation of existing processes, technological capabilities, resource availability, and organizational readiness can help determine the most suitable approach for maximizing the benefits of Lean and I4.0 integration. In fact, the conceptual study by Tsai et al. (2022) presented findings

similar to our study, suggesting that different contexts define when humans should act as leaders and robots/machines as followers or vice versa or when they collaborate. In support of our findings, a publication by Rossini et al. (2022) also reported bidirectional integration between Lean and I4.0, without any prescribed chronological pattern. This leads to our proposition 2.

Proposition 2: *Assessment and mapping first determine the sequence of integration (Lean first followed by I4.0 or vice versa or both simultaneously)*

One further interesting finding that emerged from the interviewed managers is the concern that redesigning processes may introduce complexity through technology, rather than really cutting down costs and creating value for the customer. This is in consonance with the original thought of Taiichi Ohno (1988) about automation. Ohno (1988) kept humans as central to TPS for driving production and automation, which is also resonated in the findings reported in several publications on I4.0 (Schneider and Sting 2020; Srinivasan et al. 2020; Saabye et al. 2022; van Dun and Kumar 2023). This argument links to the next categories '*Enhanced end-to-end integration*', '*Adapting Lean Tools and Principles*', and '*Redefining Kaizen Activities and Role*'.

The three categories can be respectively viewed as macro, meso, and micro level focus on integrating Lean with I4.0 technologies for better end-to-end, horizontal, and vertical integration (Chiarini and Kumar 2021). The traditional Lean approach seems to have limitations when applied to processes that deal with customer requirements and design management (Powell et al. 2014). These limitations could be overcome through I4.0 technologies and the integration of certain ERP modules with production processes. This is particularly true for volatile markets where variability in product customization and order scheduling requires a quicker and more agile change of process settings. Thus, from the macro perspective, to achieve "enhanced end-to-end integration", it is crucial to establish a stronger connection between the customer sphere and the manufacturer sphere (Gremyr et al. 2022) and our findings highlighted how I4.0 technologies could aid in improving unstable and unreliable situations due to disruptions in the supply chain. There are several examples from our case organizations of how to use CRM, PLM, smart sensors, and geolocalization to better understand customers' requirements. Gremyr et al. (2022) stated that digitalization offers new opportunities for value co-creation. We found

traces of this concept in 11 out of 15 quotes connected with code 8b (see Table 3) coming from companies more oriented towards the production of small batches and single products. The phenomenon seems more emphasized with engineering-to-order companies such as C15-XS, C12-XS, C04-LS and C06-LS.

At the meso-, and micro-levels, other interesting novel findings connected with the trajectory of Lean is that I4.0 technologies can improve horizontal integration through more visibility and agility, overcoming and even replacing Lean principles such as JIT and pull and Lean tools such as the Kanban system. Going over the quotes from the interviewed managers, we can notice how most of the quotes came from companies where supplies belong to the typical bottleneck products. 8 out of 12 quotes linked to code 9b (see Table 3) refer to high volumes of raw materials or batches of medium-high value components, which can easily halt the production system.

At the micro or within the production process level, introducing I4.0 technologies, such as automatic process synchronization, could also render traditional Kanban or e-Kanban systems obsolete. 14 out of 16 quotes linked to code 10a belong to companies classified as generally labour-intensive or mixed production systems, producing by batches or few products. Therefore, all the capital-intensive companies with continuous production seemed not to agree with this concept, probably because the Kanban is not so used in this typology of production. From this micro-perspective, I4.0 technologies are also helping to support over time the implementation of other tools such as 5S, SMED, and TPM, reducing inspections and the fundamental self-discipline which some authors highlighted fundamental for Kaizen events and Lean tools (Aoki 2008; Glover et al. 2014). Adjacent to this concept, I4.0 technologies, especially the ones based on analytics and AI, can shift the focus from control activities, normally programmed, towards more predictive ones. For instance, our interviewed managers found this particularly adequate for autonomous maintenance activities carried out by Kaizen teams and workers.

Another important novelty from our inductive research claims that I4.0 technologies can move the focal point of the event from process corrections and adjustments to a more effective early design process. This could be obtained, for instance, through I4.0 technologies that simulate and virtualize production processes using augmented reality and digital twins. Indeed, Lean is considered too static, especially when product

specifications and quantity quickly change due to previous volatile conditions. Simulations and virtualizations can lead to quicker changes of the layout or process parameters while at the same time making the process more robust; consequently, we stated the following propositions linked to stage 3:

Proposition 3a: *The integration of Lean and I4.0 improves relationships with customers and suppliers in terms of customer needs, product requirements, specification definition, visibility, and agile requests for changes.*

Proposition 3b: *The integration of Lean and I4.0 can lead to the substitution of some Lean tools.*

The last category of our integration was identified as '*Continuous Improvement Opportunities supported by analytics and AI*'. This stage capitalizes on the tools and insights gained from the previous stages and places a strong emphasis on leveraging analytics and AI, as suggested by Tortorella et al. (2024), to delve into root cause analysis and facilitate Kaizen events. Tortorella et al. (2024) reported that when AI is properly integrated into the workplace, it can positively impact various dimensions of employee engagement—physical, cognitive, and emotional—as well as employee psychological well-being. This integration leads to higher employee commitment and job satisfaction, ultimately improving operational performance. Our findings agree with Ohno's principle of "*automation with a human touch*" (Ohno, 1988). Indeed, Kaizen principles can surely be advanced by analytics and AI but under two very important conditions – the simplicity of the AI application and, most importantly, driving out any concern about AI and its negative impact on jobs. Interestingly, in fact, we can find authors who sometimes contradict each other. For instance, PwC (2021) stated that all kinds of jobs could be at risk due to digitalization and automation; a study from the European Commission (2017) showed how 72% of a sample of 27,901 citizens agreed with the statement that "robots and AI steal people's jobs". However, research in the US led by Reinhart (2018) showed that 77% of employees are confident of not losing their jobs due to automation and AI, and similarly, 72.5% of Italian white-collars do not fear AI (Chiarini et al. 2023).

In any case, according to van Dun and Kumar (2023), a psychologically safe organizational environment is important for developing employees' innovative work behaviour and, as discussed before, leaders are key to developing such an environment

(Anderson and Sun 2017; Schneider and Sting 2020; van Dun and Kumar 2023). Cultivating a culture where fear is mitigated among employees is crucial, and leaders play a pivotal role as learning facilitators. Chiarini et al. (2023) have also emphasized the need for companies to create a sense of trust among employees. However, their study did not delve into the factors that contribute to this sense of trust. Traditional Lean, as exemplified by Ohno (1988), places humans at the heart of production and decision-making. The integration with I4.0 challenges balancing human-machine interaction and developing such a human environment for employees. Finally, we introduced:

Proposition 4: *When implemented in a simple and non-threatening manner, AI can significantly enhance continuous improvement initiatives.*

Our research aligns with the literature on Industry 5.0 (Xu et al. 2021; Adel 2022; Grosse et al. 2023; Horvat et al. 2024), advocating for a human-centric approach to technology deployment during digital transformation. This aspect has received less attention in the Industry 4.0 literature. For instance, Horvat et al. (2024) emphasized the necessity of establishing and implementing a human-centered Industry 5.0 strategy to improve product innovation outcomes. To effectively manage these changes, organizations should focus on the context of human-machine interaction and invest in skills and capabilities development training programs for employees (Tang et al. 2022; Tsai et al. 2022; Cimini et al. 2023; Frank et al. 2024). A consistent theme found across categories 4-7 of our integrated approach is the requirement for employees to adapt and evolve to remain relevant and effective in managing the digital transformation (Cimini et al. 2023; Tortorella et al. 2023). This concern has also been noted by Tang et al. (2022), who reported that, despite the significant benefits of utilizing intelligent machines, it negatively impacts conscientious (i.e., orderly) workers. In essence, there is a need to strike a balance between the socio and technical aspects of digitalization-induced change brought about by I4.0 technologies.

Integrating Lean with I4.0 offers significant opportunities for manufacturers but requires careful planning. Managers should recognize that I4.0 technologies are meant to complement human skills and involve employees in the integration process, thus enhancing their well-being, job satisfaction and overall productivity. Managers should focus on a holistic approach that balances technical and social aspects, prioritizing

vertical integration to improve visibility in manufacturing processes. In general, managers should integrate technologies based on strategic needs and avoid a fragmented approach. When adopting I4.0 technologies, managers should prioritize vertical integration as a fundamental step to enhance visibility and transparency in the manufacturing processes (Tabim et al. 2021; Chiarini and Kumar 2021).

Our findings, supported by Komkowski et al. (2024), emphasize the importance of the initial stages of integration, understanding context, and building resources. This involves strong leadership driving digitalization-induced change in the organization, training staff to identify waste, and establishing long-term principles. This means carefully planning and allocating resources to these crucial areas, which can include training and development. The proposed framework guides organizations from strategizing to execution, allowing for self-assessment of integration progress. Given that traditional sequential approaches to Lean and I4.0 integration have high failure rates, managers should consider adopting a concurrent approach, or decide the sequence based on the outcome of the mapping exercise. By carefully considering these implications, managers can navigate the complexities of integrating Lean and Industry 4.0 and leverage these two approaches to achieve enhanced performance.

6. Conclusions and future research directions

The research presented in this paper aims to address three key questions, positioning it as a pioneering study that offers a comprehensive practical framework for integrating both "soft" and "hard" dimensions of Lean and I4.0 technologies. Insights gathered from interviews with managers provide valuable guidance for both academics and practitioners, irrespective of the initial state of a manufacturing company. This ensures that the findings are applicable across various organizations, regardless of their level of Lean implementation or geographic location.

An essential element identified is the emergence of a new type of leadership. Future research may explore potential geographical differences in leadership styles. Practitioners are encouraged to ensure that leaders adopt the role of learning facilitators to enhance communication, raise awareness, and create opportunities for employees at

every level. Comprehensive training programs should be implemented to foster "digital literacy" among all staff, followed by role-specific training to meet individual needs.

It is crucial that the mapping process simplifies the implementation of I4.0 technologies, in line with Taiichi Ohno's (1988) recommendations, so as not to introduce unnecessary complexity into the organization. Tools such as Value Stream Mapping (VSM) should be utilized to avoid static representations, incorporating elements like virtualization and real-time data tracking. A thorough evaluation of existing processes, technological capabilities, and available resources is necessary to determine the most effective sequence for implementing Lean and I4.0, whether individually or in tandem.

Both researchers and practitioners should consider adopting digital and automated solutions as alternatives to traditional Lean tools to better capture customer requirements, ultimately improving visibility and agility in production processes and supply chains. Practitioners need to be mindful of Lean tools, such as Kanban, which may be entirely replaced by new digital technologies. Managers should support Kaizen teams in leveraging simulations and virtualizations during the initial design phase to acquire valuable insights and optimize processes. Additionally, leaders ought to champion the use of analytics and artificial intelligence (AI) to enhance continuous improvement and Kaizen initiatives at all organizational levels. It is important for managers to simplify the approach to I4.0 technologies to foster employee comfort and facilitate adoption. Furthermore, leaders play a crucial role in addressing employee concerns regarding potential job displacement, ensuring a supportive transition to new technologies.

This study has some limitations that call for further research. Firstly, the categories and propositions need to be tested for researcher biases emerging from the coding process (Glaser 2001) and improved throughout more research. For instance, some differences connected with the kind of product and process managed by the companies emerged. Besides, different geographical areas could influence factors such as leadership and I4.0 technology access. In this paper, we have only discussed the role of a leader as a learning facilitator. However, other crucial characteristics, such as empathy, emotional intelligence, and other leadership attributes, can help alleviate employees' fear during a digital transformation. As we delved into the topic of overcoming the fear of digitalization, we discovered various situations among our sample and some

contradictions in the literature review. While leadership is undoubtedly a critical factor, we also found that trust in the company and developing a more receptive organization to AI and its potential were equally important but not analysed as much.

Future research should focus on improving mapping tools such as VSM using Industry 4.0 technologies, managing kaizen events and teams, and enhancing people's competencies in digitalization. The claim that Lean is a prerequisite for Industry 4.0 remains a topic of debate and requires further investigation. We conclude this research from where we began. Our findings showed a transformation and even a substitution of some Lean tools and principles when integrated with I4.0, supported by a leader taking the role of learning facilitator. On that account, we invite others to investigate these phenomena, trying to predict the future of the "Lean stars." Is I4.0 going to kill Lean star?

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Table 1: The most relevant papers dedicated to the integration of Lean and I4.0

Author	Methodology	Findings	Limitations
Kolberg et al. (2016)	Case studies, direct examination, and modelling	Lean Production is unsuitable for fulfilling the market demand for highly customized products. I4.0 focused on workstations with a common unified interface, and new Kanban methods required.	The paper only focuses on the Kanban tool and the architecture of the interface between workstations as a solution to integrate Lean with I4.0.
Davies et al. (2017)	Literature review	Lean is an enabler for I4.0. I4.0 enables enhancements in some Lean tools and principles. Socio-technical considerations of I4.0 should be taken into account. There is a need for changes at the executive level of the firm, dissemination of the shared knowledge, and workers who will become knowledge workers	No theoretical framework for the integration is discussed. The paper does not delve into the proposed changes regarding executive levels, management, and workers' involvement.
Dombrowski and Richter (2017)	Analysis of use cases and interviews	A catalogue of new Lean production system 4.0 methods is introduced. All Lean tools and principles could be digitalized in some way.	No theoretical framework for the integration is discussed. There is no discussion of how I4.0 technologies can enhance the Lean methods. Aspects related to leadership, management, and people involvement are not taken into account at all.
Tortorella and Fetterman (2018)	Survey	Companies that are implementing Lean are more likely to adopt I4.0	No theoretical framework for the integration is discussed. Aspects related to leadership, management, and people involvement are not taken into account at all.
Prinz et al. (2018)	Literature review	I4.0 can only succeed after Lean implementation. Holistic teaching of Lean and digitization at different company levels is required.	No theoretical framework for the integration is discussed. Aspects related to leadership management are not discussed.
Tortorella et al. (2019)	Survey	Socio-technical organizational changes introduced by Lean can reinforce I4.0 implementation. I4.0 effects increase when Lean is implemented simultaneously	No theoretical framework for the integration is discussed. Aspects related to leadership, and management are not discussed.
Agostini and Filippini (2019)	Survey and interviews	Companies implementing I4.0 technologies more intensely have significantly higher levels of other organizational and managerial practices such as highly	No theoretical framework for the integration is discussed. Aspects related to leadership,

		skilled employees, Lean and IT technologies. Lean increases the knowledge of processes, avoiding the “digitalization of waste	management, and people involvement are not deeply analysed.
Bittencourt et al. (2021)	Systematic literature review	All 33 papers positively discussed how I4.0 can support and improve Lean. 15 papers out of 33 highlighted that Lean acts as a trigger for I4.0 implementation. A Lean process mapping must precede the integration of digital technologies. The human factor must be integrated with existing models derived from Lean.	No theoretical framework for the integration is discussed. Aspects related to leadership, and management are not analysed
Chiarini and Kumar (2021)	Case studies	Companies need to implement Lean before I4.0. Some Lean Six Sigma tools and principles are affected by I4.0 technologies. Introduction of a Lean Six Sigma 4.0 model based on previous I4.0 three dimensional models. Introduction of a smart VSM and other digital Lean tools	Specific framework dedicated to integrating Lean Six Sigma and I4.0 following an existent three-dimensional I4.0 model. Aspects related to leadership, management, and employee’s involvement are poorly discussed.
Rossini et al. (2021)	Case studies	The study proposes two different models for Lean and I4.0 integration; sustaining digital transformation and disruptive digital transformation. The latter one is more focused on capital-intensive companies and does not give value to people like the first one.	The two proposed frameworks are more a clustering of different variables than proper theoretical models. Aspects related to leadership, and management are not analysed.
Nounou et al. (2022)	Case study	The paper shows a lean-based industry 4.0 architecture. This ICT model integrates a VSM 4.0 for a real-time decision-making process.	There is no discussion how I4.0 technologies can enhance the Lean methods. Aspects related to leadership, management, and people involvement are not taken into account at all
Rossini et al. (2022)	Survey	A multi-dimensional Lean automation framework is developed. Focus on improving the stability of processes upstream of the supply chain and fastening the process to reach customers. Lean - I4.0 integration is closely connected in both ways without a precise preceding aspect.	Limited model, which proposes some bundles between Lean tools and I4.0. No discussion on Leadership, managerial aspects, and people involvement

Rossi et al. (2022)	Systematic literature review	The research depicts a six-step scheme for a theoretical framework for Lean 4.0 implementation named D-LEaMIN (digital lean manufacturing implementation). Lean 4.0 is important to align people and technology and training at all levels. New digital tools such as VSM 4.0 and Kanban 4.0.	A purely theoretical model based on Lean 4.0 main trends. Confusing use of different terminology and concepts. Poor discussion on managerial aspects and people involvement
Tissir et al. (2023)	Systematic literature review	The authors concluded that no study has presented a validated model for the practical integration of Lean and I4.0. There are very few investigations connected with teamwork, Kaizen teams and I4.0.	The paper only classifies previous studies, mainly proposing avenues for new research.
Kumar et al. (2023)	Bibliometric analysis	The paper only proposes three clusters of Lean-I4.0 papers.	There is no analysis regarding differences and similarities between the reviewed integrated models and frameworks. No discussion on Leadership, managerial aspects, and people involvement.
Saraswat et al. (2024)	Systematic literature review	The study proposes a theoretical framework which shows all the possible combinations between I4,0 technologies and Lean tools	There is a poor discussion on the possible integrations and no discussion on Leadership, managerial aspects, and people involvement
Frank et al. (2024)	Integrative view of five papers from a special issue	The study proposes a framework where Lean-I4.0 could improve different performance in terms of outcomes for workers	Findings are focused on outcomes for workers. There is a poor discussion about leadership and managerial aspects as well as a potential adaptation of Lean tools with technologies and specific integration patterns
Komkowski et al.(2024)	Semi-structured interview and survey	The study focuses on practices linked to integrating Lean with I4.0 using dynamic capabilities framework.	The research highlights the importance of routines, learning practices, and cultural factors in successful integration, while noting that governance and execution practices are less critical than the initial stages.

Table 2: List of participating companies in the order sampled and interviewees

Company	Description (product, processes)	Size	N. of interviewees	Job
C01-CB	Fabrics, prevalence of machinery	390	1	Production manager
C02-XS	Automobile, machinery and assembling lines/cells	3200	1	Continuous improvement manager
C03-LB	Pursue and hand bags, prevalence of cells and manual stations	330	2	Managing director Production managers
C04-LS	Pharmaceutical machines, prevalence of assembling stations	350	1	Plant manager
C05-CC	Pigments, prevalence of machinery	260	1	Managing director
C06-LS	Automatic lines and machines, prevalence of assembling lines and cells	260	2	General manager Production manager
C07-XB	Air conditioning units, machinery and assembling lines/cells	350	1	Continuous improvement manager
C08-XB	Automotive components machinery and assembling lines/cells	280	1	Continuous improvement manager
C09-XS	Motorbikes, machinery and assembling lines/cells		1	Continuous improvement manager
C10-CB	Compounds, continuous and batch productions	900	2	Production managers
C11-XS	Aerospace components, machinery and assembling lines/cells	930	2	Production managers
C12-XS	Defence systems, machinery and assembling lines/cells	850	2	Production managers
C13-CC	Coatings, continuous productions	560	2	Production managers Continuous improvement manager
C14-XB	Electronics for telecommunication, machinery and assembling cells	440	1	Production manager
C15-XS	Defence systems, machinery and assembling cells	290	2	Managing director Process Engineer

First column legend. C=Company; L=generally Labour-intensive; C=generally capital-intensive; X=miXed production system; B=Batch production; C=Continuous production; S=production of Single or very few products

Table 3: Seven categories linked to Lean and Industry 4.0 integration

Axial coding - Categories	Open coding – 2 nd order concepts	Open coding – 1 st order concepts	Count	Most relevant quotes
Leaders as learning facilitators	1. Evolving Leaders in I4.0 era	1a. Traditional Leader	20	<i>Our CEO believes Lean has to be implemented in the “original way”, simplifying processes using paper for everything. Therefore, we are using A3 VSM with post-its, cards for Kanban, visual A3 posters for problem-solving and so on. This is not a bad thing, but the message for the company seems to be that digitalization would get things complicated. (C03-LB)</i>
		1b. Digital Leader	16	<i>Digitalization and automation need open-mind management with no prejudices about this new trend. Several managers, due to their ignorance or maybe because they fear losing jobs, keep on giving wrong messages within the organization, slowing down the digital transformation process. Digital Leadership is everything. (C05-CC)</i>
	2. Raising awareness of Lean and I4.0	2a. Improving I4.0 literacy	21	<i>I think we definitely need Industry 4.0 literacy, strong communication and more awareness by showcasing the benefits through used cases. (C15-XS)</i>
		2b. Improving communication to share the benefits of integration	10	<i>Lean and I4.0 integration first requires managers to be aware of the opportunities that can be brought by new technologies and communicate the ‘what’ and ‘how’ benefits of Industry 4.0 when combined with Lean. (C10-CB)</i>
	3. Supporting learning through skill development and training	3b. Specific training for specific roles and hierarchy	17	<i>Training, training and again training. While Lean is relatively simple, and we have known it for twenty years, I4.0 is often complex and considered just for geeks. We do not need AI programmers but specific training for the specific roles, including managers, operators and kaizen teams. Of course, we also need advanced training for our engineers who are supporting kaizen teams. (C02-XS)</i>

		3c. Change in recruitment strategy	11	<i>We have implemented Lean in the last fifteen years. Now that we are introducing I4.0 and the new ERP, our multinational company is taking on new production managers who have previously implemented both Lean and I4.0. We are noticing a big impulse in terms of integration and results. Their leadership style, attitudes, communication and ability to instill awareness towards I4.0 are completely different. I think this is at the foundation of I4.0 implementation: a leader who can continuously keep up with the new I4.0 technologies and keep the attention on them. (C06)</i>
Dynamic mapping processes in new scenarios	4.VSM integrated with other software	4a. Moving from static VSM to dynamic VSM	10	<i>Integrating Lean with I4.0, we have the important chance to improve all the mapping tools like the VSM, transforming them into something more focused on real-time changes and product/process characteristics. (C15-XS)</i>
		4b. Integration with software for easy to deal I4.0 solutions	11	<i>I4.0 brings the opportunity to use mapping tools in a different way. More connections are needed with the real-time conditions of the factory. You should integrate VSM with other ERP modules like the MES and the PLM (C02-XS)</i>
	5.Use of dynamic mapping tools based on simulations, virtualizations and real-time data	5a. Real-time data access for capturing changes in processes	16	<i>Nowadays, the external context is tremendously dynamic; you have to simulate new scenarios in real-time. Consequently, you need data from processes straight away and automatically. For instance, we are integrating the VSM with the MES (C04-LS)</i>
		5b. Use of simulations and virtualisation for process understanding and addressing limitations of VSM	11	<i>I think the VSM was conceived in the past for companies with high levels of waste and more stable markets. Once you have improved your processes, you need to quickly understand the impact of each change in terms of product specifications, quantity, and raw materials. I believe I4.0 technologies can help improve mapping tools through simulations, virtualizations and AI. This is one of our goals (C06-LS)</i>
Sequence of Lean and Industry 4.0 implementation	6. Mapping and Analysing the current situation	6a. Focus beyond wastes of Lean	16	<i>In the beginning, you always have to analyse and map your processes; Lean or non-Lean, you have surely, at first, to make the process more efficient. For example, you could remove an activity, change the job description to an employee; it is not just a matter of removing the 7 Lean wastes. (C07-XB)</i>
		6b. Understand the context and then decide on the	18	<i>Trainers suggest that you implement Lean before I4.0. Nevertheless, I think this is not entirely true. Let me say that if you just automate a process without knowing it you could end up introducing complexity and costs. In this regard</i>

		combination of Lean and I4.0 solutions		<i>is more a matter of analysing and mapping processes finding the right solutions (C01-CB)</i>
	7. Lean and I4.0 implemented together or in sequence	7a. Current state of process decide the sequence or simultaneous implementation	14	<i>I think there is no right sequence of implementation stages. Obviously, you have to initially analyse your current situation, identify wastes, bottlenecks, inefficiencies, etc. then implement actions to improve the situation. To this aim, you could use just Lean tools, a combination of Lean tools and I4.0 technologies or just I4.0 technologies. It depends on your initial situation. (C15-XS)</i>
		7b. Type of process influence the sequence	15	<i>We prefer to implement Lean and I4.0 together. Lean is good for reducing production wastes but less for improving processes connected with design, sales, supply chain, HR, etc. (C11-XS)</i>
Enhanced end-to-end integration	8.I4.0 for a more agile management of customers' or suppliers' needs	8a. Variability in customer orders	12	<i>We were used to receiving a stable monthly program from our customers. Now, orders are fluctuating, and even technical specifications can suddenly change. Lean cannot do anything about this. Through I4.0 technologies, we integrate our CRM directly with the PLM software and machine settings. Operators can then be equipped with AR apps on tablets or 3D glasses. (C02-XS)</i>
		8b. Better understanding of customer /supplier requirement	15	<i>I think the future will be Lean tools for the production process and agile relationships with customers and suppliers through I4.0 technologies. (C15-XS)</i>
	9.I4.0 for enhancing supply chain integration	9a. I4.0 technologies for improving visibility	14	<i>We have a long supply chain with different tiers. For specific components, we know in real time if supplier products are still available and where they are. We have invested with some suppliers in new pieces of software based on RFIDs, smart sensors and geolocalization. (C08-XB)</i>
		9b. I4.0 technologies for Improving supplier integration	12	<i>Before the pandemic we had a perfect Lean Kanban tool with a very stable supplier lead time. Now it works only with some products. For others, we just buy them when they are available. We are sharing advanced software with our suppliers for better product visibility. (C05-CC)</i>
Adapting Lean Tools & Principles	10. Automatic process synchronization	10a. Replacing Kanban	16	<i>As we continue implementing synchronization and communications between machines and assembling stations by means of I4.0, we realise we do not need the Kanban card anymore. (C02-XS). Very similar words from C07-XB</i>

		10b. Less control and self-discipline	14	<i>Once Lean tools have been implemented, using I4.0 you do not need to sustain Lean implementation anymore. All these new I4.0 technologies can monitor, track down and warn you if something is not “by the Lean book”. We definitely need less human control and less self-discipline. (C06-LS)</i>
	11. From scheduled controls to predictive activities	11a. Smart sensors and automatic alarms develop predictive capability	19	<i>We have introduced smart sensors and automatic alarms everywhere. This way, we dramatically reduce indirect costs due to audits and controls. (C15-XS)</i>
		11b. AI and Smart sensors for predictive maintenance and quality control	18	<i>You will reduce your scheduled checks and inspections using AI and smart sensors. We are moving towards a more predictive production environment. In the next few years, methods such as TPM, production scheduling and quality control will be based on predictive activities and analytics. (C13-CC)</i>
Redefining Kaizen Activities and Roles	12. Evolution in conducting Kaizen	12a. Kaizen events using virtualizations and simulations	11	<i>I4.0 allows you to reduce all the corrections and adjustments typically made after implementing Lean tools. Think about all you can do using I40 technologies in advance, simulating and virtualizing lines, cells, material flows, etc. (C12-XS)</i>
		12b. Managing swift changes in production process	12	<i>During our kaizen events, we use augmented reality when we have to redesign parts of the layout. This way, you can reduce further changes once you arrange your workspaces and materials. This is very convenient, especially when you often have to change your layout due to market conditions. (C08-XB)</i>
	13. Shifting Kaizen events to early design processes	13a. Kaizen events focused on early design	12	<i>In our company, the integration between Lean principles and the I4.0 technologies has shifted the focus from typical problems connected with production and logistic processes to problems more connected with process design. Using digital twins and virtualizations of production processes, we can immediately understand if something goes wrong from the early process design. As a consequence, our kaizen teams are now made up of more people from the design department. (C12-XS)</i>
		13b. Kaizen Team involving design department.	10	
	14. Simple Analytics and AI at all levels	14a. AI based Analytics for Kaizen	16	<i>During our kaizen initiatives, we are employing analytics and AI. In any case, analytics for Kaizen team should be simple and intuitive; for instance, you</i>

Continuous Improvement Initiatives supported by analytics and AI				<i>should use your smartphone or tablet without learning complex algorithms. (C09-XS)</i>
		14b. AI based Analytics for root-cause analysis	16	<i>We are noticing that analytics based on AI could be very useful for finding root causes when we deal with problems of any kind at all levels. (C08-XB)</i>
		14c. Simplifying AI for ease of use among employees	20	<i>We are developing pieces of software based on Python with an unimaginable power to solve complex problems, find patterns within data, making decisions; they are simple and can be used by anyone, from production workers to the board of directors. I think this can be considered the modern Kaizen. (C12-XS)</i>
	15. Drive out the fear of AI	15a. AI as a tool supporting and augmenting Human decision-making. No worries about jobs	18	<i>Our employees do not fear AI at all. Probably because we are proposing AI just as a tool and not as something that will stand in for people (C09-XS)</i> <i>Unfortunately, AI is seen as something that can steal your job. Some employees fear this as a future condition (C14-XB)</i>

