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Driving Continuous Improvement with Industry 4.0 Technologies: Lessons from Multiple Use Case Analysis

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Abstract: Background: The integration of lean management and Industry 4.0 offers great potential for improving the efficiency and effectiveness of production. However, there is still minimal empirical research on how these two approaches interact in practice, including possible synergies and conflicts. In this paper, we use empirical observations to examine how and why Industry 4.0 technologies can support and enhance the continuous improvement process, a fundamental aspect of lean management. We discuss how these technologies specifically contribute to continuous improvement and their overall impact on operational efficiency. Methods: Our research drew on five case studies, capturing the firsthand experiences of industry professionals—specifically, digitization managers and production managers from manufacturing companies across Europe. We analyzed data using qualitative content analysis, applying a structured approach of coding, summarizing, and cross-case comparison to identify key patterns and insights. Conclusions: Our study has shown that digitalization can contribute to an advanced continuous improvement process in several ways. Through a literature review as well as the analysis of use cases, we were able to develop a new model that describes how I4.0 technologies improve the continuous improvement process, a key lean principle. The model highlights five key areas of impacts: increasing flexibility, transparency, and reliability, as well as improved decision-making and acceptance of change processes.

Keywords: lean; lean management; Industry 4.0; lean Industry 4.0; continuous improvement; kaizen; sustainability

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1. Introduction

The manufacturing industry has changed considerably over the past 30 years, leading to significant changes in management practices and product and process technologies, as well as customer expectations [1]. Today's economic landscape is increasingly characterized by dynamic economic changes (such as in costs, resources, productivity, and the complexity of products), social elements (including discerning customers, changing markets, and evolving organizational cultures), and environmental considerations (such as energy efficiency, waste reduction, and the impacts of climate change) [2–4]. Manufacturing industries also face challenges such as geopolitical crises, raw material shortages, and sustainability regulations, and growth is constrained by the economic worries, skills shortages, and supply chain problems that were still present in 2023 [5,6]. To remain competitive in this ever-changing environment, new approaches must be found to ensure sustainable

competitiveness and adaptability [7]. The continuous adaptation and improvement of manufacturing processes is essential in this regard, helping companies to meet the demands of internal and external stakeholders and thus remain competitive [8]. Efforts therefore continue to focus on optimizing costs, improving quality, reducing waste, streamlining production processes, and increasing the production throughput. To keep pace with continuous change, continuous improvement (CI), a key lean principle, needs to be in place, which aims to achieve consistent operational progress while involving and empowering all employees of the organization [1]. Various studies have argued that approaches such as the use of digital technologies [9–13], as well as a comprehensive lean approach [14–20], are necessary for operational progress. A combination of these approaches is increasingly seen as an answer to operational challenges in retaining competitiveness, especially in high-cost countries [21–24].

The question of effective influences and challenges in the combination of digitalization and lean practices is well recognized and widely discussed [9,16,22,25–32]. The implementation and connection with lean practices is still very theoretical [27]. The research to date has largely focused on the theoretical aspects of this issue, while the practical interactions between the two areas are not yet fully understood and lack empirical evidence. However, research on the combined topic of lean practices and I4.0 has gained increased momentum since 2019 [27]. Alsadi et al. [27] identified several benefits of integrating lean practices and I4.0 in previous research. These include efficient communication, better decision-making, increased flexibility, productivity, quality, and reliability, as well as reduced inventory, and overall performance improvements. Yet, Alsadi et al. [27] found that more research is needed to show how I4.0 tools and lean approaches affect performance, as this area has not been explored in sufficient detail. They found that there was a significant research gap due to the lack of case studies in this area. In particular, the role of I4.0 and CI as a key lean principle is neglected widely and needs further investigation [27].

Our goal is to bridge the gap between the insights and perspectives of academics and practitioners through empirical research by analyzing the topic with relevant use cases from different manufacturers. The focus of our work is to explore how I4.0 technologies can reinforce the CI process as a key lean management approach. We focus on CI, as we argue that this area can benefit from the implementation of I4.0 technologies, significantly increasing production effectiveness and efficiency. The overall equipment effectiveness (OEE) is a central key performance indicator (KPI) that evaluates a machine's performance, availability, and quality. It aggregates all types of waste in a lean context and serves as a key performance indicator for CI in measuring effectiveness and efficiency [33–36]. The automatic data-driven implementation of the KPI OEE requires I4.0 technologies. A manually collected OEE does not have the same value for the CI of companies as automated and fact-based collection with I4.0 technologies, as it is more prone to errors. In our paper, we intend to analyze the literature on lean management, CI, and I4.0 to explore their definitions and potential combined benefits. This is supported by a review of the current state of research in this area. We extend the theoretical findings with case studies that reflect the experiences of industrial companies. In this context, we interviewed five companies with different experience profiles and compiled the resulting findings in a cross-case analysis and expanded the theoretical findings. Finally, from the results obtained, we derive further research recommendations for the interaction of lean management and digitalization, especially with regard to CI and the OEE.

2. Literature Review

The following literature review provides a definition of lean management with a particular focus on the aspects of CI and the OEE. Following this, an overview of the

concept of Industry 4.0 (I4.0) and the technologies associated with it will be presented. This section highlights the state of the research to date that has examined the interactions between lean management and I4.0. This is intended to identify research gaps and thus provide directions for our research on this topic.

2.1. Continuous Improvement in Lean Management

Developed by Toyota's Taiichi Ono as a response to the company's inability to match the production volume of American car manufacturers, lean management has become the third design of production systems, in addition to mass production and manual work [9,26,37–39].

While the early lean literature primarily emphasized tools and techniques for shop floor management, it has evolved into a comprehensive sociotechnical approach that places human involvement at the forefront of improvement, incorporating strategic and cultural dimensions, a systems perspective, and an emphasis on organizational learning, as well as leadership methodologies and behavior [26,40–44].

Regarded as a multifaceted approach to production, lean management aims to identify value-adding processes from the customer's perspective and seeks to optimize the efficiency of these processes by ensuring smooth operations [21,38,45]. It seeks to improve the flow within value streams by eliminating waste, resulting in reduced production costs, improved delivery times, and improved product quality, thereby meeting or exceeding customer expectations [26,31,37,46,47]. Kaizen, also known as the CI process, is at the heart of lean management and is a structured, equipment-centric improvement approach with the ultimate drive to optimize production efficiency and effectiveness. The core of the CI approach is to identify and improve the production system in small steps through the active team-based participation of employees at all hierarchical levels in the company. By additionally involving a set of lean methods (e.g., SMED, TPM, Kanban, etc.), aspects such as the availability, performance, quality, reliability, and safety of production resources are optimized [1].

The value of CI lies in creating an atmosphere of constant learning in an environment that not only accepts change but welcomes it. There are a wide range of process approaches to Kaizen. One such approach is, for example, Deming's "Plan-Do-Check-Act" circle. In such CI processes, self-management, group discussions, and decision-making among employees must be encouraged, which is intended to create the above-mentioned atmosphere and environment [48]. Effective decisions and actions are based on the analysis of information and data. Through a detailed analysis of the information and data obtained, an assessment can be made that supports decision-making at different levels of the organization [1]. A KPI used for decision-making in lean management and associated CI processes is the OEE. It is a critical production statistic and powerful benchmarking tool that evaluates the performance, availability, and (output) quality of a machine and has found applications both as an operational metric and as an indicator of improvement efforts in manufacturing environments [1,33–36,49–51]. CI is the key to unlocking hidden potential in factories by using the knowledge of the workforce. The OEE can be used as a metric to calculate the current efficiency of the plant and, more importantly, to show areas for improvement within the plant based on facts instead of assumptions [52].

2.2. Industry 4.0

Since its introduction at the Hannover Fair 2011, the phrase "Industry 4.0" (I4.0) has gained significant popularity both in academia and in business [26,29,53]. However, the absence of a precise definition has made it a fuzzy catchphrase, complicating communication and impeding the development and application of I4.0 solutions [9,29]. The concept

of I4.0 is still highly theoretical, as there is a lack of empirical data, resulting in a vast number of definitions in the literature with differences in semantics and content. This ambiguity in the definition makes it harder for practitioners to understand and align with research in the area, leading to the empirical testing of an imprecise concept [21,27,28,54]. Etymologically, the term I4.0 is a reference to the fourth industrial revolution. Preceded by the first industrial revolution, which was characterized by the mechanization of production through water power and steam engines, the second saw the introduction of mass production and electricity, and the third revolution introduced automation and the introduction of computers and information technology [55]. The increasing processing power of hardware has led to the fourth industrial revolution and a rise in research on I4.0, digitization, digitalization, and digital transformation [27,28]. I4.0, a transformational concept, defines a future-oriented vision for the production industry. Here, the focus lies on the comprehensive use of modern digital technologies to develop and realize intelligent and networked production facilities through their powerful capabilities [9,29]. The vision is to create a network of real-time data so that networked systems enable optimized, sometimes autonomously controlled, and dynamic production [9,22,46]. It is common to use terms such as digitization, digitalization, or digital transformation synonymously to describe the process that ultimately leads to the introduction of I4.0 [28,56–58]. To provide clarity, Buer et al. [28] have defined a distinction between these terms, where digitization refers to the conversion from analog to digital, digitalization involves the use of digital data and technology to optimize processes, and digital transformation involves the creation of new business opportunities using digital data and technology [27,28]. Digitalization consequently signifies the development of industrial manufacturing towards networked production systems [59]. It creates a system where people, machines, and products interact to increase efficiency and transparency [21,22,26,27,31,53,60]. This is achieved through the use of digital data and the application of modern information technologies with the aim of accomplishing the vision of I4.0. These technologies, known as I4.0 technologies, here include the Internet of Things (IoT) for data collection, cyber–physical systems (CPSs) for the networking and aggregation of the data of all systems, and the ability to process and analyze data efficiently [26,61,62].

2.3. Lean Management and Industry 4.0

2.3.1. Current Trends in Lean Management and Industry 4.0 Research

The combination of lean management and the I4.0 vision has gained popularity as a means of enhancing productivity in manufacturing [27,29,37]. The literature often refers to the combination of lean management and I4.0 as “lean 4.0”, “lean automation”, “smart lean manufacturing”, and “lean Industry 4.0” or “lean digital transformation” [26,27,31,62]. Alsadi et al.’s [27] bibliometric research examined the macroscopic view of “lean Industry 4.0” and “lean digital transformation” within the literature, as well as the current state of and scientific gaps in this research area. Alsadi et al. [27] noted that the combination of these topics (i.e., lean Industry 4.0/lean digital transformation) is increasingly studied in academia, with significant growth since 2019, with Sustainability (MDPI) showing the highest number of publications on lean Industry 4.0 and the International Journal of Lean Six Sigma (Emerald Group Publishing) for lean digital transformation. With regard to the size of the companies studied in this research area, the focus has been on SMEs [27]. The top five articles most cited for lean Industry 4.0 have been Sanders et al. [21], Buer et al. [29], Kolberg and Zühlke [46], Horváth and Szabó [63], and Tortorella and Fettermann [64] and Küsters et al. [56], Dutta et al. [57], Ghobakhloo and Fathi [65], Teizer et al. [66], and Romero et al. [67] for lean digital transformation [27]. Among the top ten articles cited for lean Industry 4.0, two examined the effects of lean management and I4.0 on

manufacturing companies. One study presented a framework for evaluating the integration of lean management and I4.0 in sustainable supply chain management. The remaining articles performed literature reviews and exploratory investigations of factors that enable or hinder the integration of lean management with I4.0. Consequently, theoretical studies, particularly systematic reviews of the literature, have received more citations compared to other types of study [27].

The research in the top 10 papers cited on lean digital transformation includes various types of studies. Exploratory studies have been conducted to investigate the integration of lean transformation and digital transformation and to identify the key factors that would facilitate this integration. In addition, conceptual studies have been conducted to assist in the development of digital strategies and motivate the adoption of lean tools and technologies for digital transformation. The remaining publications include overview studies that focus on the prerequisites and benefits of combining lean and digital transformation [27].

While most research focuses either on specific technologies or on performance improvements achieved through a single digital technology implementation, it is still unclear how the intrinsic characteristics of lean manufacturing may influence specific cases of digitalization, the impacts they will have, and vice versa [27,68–70]. Therefore, the impact of I4.0 on established management practices such as lean manufacturing and the impact of lean management on I4.0 has not been well researched [27,29]. There is confusion and disagreement in the academic literature about how these two topics fit together even though they both strive to increase efficiency in industrial operations. There is a broad theoretical consensus about the synergetic effects of lean management and digitalization [21,26,37,46,71,72]. According to Hines et al. [26], Rossini et al. [37], Schumacher et al. [47], Mrugalska and Wyrwicka [53], Tortorella and Fettermann [64], Prinz et al. [73], and Kamble et al. [74], research on this topic shows that the latter is likely to be the case and that the two approaches complement rather than interfere with each other, but there is a lack of long-term studies on the effects of the I4.0 vision, and it remains to be seen how these two approaches can be effectively integrated. Although lean management and I4.0 are two distinct approaches, they share the goal of increasing value in manufacturing. I4.0 is a technology-driven approach that aims to further improve digitalization and automation by establishing cyber–physical systems (CPSs); lean management focuses on reducing waste through employee engagement and CI [21,29,53,73].

2.3.2. Lean Industry 4.0: An Analysis of Interactions

According to Cifone et al. [22], Alsadi et al. [27], Rosin et al. [32], and Núñez-Merino et al. [75], the discussion around the concept of lean management and I4.0 focuses on two main perspectives that examine the relationship between them. The first perspective views lean management as the foundation for implementing I4.0. In other words, lean management must be implemented before digitalization. They argue that the elimination of waste and standardization are two key prerequisites for successful digitalization [29,31,71]. To achieve higher efficiency, flexibility, and interoperability, it is essential to eliminate waste (muda) and standardize the process prior to digitalization [31,71]. Digitalizing (or automating) an inefficient process will only increase the inefficiency and costs [29]. The second perspective sees I4.0 as a reinforcement for lean management. The accuracy and precision of traditional lean management (meaning without I4.0) are compromised by the lack of data-driven improvement processes. The insufficient use of data in decision-making processes within organizations leads to less effective execution and therefore lost potential for improvement and optimization [27,76,77]. Using I4.0 technologies, lean practices can be extended and made more effective and flexible, overcoming existing limitations and directly strengthening and enhancing the CI process and its results. Perspective two

therefore states that, in an environment that is already largely optimized according to lean principles, classic lean approaches reach their limits and I4.0 offers a solution to overcome these limitations. As a result, it has the potential to further increase productivity [22,47]. Both perspectives recognize that lean manufacturing is not eliminated by the adoption of I4.0, but that its maturity reinforces I4.0, and suggest that the two concepts coexist with and support each other, with lean management providing the foundation for I4.0 and I4.0 helping to remove barriers to lean optimization [29,31,46]. Alsadi et al. [27], in their bibliometric analysis (see Table 1), have identified several benefits of integrating lean management and I4.0, including "*more efficient communication*" [78], "*real-time decision-making*" [79,80], "*higher flexibility*" [21,46,79,81–84], "*increased productivity*" [14,21,81,84–86], "*improved quality*" [37,87,88], "*reduced inventory*" [46,68,82,85], "*higher reliability*" [68,83], and overall "*performance improvements*" [29,81,85,89,90]. For the successful application of I4.0 technologies, effective data management and the interaction between the human-centric and organizational structures of lean management are crucial [47]. The combination of specific lean principles and techniques with I4.0 technologies is an area that has been largely neglected to date. While Kanban is considered the most widely used lean tool in conjunction with I4.0 technologies (at least in the literature), other tools such as Kaizen have received less attention [21,27].

Table 1. Exploration of current literature: benefits, challenges, and combinations of lean tools and I4.0 technologies. Adapted from Alsadi et al. [27].

	Focus and Effects	**References**
Benefits	*Flexibility* *Productivity* *Performance Improvement* *Reduced Inventory* *Quality* *Reliability* *Real-Time Decision-Making Costs* *Achieve Lean Targets* *Efficient Communication* *Managing Customer Needs* *Identify Core Competencies Safety* *Delivery* *Service Level*	Sanders et al. [21], Kolberg and Zühlke [46], Tamás et al. [79], Gallo et al. [81], Kolberg et al. [82], Ma et al. [83], Wang et al. [84] Dombrowski et al. [14], Sanders et al. [21], Tortorella and Fettermann [64], Gallo et al. [81], Wang et al. [84], M. Zarte et al. [86] Buer et al. [29], Tortorella and Fettermann [64], Gallo et al. [81], Rauch et al. [89], E. R. Zúñiga et al. [90] Kolberg and Zühlke [46], Tortorella and Fettermann [64], Wagner et al. [68], Kolberg et al. [82] Rossini et al. [37], Ghi and Rossetti [87], A. Jayaram [88], Wagner et al. [68], Ma et al. [83] Tamás et al. [79], Tamás and Illés [80], Sanders et al. [21], Ma et al. [83] Mayr et al. [31], Ramadan and Salah [91], Doh et al. [78] A. A. F. Saldivar et al. [92], Tonelli et al. [93], Tortorella et al. [94], Tortorella et al. [94]
Challenges	*Validation and Verification* *Internet Facility* *Framework Required* *Detailed Methodology* *Failure* *Human Factor* *Technological Readiness* *Cost*	Dombrowski et al. [14], A. A. F. Saldivar et al. [92] Doh et al. [78] Kolberg and Zühlke [46] E. R. Zúñiga et al. [90] Mayr et al. [31] Gallo et al. [81] Yilmaz et al. [95] Yilmaz et al. [95]

Table 1. *Cont.*

	Focus and Effects	References
Lean Tools and I4.0 Technologies	*Kanban*	Mrugalska and Wyrwicka [53], Satoglu et al. [96]—RFID; Krishnaiyer and Chen [97], Shahin et al. [98]—Cloud Computing; Mrugalska and Wyrwicka [53]—Real-Time Data; Dave et al. [99]—Wireless Networks; Mrugalska and Wyrwicka [53]—Big Data; Satoglu et al. [96]—RFID; Mrugalska and Wyrwicka [53]—Cloud Computing; Satoglu et al. [96]—Human–Machine Interface
	Poka Yoke	Ma et al. [83]—RFID;
	Jidoka	Ma et al. [83]—Real-Time Data; Ma et al. [83] –Wireless Networks;
	TPM	
	VSM	Ma et al. [83]—Human–Machine Interface; Wagner et al. [68]—Big Data;
	SMED	
	Andon	Hambach et al. [23]—Cloud Computing; Sanders et al. [21]—Human–Machine Interface
	5s	
	Kaizen	Mrugalska and Wyrwicka [53], Meudt et al. [100]—Real-Time Data; Meudt et al. [100]—Wireless Networks
	Heijunka	

Sanders et al. [21]—Big Data; Karre et al. [101]—RFID
Ma et al. [83]—Real-Time Data
Karre et al. [101]—Human–Machine Interface; Sanders et al. [21]—Human–Machine Interface; Kolberg et al. [82]—Human–Machine Interface

2.3.3. Digitalization and Continuous Improvement

So far, the integration of I4.0 and lean management with a focus on the CI process has not been adequately addressed [21,27,102–105]. Although no direct connection between CI and I4.0 is made, several insights from the lean approach for CI and I4.0 can be implicitly derived from the work of Sanders et al. [21]. First, in the context of lean management and I4.0, it states that I4.0 can help minimize waste through digitalization and automation. Second, it can improve product quality by enabling tighter control over the production process and detecting defects early. Third, I4.0 should be able to increase production flexibility and help companies better adapt to change. Finally, it is believed to optimize availability and delivery performance by improving planning and control capabilities [21,22,29,53]. As highlighted before, there is significant synergistic potential shared between I4.0 and the CI process for identifying waste based on data-driven facts. Hambach et al.'s [23] article included a study on the digitalization of CI processes, but not the link between CI and Industry 4.0. According to this paper, CI increases both the stability and performance of processes and, in parallel, promotes the development of the skills of employees. In the CI approach, employees receive active guidance and coaching from a leader to serve as the foundation of a learning organization. The overarching objective is derived from the corporate strategy, vision, and a mission statement, with all goals aligned to this objective. A KPI, such as the OEE, is used to quantify the company's goals. CI considers metrics and KPIs such as the OEE, as well as qualitative descriptions of the current and future process. The success and documentation of the improvement steps are strongly dependent on the systems used, the control mechanisms in place, and the management skills deployed. Hambach et al. [23] found that in many companies, CI is either completely unstructured or traditionally implemented by means of paper-based documentation. [23] From our point of view, this clearly highlights the fact that digitalization can help increase the effectiveness and efficiency of a CI system in these situations through many avenues. Digital storage improves data distribution and supports users in finding information.

Digital communication improves employees' communication, specifically when it needs to be flexible in terms of time and space. Furthermore, Hambach et al. [23] see visualization capabilities as an integral part of the CI process as they make problems quickly recognizable and display information transparently. Lastly, data analytics improves coaching and thus increases employees' competency. It can be seen that the combined use of lean techniques and I4.0 technologies improves several areas (i.e., increases visibility, flexibility, and responsiveness and reduces errors) [21–23,71]. Furthermore, Hambach et al. [23] showed that digital CI can facilitate employee communication, documentation, and learning during the improvement process and can thereby promote the development of employee competency, increase the transparency of CI process activities, and solve problems that current CI approaches often have. In doing so, digital CI supports the targeted use of resources and increases the adoption of improvements.

The further development of Industry 4.0 to Industry 5.0 represents a concept to achieve mass product and service personalization, sustainability, and resilience by using digital technologies and an intelligent interplay of humans and machines [106,107]. This human centricity aspect is in line with a lean management philosophy and the CI aspiration of manufacturing companies. Thus, the combination of lean management and digital technologies remains an important aspect for Industry 5.0 implementations as well.

2.4. Research Gap

Lean management strives to optimize production processes by identifying added value and eliminating waste. At its core is the CI principle, which encourages employee participation, self-management, and decision-making, underscoring a strong focus on employees. A KPI in lean management that identifies all types of waste is the OEE. Since 2019, research has been intensively discussing the integration of lean management and digitalization, although the exact interplay between the two is not yet fully understood. I4.0 is strongly technology-oriented, while lean management focuses on processes, people, and CI. Two perspectives can be distinguished here. Lean management is seen as the foundation for I4.0, as processes must first be optimized and standardized before new technologies can be implemented. The other perspective recognizes the limitations of lean management in specific contexts and views I4.0 as an opportunity to overcome them. Linking CI as a core principle of lean management and I4.0 is a promising approach to increase efficiency. It enables more effective communication, as I4.0 technologies can improve the interaction between people, machines, and products. It also promotes real-time decision-making through improved data collection, transparency, analysis, and visualization. In addition, lean management and I4.0 increase flexibility and productivity in production by minimizing waste and automating processes. They improve quality by allowing for better control over the production process and identifying defects early on. Finally, the integration of lean management and I4.0 can help reduce inventories and increase the reliability of production processes, leading to an overall increase in performance. The research up to now has not highlighted the influence of digitalization and CI.

Theoretical research is characterizing the link between and influence of lean management and I4.0. There is a need for empirical research on how lean management and I4.0 can be effectively combined and implemented in practice. We have also seen in Table 1 that topics such as "Flexibility", "Productivity", and "Reduced inventories" are already being investigated to a greater extent. On the other hand, "Quality", "Reliability", and "Real-Time Decision-Making", as well as "More efficient communication", are still little-investigated areas. In the case of the combination of lean tools and I4.0 technology, we have also showed that "Kanban" and "Poka Yoka", for example, have been studied a lot, whereas Kaizen, among others, has received little to no recognition.

We suggest that the Plan–Do–Check–Act (PDCA) cycle provides a good framework for continuous improvement (CI) through Industry 4.0 (I4.0) technologies. PDCA is a key method for CI. We hypothesize that in the Plan phase, real-time data analytics, digital twins, and IoT sensors could provide accurate insights for informed decision-making. In the Do phase, automation, MESs, and digital work instructions could be used to ensure accuracy and consistency. In the Check phase, more accurate and detailed analytics and real-time dashboards could enable continuous performance evaluation. In the Act phase, digital documentation and cloud-based knowledge management could standardize improvements and promote iterative learning. By embedding digitalization into each PDCA phase, we suspect companies will increase their transparency, accuracy, and adaptability, ensuring sustainable process optimization.

The literature review outlined above emphasizes that more practical research is needed to show how specific lean principles and tools are impacted by digitalization, as this has not been adequately researched. CI is one such lean principle for research. An additional significant gap in the research is the availability of use case studies.

3. Research Methodology

3.1. Approach and Objective

In our study, we employed an approach that examined multiple case studies (5 in total) on the subject of the same research, applying the method of "cross-case analysis" described by Eisenhardt [108] and Stake [109]. This method entails a qualitative research technique with the goal of uncovering both similarities and differences in the observations of multiple cases. For this purpose, we first determined which cases to include in the analysis (see Section 3.2) based on criteria that ensured the comparability and relevancy of the cases' respective information. To select the different case companies, we used a network of many professors of OST and HSG and an industry network (swissmem) to identify case companies. After selecting the cases, the corresponding data were collected, which was carried out for each case through interviews (see Section 3.3). With the individual case analysis that followed (see Section 4.1), we formed the foundation for the subsequent cross-case analysis (see Section 4.2). Lastly, based on the information collected and the cross-case analysis, we drew conclusions (see Section 5), which ultimately served to address the identified research gap and help us formulate hypotheses for future research.

3.2. Cases

As a selection criterion, we looked for manufacturers of tangible goods located in Europe and which were already classified as large companies according to Fueglistaller's [110] definition (i.e., more than 250 employees). Naturally, it was vital that all of them already had initial experience in the use and handling of I4.0 technologies and lean management. We chose to look at large companies as the literature review showed that previous research has primarily focused on SMEs. Overall, we looked for a combination of manufacturers that produced engineered products, such as machines and solutions, on the one hand, and companies that produced serial products on the other. The selection of different types of manufacturers allowed us to challenge our hypotheses from a wide range of different viewpoints.

The use cases show the adoption of various Industry 4.0 technologies. The case companies use sensors and ERP systems, which work together as cyber–physical systems (CPSs) for real-time data collection and workflow automation. In addition, Manufacturing Execution Systems (MESs) have been integrated for monitoring performance and supporting automation, often complemented by digital twins for process visualization and planning. Technologies such as image recognition and cycle time analysis are in place to identify

inefficiencies, while OEE monitoring is implemented through dashboards that provide clear insights for continuous optimization.

Companies 1 to 5 are active in a range of specialized manufacturing industries in Europe and are each characterized by individual business and market strategies. Company 1 is an international pharmaceutical manufacturing company. With a team of just 2000 employees, it generates USD 2 billion in profits, indicating efficient operations. In contrast, Company 2 focuses on the development and production of environmentally friendly coating systems. Despite its relatively small size of just more than 500 employees, it generates a revenue of around USD 200 million. Company 3, a global technology company, is active in a variety of sectors. With 20,000 employees and revenues of approximately USD 4 billion, it represents the largest company among the five. Its focus on sustainable technologies and digital solutions demonstrates its commitment to innovation. Company 4 supplies diverse industries with fastening systems and precision parts. It generates sales of nearly USD 3 billion with about 15,000 employees. Lastly, Company 5 is a provider of sensory solutions with nearly USD 4 billion in sales and more than 15,000 employees. All companies are performing well in their respective sectors. They focus on developing and improving their products and technologies, with the value added per employee varying from USD 200,000 to USD 1,000,000.

Table 2 provides a detailed overview of the profiles of these companies.

Table 2. Company profiles.

	Company 1	**Company 2**	**Company 3**	**Company 4**	**Company 5**
Industry/Product	Pharmaceutical	Powder Coatings	Machinery	Fastenings	Sensory
Revenue	\$2b	\$200m	\$4b	\$3b	\$4b
# Employees	2k	0.5k	20k	15k	15k
Rev./Empl.	\$1000k	\$400k	\$200k	\$200k	\$265k
Location	Europe	Europe	Europe	Europe	Europe

3.3. Data Collection and Analysis

For the data collection, we conducted structured interviews using predefined questionnaires. In the 1 h interviews, we talked to the managers of the five companies who were responsible for digitalization and production (see Table 3). Additionally, we conducted three alignment workshops where we discussed and aligned the findings and challenged the hypothesis to obtain more insights.

We divided the questions into three topics. Firstly, we were interested in which I4.0 technologies were used in production, what benefits they brought, and what impact they had on the quality, performance, and availability of the machines. This gave us a picture of the current digitalization maturity of the companies. Moreover, we wanted to find out how lean management and the CI process in particular was applied, how it was connected to digitalization, how they had benefited from I4.0 technologies, and where possible difficulties or conflicts had arisen. In the third section, we discussed whether the OEE was used to measure the success of lean and CI processes and how this had changed using I4.0 technologies. A particular focus was placed on their accuracy, credibility, and applicability in decision-making. We analyzed the data collected through qualitative content analysis, using the process of coding, summarizing, and then making comparisons between cases. In practice, we conducted interviews via Teams, which were recorded and converted to text using the integrated transcription function. During the coding phase, we identified and marked sections that were relevant to our focus. We thereby employed an inductive approach to selecting topics (i.e., thematic "codes" emerged as we reviewed and analyzed

the data). We took the lessons learned for both individual cases (see Section 4.1) and for all cases as a multiple case analysis/comparison (see Section 4.2). This process was repeated iteratively to ensure that the topics identified were accurate and significant.

Table 3. Interviewees and positions.

Company 1	Global Head of Technical Development and Program Lead for Digital Manufacturing	2 interviews (1 h), alignment workshop	2 researchers present (1 h per interview), alignment workshop was 2 h (2 researchers present)
Company 2	Head of Quality Management and Digitalization, CEO	2 interviews (1 h), alignment workshop (+ manufacturing head)	2 researchers present (1 h per interview), alignment workshop was 2 h (1 researcher present)
Company 3	Director of Smart Operations and Director of Lean and Digital Operations	2 interviews (1 h)	2 researchers present (1 h per interview)
Company 4	Head of Kaizen	1 interview (1 h), workshop on digitalization (2 h, + manufacturing dep. heads)	2 researchers present (1 h per interview), alignment workshop was 2 h (1 researcher present)
Company 5	Senior Production Manager and Project Manager for Technical Engineering	2 interviews (1 h)	2 researchers present (1 h per interview)

4. Results

The results of the interviews and workshops are summarized for each company case along with the PDCA cycle dimensions. This is the basis for the cross-case analysis where we describe how digitalization has influenced the CI process in the respective companies. To examine the impact of digitalization on the CI process within the lean approach, we show our results in the matrix depicted in Table 4. Along the vertical axis, we use a well-established mechanism (Deming Cycle) of the CI process, which consists of the "Plan", "Do", "Check", and "Act" phases. The "Plan" phase involves examining the present state, identifying potential issues, and preparing possible suggestions for improvement. The "Do" phase involves testing the solutions developed. The "Check" phase analyzes the impact of the tested changes, and the "Act" phase includes the final decision and implementation of the improved proposal [1].

4.1. We Summarized the Answers as Follows—Plan

For the "Plan" phase, I4.0 technologies helped to improve process transparency and thereby deepen the understanding of these processes based on data. They enabled respondents to monitor and record important parameters more precisely, clarify the "black boxes" in the processes, and replace intuitive assumptions with data-based insights. We observed that current differences in the process could be captured by facts that would otherwise have been difficult or impossible to observe. The collected, analyzed, and centrally provided data, visually processed, help to identify waste better and faster as well as to minimize it and thus to uncover potential for improvement in the processes. Data, which previously required considerable effort to collect, are now straightforward and quick to collect and directly accessible in a short time and with little effort. The focus on data collection has also brought together approaches to integrate data from different systems into one source. All companies have seen a great benefit by applying data-driven approaches using I4.0 technologies.

Table 4. Cross-case comparison of lean continuous improvement realized through digitalization.

	Company 1	Company 2	Company 3	Company 4	Company 5
Plan	- A prerequisite for successful improvement and automation was a comprehensive understanding of the process and the accurate recording of important parameters, which was only achieved using I4.0 technologies. - By networking the systems, the data could be evaluated and made available centrally, which helped to find potential for improving the processes. - Sensor data enabled them to observe occurring phenomena and differences that would have been impossible to capture without their use. - A CPS collects and evaluates all the relevant information in a short time and with reasonable effort.	- Employees could now see and observe the process. The "black boxes" in their processes had been replaced with data-driven insights and their gaps closed. - Employees were involved in the planning and design of projects, which helped to show them the motives and motivation behind the changes and to carry them forward.	- I4.0 technologies have increased transparency in several areas of the company, e.g., through image recognition and cycle time analysis. - Data collected, analyzed, and visually processed in the CPS helped the company to identify and reduce waste, thus not only reinforcing but also supporting the lean approach.	- Customers demanded data on products. I4.0 was the tool to create transparency in processes, provide customers with the necessary information, and also identify potential for improvement. - Data collected by I4.0 technologies are processed with statistical tools to perform various calculations and analyses, which in turn serve as a basis for further improvement identification. - Before I4.0, the actual state first had to be laboriously determined. Now, the data are directly available and can be used for process optimization. - In the past, a lot of data were collected manually, which led to inaccurate results and misjudgments. Today, processes are more transparent, and the company can access real-time data to make targeted improvement efforts.	- The company claims it is moving away from digital processes and returning to manual processes. As a result, there is a lot of uncertainty about production metrics. Each employee has an individual understanding of the OEE, which makes the quality of the data highly dependent on the machine operators.

Table 4. *Cont.*

	Company 1	Company 2	Company 3	Company 4	Company 5
Do	- The process could only be improved slightly without I4.0 because it was subject to certain physical limits. This limit could be exceeded after digitalization. - The integration of I4.0 technologies enabled better communication, faster data transfer, and ultimately an acceleration of processes.	- All administrative and production processes are mapped in the ERP, which provides a comprehensive overview and control of the processes.	- I4.0 technologies have led to the simplification of information flows, greater clarity of information, and a reduction in paper through digital storage.	- The transparency created about the actual process flow helps employees to concentrate on the essentials. Raw data such as downtimes or alarms leave no room for interpretation. This means that employees know what they need and what to do in order to improve. - Digitization has made it possible to work on the basis of up-to-date and accurate data, which ultimately leads to better results.	
Check	- The OEE is used to monitor process efficiency and the success of technologies (physical or digital) and continuous improvement activities. - The data quality is a key factor in calculating the OEE. It was found that automatic collection had increased the accuracy of the OEE and that there was further potential for improvement.	- The machines are integrated directly into the ERP system as data suppliers, which improves the data quality and integrity. Fully automated sensor technology is used for data acquisition, which has been proven to eliminate errors and increase process efficiency. The data quality becomes problematic once employees are involved in the data entry process. When data must be manually entered by employees, errors are common and the lean effectiveness suffers.	- Differences were found in the accuracy and quality of the automatic and manual OEE assessments.	- Employees regularly apply the fully digitally calculated OEE as the most important KPI to drive continuous improvement and increase the efficiency of production processes.	- The OEE in the company is only measured in different and nonstandardized ways, which leads to inconsistent results.

Table 4. *Cont.*

	Company 1	Company 2	Company 3	Company 4	Company 5
Act	- Digitization and automation directly improved the data quality, transparency, and availability and thus compliance, which in turn increased the overall quality of products and their validation. - Employees were able to participate in the discussion and decision-making process, which increased their acceptance and understanding of the changes. - The results achieved were important in convincing management and employees of the benefits of lean management and digitization.	- It has been found that the success of their lean projects often depends on accurate data. The company replaced gut feelings and opinions with numbers, data, and facts and has seen success. - A dashboard for the OEE that visualizes information and gives employees a quick and easy decision-making tool has been introduced.	- The OEE is only used in this business to determinate the trend for performance. Due to the nature of the business, i.e., small batches and a large variety of products, the OEE is not the most important parameter and is therefore not used as a basis for decision-making.	- The newly automated OEE determinations have led to several findings about past improvement decisions. It has been shown that some previous improvement decisions were wrong due to errors or missing data. - The gut feeling of many employees has been replaced by accepted and consistent data that support improvement and decision-making processes.	- While the OEE can be interesting, it is not really applicable in a larger context, e.g., a management discussion, and therefore is not relevant for decision-making.

4.2. Do

In the "Do" phase, I4.0 technologies were already able to help provide additional insights into and better control of the processes and their improvement potential during the implementation phase. Through the increased amount of data and information, the approach could be developed in a way that brought significant results in operation. In addition, the available data already helped to highlight the potential of the processes. The data were made more transparent and gave transparency to the process flow, enabling a focus on potential improvements based on facts. The result was a better process through the simplification of information flows, a better and increased clarity of information, and better communication, as well as faster data exchange. As a result of these process improvements, employees can now work based on current and accurate data, leaving no room for misinterpretation.

4.3. Check

The "Check" phase has shown that data can now be used as a real-time indicator and monitor for process performance improvements. Fact-based decision-making for process improvements has been shown to be fundamental. Automatic collection has improved the data quality, reliability, and accuracy, as well as eliminating errors caused by manual measurements. We have also seen that nonstandard manual measurements can lead to inconsistent results, and that a KPI (e.g., the OEE) could not be used to monitor improvements appropriately. The data quality is critical and drives the acceptance and results. The cases have shown that manual entries are less accurate than, e.g., the sensor data of machines and direct and automatic entries of data are preferrable. A data-driven approach based on automatic data collection has increased the acceptance of information. This has created better and faster actions on all levels.

4.4. Act

For the "Act" phase, we were able to learn from various interviewees and alignment workshops that previous improvement decisions were suboptimal or even wrong due to errors or missing data. This has already been demonstrated in the previous section with the improved accuracy of data-driven decisions based on sensor data and through automated collection. The newly improved data quality, transparency, and availability greatly assists decision makers by increasing trust in the quality of data. Moreover, employees still need to be involved in the discussion and decision-making process, which increases their acceptance and understanding of the changes needed. The data used as a basis for decision-making need to be verified (also with the help of visualizing information as a quick and easy tool for decision-making). The verification helps to improve the acceptance of change decisions.

5. Findings

In the following chapter, we want to put the results of the use cases in the context of previous research. We showed in the previous literature review chapter that, according to Alsadi et al. [27], the integration of lean management and digitalization has been discussed more intensively since 2019. From this, it has become apparent that the exact interplay between the two topics, however, is not yet fully understood. There are various indications that linking lean management and I4.0 is a promising approach to increasing efficiency. Despite these expected benefits, we have shown that there is still a need for empirical research on how lean management and I4.0 can be effectively combined and implemented. In particular, the role of CI in a digitalized production environment is an area that needs further investigation. When we discuss the sequence or prerequisites for

implementing lean management and I4.0, there are two perspectives in the discussion on the topic to date [22,27,32,75]. Lean management is seen as the basis for I4.0, which implies that processes must first be optimized and standardized before new technologies can be used [29,31,71]. The second perspective recognizes the limitations of lean management in certain contexts and sees I4.0 as an opportunity to overcome them [22,27,47,76,77]. Our use cases have shown that companies need to have reached a certain level of lean maturity before implementing digitalization. Lean and standardized processes are of particular importance here. These take the complexity out of digitalization and enable the simplified implementation of technologies across the board and prevent "waste" from being digitalized instead of eliminated. We were able to use a negative example to show that the failure of both lean management and digitalization projects can occur if these points are missing. Accordingly, with the use case experiences, we confirmed the view of Sanders et al. [71], Mayr et al. [31], and Buer et al. [29]. We saw that it is advisable to have lean management prior to digitalization to a certain degree. The second perspective, according to Cifone et al. [22], Alsadi et al. [27], Rosin et al. [32], and Núñez-Merino et al. [75], also states that digitalization extends the boundaries of lean management and can also support lean methodologies [22,27,47,76,77]. Lean management and I4.0 combined can increase flexibility and productivity in processes by better identifying and eliminating the waste therein [21,46,79,81–84]. They accomplish this by promoting better communication and real-time decision-making through improved data collection, transparency, reliability, analysis, and visualization [23,68,78–80,83]. They improve quality by enabling better control over the production process and detecting errors at an early stage, ultimately increasing the reliability of processes [23,68,83]. Furthermore, we have learned that improved communication, documentation, and employee learning is enhanced by digitalization, thus promoting the development of employee competencies [23]. In our case study, we used the specific example of CI to examine the benefits of digitalization. To do this, we identified the respective collected benefits and added them to Table 5 (see below). It provided transparency for processes and facilitated the identification, planning, and implementation of the potential/solutions for improvement. This was driven by increased flexibility in the collection, accessibility, and usability of data, which enabled improved communication and more efficient information sharing. Furthermore, the improved transparency and flexibility gained through digitalization increased the reliability of data, due to the reduced risk of errors and data corruption. Decision-making processes benefited from the increased reliability of the information provided, its easy accessibility, and the ability to review and visualize it. Consequently, the acceptance of change processes increased as employees became more understanding and involved in the decision-making process.

With reference to the advantages of digitalization defined in the literature, we can thus confirm that increased flexibility [21,46,79,81,83,85], transparency [21–23,26,27,31,53,60], reliability [68,83], decision-making capabilities [23,79,80], and acceptance have been gained in connection with the CI process. We can also confirm that greater employee participation in the process can be achieved. What were not directly noticeable in the examined cases were the additional advantages listed, such as reduced inventory [46,68,82,85] or direct effects on the production line and the measurable increase in productivity of the output [29,81,85,89,90]. The focus was on the improvement process itself, which has become more efficient and effective. Table 6 combines the improvement factors from Tables 4 and 5 and lists the underlying causes for each improvement factor. Its purpose is to show in more detail the specific differences between CI without digitalization and CI with digitalization.

Table 5. Summary—observed and generalized improvement factors provided by digitalization for lean management.

	Observed Improvement Factors
Plan	- Transparency for processes and improvement potential identification - Improved planning/optimization possibilities through better process understanding - Flexibility in data acquisition, access, and application - Acceptance of change through involvement and identification of potential
Do	- Improved communication and more efficient exchange of information/data of process through data collection - Improved transparency in process flows and change events through data collection
Check	- Sensor-based data increases reliability of data/results with less likelihood of error sources and corruption - Data-based decision-making increases the improvement potential
Act	- Improved decision-making processes through the reduction in errors in information used as a basis for decisions - Acceptance through visualization of results and trustworthiness of data

Table 6. Continuous (process) improvement through digitalization.

	Continuous Improvement Without Digitalization	**Continuous Improvement Reinforced by Digitalization**
Flexibility	manual, tedious, time-consuming data gathering/access	automated, fast, transparent, reproducible gathering of/access to data
Transparency	unclear by who, how, when, and where data were collected process "black-boxes" unclear where process improvements are hidden	at any time, it is known where the data come from and by who, when, and how it was collected; improved process understanding better visibility of the potential for improvement.
Reliability	error-prone due to human involvement, possibility of dressing up numbers, differences in OEE calculation	reproducible, low risk of falsification, automatic and consistent collection and calculation
Decision-making	half-true and inconsistent OEE, instinct, gut feeling, interpretation	reflects facts, is verifiable, uniform decision base
Acceptance of change	susceptibility to errors known, different data and calculation methods produce different results, poor visualization	transparency in data collection, demonstrable, verifiable, visualization of decision bases

6. Conclusions

Despite increasing as the focus of discussions since 2019, the interaction of lean management and I4.0 is not yet fully understood. We have taken two main perspectives from the existing literature: The first sees lean management as the foundation for I4.0, as processes must first be optimized and standardized before new technologies can be introduced. The second recognizes the limitations of lean management and sees I4.0 as an opportunity to overcome them. Based on previous research, the integration of lean management and I4.0 promises more efficient communication, real-time decision-making through improved data collection, transparency, and analysis, and increased flexibility and productivity by minimizing waste in processes. Despite these already-known potential benefits, there is a need for empirical research to observe these in practice and better understand how lean management and I4.0 are and can be effectively combined and

implemented. With our studied use cases, we have shown that companies must first reach a certain level of lean maturity before they can implement digitalization, confirming perspective one. Lean and standardized processes take the complexity out of digitalization, enable the easier implementation of technologies, and prevent waste from being digitalized instead of eliminated. Digitalization should be built on a firm lean foundation and should not be viewed as a separate process, but as a tool to reinforce and build on the efficiency gains achieved through lean management. Our study has further shown that digitalization enhances lean management by contributing to an advanced CI process in several ways. We have identified and confirmed known benefits from the literature, now specifically for CI. These include creating transparency in processes and supporting the identification, planning, and implementation of improvement opportunities. We have continued to show that increased flexibility, transparency, reliability, decision-making abilities, and acceptance can be achieved through digitalization and that employees can be more involved in the process. With our research, we have thus contributed to the empirical evidence for what has been mainly theoretical research. With the CI process, we have examined an area that is virtually unstudied, and with the size of the companies (large), we have made further contributions to what have so far been studied on a smaller level. The biggest limiting factor of our research is the somewhat low empirical validity due to the comparatively small number of cases presented, which makes us call further to feed this topic area with empirical evidence. We have nonetheless found leads and therefore propose further research in this segment. There is a need for further research, especially on the long-term effects of this integration. Future work should therefore aim to further deepen this understanding and develop a comprehensive model to illustrate the synergy between lean management and digitalization. Our literature review, use cases, and subsequent model suggest that I4.0's data collection and distribution improve CI processes, especially in the areas of flexibility, transparency, reliability, decision-making, and acceptance. To investigate this further, we suggest a larger scale or long-term study.

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