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"INTEGRATING LEAN MANUFACTURING AND INDUSTRY 4.0 FOR ENHANCED OPERATIONAL PERFORMANCE"

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Firma (signature) Giulio Filippini ……………………………

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AR	Augmented Reality
AI	Artificial Intelligence
CPS	Cyber Physical Systems
ERP	Enterprise Resource Planning
FsQCA	Fuzzy Set Qualitative Comparative Analysis
GIS	Geographic Information System
GPS	Global Positioning System
HRM	Human Resource Management
I4.0	Industry 4.0
ICC	Intraclass Correlation Coefficient
IIoT	Industrial Internet of Things
INUS	Insufficient but Necessary part of an Unnecessary but Sufficient Condition
JIT	Just in Time
KPIs	Key Performance Indicators
LA	Lean Automation
LM	Lean Manufacturing
LP	Lean Production
MES	Manufacturing Execution System
ML	Machine Learning
QCA	Qualitative Comparative Analysis
RFID	Radio Frequency Identification
ROA	Return on Assets
SMEs	Small and Medium Enterprises
TPM	Total Productive Maintenance
TPS	Toyota Production System
TQM	Total Quality Management
VSM	Value Stream Mapping

INTRODUCTION

In recent decades, the manufacturing industry has witnessed profound transformations, fueled by the need to increase efficiency and meet evolving customer demands. Two prominent methodologies have emerged as central to this evolution: Lean Manufacturing and Industry 4.0. Originally developed as the Toyota Production System (TPS), Lean Manufacturing is a systematic approach aimed at maximizing customer value while minimizing waste, enhancing operational efficiency, and fostering a culture of continuous improvement. The principles of Lean Manufacturing have since been applied across various sectors, helping organizations improve quality, streamline processes, and create superior value for customers. Despite its beneficial potential, Lean Manufacturing still has room for improvement for its successful implementation within companies. This thesis analyses the necessary conditions for a proper application of Lean Manufacturing, with a focus on its complex yet synergic relationship with digital technologies.

Industry 4.0, meanwhile, represents the latest phase of manufacturing digitalization, combining advanced technologies such as Big Data analytics, cyber-physical systems, and the Industrial Internet of Things. By creating interconnected, "smart" factories, Industry 4.0 enables companies to swiftly adapt to demand fluctuations, produce customizable products efficiently and especially make data-driven decisions in real time. While the two approaches—Lean Manufacturing and Industry 4.0—share common goals of productivity, efficiency and waste reduction, their operational focus is significantly different. Indeed, while Lean emphasizes simplicity and human-centric improvements, while Industry 4.0 prioritizes technological innovation and automation.

The integration of Lean and Industry 4.0 is promising to unlock their complementary strengths. However, many challenges arise in aligning the two approaches. Key problems are represented by the tension potentially created between automation and human-driven improvements, as well as by the necessity for employees development and the need for large investments in technology.

This dissertation explores the challenges and synergies of combining Lean Manufacturing and Industry 4.0. In particular, using Qualitative Comparative Analysis, data from different Italian manufacturing companies was examined with the aim to identify the combinations of Lean practices and digital technologies able to yield superior operational performance. More in depth, the resulting configurations will include *Total Quality Management (TQM), Just-In-*

Time (JIT) and Total Predictive Maintenance (TPM) as Lean practices. For Industry 4.0, we considered data acquisition technologies and integrated communication technologies.

The findings suggested how sometimes Lean works best with a limited adoption of data acquisition technologies. On the contrary, the match between Lean and integrated communication technologies improves the flow of information within the company, and therefore leads to improved financial outcomes. Moreover, we discovered that implementing specific technologies without the prior implementation of Lean brings lower levels of performance.

The first part of the thesis will be dedicated to exploring the concepts and applications of Lean Manufacturing and Industry 4.0. The methodology for the Qualitative Comparative Analysis will be thoroughly explained in Chapter 3, alongside description of the sample data. Finally, results of the analysis will be discussed in the fourth chapter.

1. A BRIEF INTRODUCTION TO LEAN MANUFACTURING

1.1. Definition, origins and development of Lean Manufacturing

The term "*Lean*" was coined in 1988 by American entrepreneur John Krafcik in his article "Triumph of the Lean Production System" and later defined in 1996 by J. Womack and D. Jones as a systematic approach to identifying and eliminating waste through continuous improvement.

Lean Manufacturing traces its roots to the Toyota Production System (TPS), developed in the late 1940s by Kiichiro Toyoda and Taiichi Ohno. TPS was built on two key principles: **Jidoka** (automation with a human touch) and **Just-In-Time (JIT)** production. Jidoka focused on preventing defects by halting production when errors occurred, while JIT aimed to align inventory with production schedules, reducing excess and improving efficiency. Stability and standardization, as well as respect for people are also fundamental pillars of Lean Manufacturing.

The global recognition of Lean began in the 1970s, spurred by the 1973 oil crisis which exposed inefficiencies in traditional mass production. The publication of "The Machine That Changed the World" by James Womack and colleagues in 1990 played a crucial role in introducing Lean principles to Western industries. Throughout the 1980s and 1990s, Lean methodologies spread beyond automotive manufacturing to sectors like aerospace, electronics, and consumer goods, leading to significant efficiency gains. In the 21st century, Lean principles have been adapted for use in healthcare, software development, and services, culminating in the five core principles of Lean Management, elaborated by researchers James Womack and Daniel Jones in their book "Lean Thinking: Banish Waste and Create Wealth in Your Corporation" (1996). The five principles are:

1. **Define Value.** According to Womack and Jones (1996): "Lean Thinking […] must start with a conscious attempt to precisely define value in terms of specific products with specific capabilities offered at specific prices though a dialogue with specific customers". Value, therefore, can be defined only by customers and is meaningful only when expressed in terms of a specific product. More precisely, defining value means

finding the problem that the customer needs to solve and making the product the solution. Any process or activity that does not add value to the final product is considered waste and should be eliminated. For Japanese firms, *where* value is created is of paramount importance. To define value, a backwards thought-process is used.

2. **Map Value through Value Stream Mapping (VSM).** Value stream is the set of all the specific actions required to bring a specific product through the three critical management tasks of any business: the *problem-solving task* running from concept through detailed design and engineering to production launch, the *information management task* running from order-taking through detailed scheduling to delivering, and the *physical transformation task* proceeding from raw materials to a finished product in the hands of customers. Value stream mapping helps managers visualize which processes are led by what teams and identify the people responsible for measuring, evaluating and improving the process. This visualization also helps managers classify activities and decide on their future:

    i. Activities that unambiguously create value must be developed and improved
    ii. Activities that do not create value but to are unavoidable with current technologies and production assets should be minimized
    iii. All activities that create no value and can be avoided must be immediately removed.

3. **Pull.** The implementation of a pull system is critical to maintaining a stable continuous workflow, ensuring that work assignments are completed more efficiently and with reduced effort. The pull system minimizes waste across production processes by initiating new tasks only in response to existing demand. This approach offers significant advantages, including the reduction of overhead costs and the optimization of storage requirements, as it prevents the overproduction of goods and the accumulation of excess inventory. By aligning production output with real-time demand, the pull system enhances operational efficiency and resource utilization**.**

4. **Flow**. Establishing a continuous workflow involves ensuring the seamless progression of tasks within each team's operations, while simultaneously mitigating bottlenecks or interruptions that often arise. *Kanban* (visual card), a lean management technique employing visual cues to trigger actions, plays a vital role in facilitating communication between teams, allowing for the clear identification of tasks and their respective timelines. By breaking down the overall work process into smaller, manageable

components and visualizing the workflow, organizations can effectively identify and eliminate process disruptions and roadblocks, thereby enhancing operational efficiency and productivity. The main issue is that making the steps of the value creation process *flow* goes against the diffused practice of producing in batches, and therefore the implementation of this principle could face workers' reluctancy, especially once departments and specialized equipment for batch production at high speed are put in place. Regardless of this problem, the switch from departments and batches to product teams and flow enables the reduction of **lead time.** Products requiring years to design are done in months, orders taking days to process are completed in hours and the weeks or months of throughput time are reduced to minutes or days.

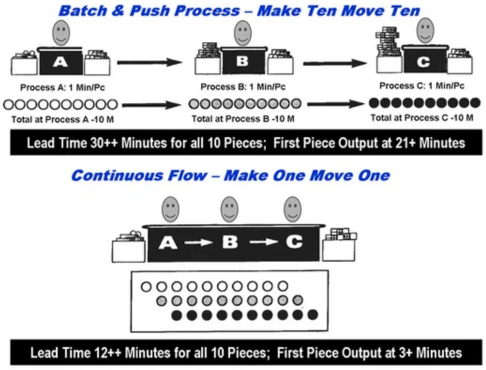


Figure 1: Difference between batch and push process and continuous flow of production

Source: Hartford Technologies Blog, 2017. Lean Manufacturing Tools for the Electronics Industry

5. **Perfection** (*kaizen*). Anticipating potential challenges and enhancing work processes through continuous incremental improvements is of paramount importance when entering a lean transformation. In this context, engaging all employees in the improvement of workflows is critical, as their collective contributions help safeguard the organization by fostering adaptability and resilience when problems emerge. This holistic involvement ensures that improvements are sustained and aligned with evolving organizational needs. Another aspect of continuous improvement is represented by *transparency,* the fact that everyone can see everything and therefore new ways of creating value can be found. Lastly, perfection is also aimed at employees themselves, pushing them to fully exploit their potential. When pursuing perfection, it is fundamental for the object of improvement to be visible and real to the whole enterprise. According to Womack and Jones: "*Perfection is like infinity. Trying to envision it (and to get there) is actually impossible, but the effort to do so provides inspiration and direction essential to making progress along the path.*"

After outlining the five principles of lean thinking, one might question what tangible and immediate benefits these principles offer in the short term. It has been proven how switching from a traditional batch production to a continuous flow and pull system results in double the labor productivity throughout the whole system. Moreover, production throughput time (nota) decrease by 90%, and inventory gets reduced by the same percentage. Positive effects appear also on job-related injuries, scrap within the production process, time-to-market for new products and capital investments. All these improvements together are called "*kaikaku*", the result of the initial, radical realignment of the value stream. Following these first milestones, improvements continue thanks to *kaizen* practices, that will be later explored, in the pursuing of perfection. In other words: "*Firms having completed the radical realignment can typically double productivity again through incremental improvements within two to three years and halve inventories, errors, and lead times during this period. And then the combination of kaikaku and kaizen can produce endless improvements." (Womack and Jones, 2003. "Lean Thinking: Banish Waste and Create Wealth in your Corporation").*

1.2. The concept of Muda (waste)

According to Womack and Jones: "Lean thinking also provides a way to make work more satisfying by providing immediate feedback on efforts to convert *muda* into value. And, in striking contrast with the recent craze for process reengineering, it provides a way to create new work rather than simply destroying jobs in the name of efficiency." But what is muda? In the context of lean management, muda represents every resource-consuming process or activity that does not add value to the final product from the customer's perspective. This concept is of fundamental importance since the purpose of lean is to maximise customer value while minimizing waste. Ohno identified seven different types of muda:

1. **Transportation**: Unnecessary movement of products or materials between locations that doesn't add value. Tools like Value Stream Mapping (VSM) can identify excess transportation in the production flow and help streamline processes to minimize movement.
2. **Inventory**: Implement Just-In-Time (JIT) production to ensure that inventory levels match immediate demand, reducing storage costs and potential obsolescence. Kanban systems, which regulate inventory replenishment, are also highly effective in avoiding excess.

3. **Motion**: analyse and redesign worker and machine movements using techniques such as **5S** (Sort, Set in Order, Shine, Standardize, and Sustain). This tool organizes workspaces to promote efficient movement and reduce time spent searching for tools or materials.
4. **Waiting**: Eliminate bottlenecks by improving process flow with techniques like **Heijunka (production leveling)**, which smooths production to prevent waiting times due to uneven work distribution.
5. **Overproduction**: Avoid overproduction by aligning production closely with customer demand using **Pull Systems**, where work is triggered based on actual orders rather than forecasted demand. This reduces waste from unsold inventory and storage.
6. **Overprocessing**: Review and standardize production processes to avoid performing unnecessary steps or using excessive materials. **Continuous improvement (Kaizen)** initiatives help identify areas where simplification can reduce waste without sacrificing quality.
7. **Defects**: Use tools like Poka-Yoke (error-proofing) to prevent defects from occurring in the first place. Root Cause Analysis and Six Sigma methodologies are also essential in identifying and solving quality issues, ultimately reducing the waste associated with defective products.

1.3. Lean techniques

To achieve waste reduction and efficiency enhancement, several lean techniques can be implemented. Methodologies such as Just-In-Time, Kanban and Kaizen and many others, focus on standardization, simplicity and employee involvement in order to create and sustain a dynamic and adaptable production system. In the following paragraphs, the most widely diffused techniques will be discussed.

Just In Time (JIT)

The Just-in-Time (JIT) inventory system is a management strategy designed to synchronize the production schedule with orders from suppliers, so as to reduce waste and increase operational efficiency by producing only what and when necessary. By minimizing excess inventory, holding costs are reduced, and risk of surplus inventory in case of order cancellations or unfulfilled demand is mitigated. To benefit from JIT, however, attention shall be put in accurate demand forecasting, to have a smooth production flow. Moreover, machinery needs to be reliable and glitch-free and the company should have a dependable supplier relationship. JIT is often used in the automobile industry, where inventory levels are kept low and are highly dependent on their suppliers to deliver the necessary components on the base of the orders received.

Kanban

The word Kanban translates to "visual card". These visual cards work as a signal and response mechanism, as they track production and alert when new materials or components must be ordered, to ensure an interruption-free production flow. Similarly to JIT, Kanban is useful to avoid excess inventory and amend bottlenecks in production, signalling the presence of inefficiencies any time the level of inventory is above the established threshold. Kanban can be broken down in four sequential steps:

1. **Visualization of the workflow** to clearly define the sequence of steps and their order of execution. In this way, employees have a deeper understanding of the task flow, which allows for better communication and coordination within teams.
2. **Limitation of Work In Process (WIP)** to reduce carrying costs of inventory. Lower WIP results in a faster turnaround, and therefore in a more efficient use of resources.
3. **Management of workflows** to eliminate potential bottlenecks or other inefficiencies through a proactive approach.
4. **Clear definition of policies** in order to create a sustainable system of production that results in lower costs for customer, faster delivery of final products and therefore a higher level of customer satisfaction.

Poka-Yoke

Poka-Yoke, invented by Shigeo Shigo and literally translating to "mistake-proofing", is a prevention system designed to ensure that all required conditions are met before a process step is executed, so as to eliminate the possibility of errors occurring. In instances where prevention is not applicable, Poka-Yoke systems identify and eliminate defects as soon as they are detectable. The importance of Poka-Yoke is attributable to its capacity of minimizing human error and ensuring process quality without the need of a specific function dedicated to it. The implementation of this system gradually makes it impossible for mistakes to occur over time, which together with quality control directly embedded in the production process, contributes to the enhancement of operational efficiency.

Kaizen

Kaizen, “change for the better" or "continuous improvement" in Japanese, is a fundamental business philosophy that pursues the ongoing enhancement of operations through the active involvement of all employees. The underlying through at the base of Kaizen is that by implementing small incremental changes over time, a company can secure benefits in the long run. Among the aims of Kaizen, we find the improvement of daily procedures, the creation of a collaborative atmosphere among teams, the increase of employee engagement and job satisfaction. Another core element of Kaizen is its inclusive nature, meaning that improvements can be created at any time by any employee, fostering a culture of continuous innovation at all levels of the organization. This concept is rooted on the belief that all employees share a common interest on the success of the firm and should actively work together to improve it. Kaizen is characterized by five principles: understanding the customer, continuous flow, “going to Gemba” (the real place where value is created), people empowerment, and transparency. Kaizen has been integrated as a core organizational value by several companies, particularly by Toyota, whose production system is strongly influenced by this philosophy.

Improvements in the context of Kaizen typically follow a predetermined path, called the PDCA cycle (Plan-Do-Check-Act). Initially, the **Plan** phase involves outlining and understanding the proposed changes and their expected outcomes. During the **Do** phase, these changes are implemented. The **Check** phase assesses the effectiveness of the solution, while the **Act** phase determines if the solution should be standardized or if further modifications are needed. If additional changes are necessary, the process recommences with the Plan phase, continuing the iterative improvement loop.

5 S

The 5 S system comes from the combination of five Japanese words beginning with the letter “S”, representing five principles to implement when entering a lean journey. These principles are:

1. *Seiri (Sort)*. Identify and remove unnecessary items (muda) from the workspace to clear clutter and create a focused environment.
2. *Seiton (Straighten).* Arrange and organize the necessary items so that are easily accessible and optimally positioned for efficient workout.
3. *Seiso (Shine).* Clean the workspace regularly to maintain a neat environment, ensuring that equipment and areas are in top condition.

4. *Seiketsu (Standardize)*. Develop and implement standard procedures to maintain organization and cleanliness consistently across the workspace.
5. *Shitsuke (Sustain)*. Cultivate discipline and habit among employees to adhere to the standards and continuously improve the process.

Implementing a 5S system can bring many benefits, among which we can find higher equipment availability, improved safety, lower defect rates, increased production agility and flexibility and improved safety. Actively engaging operators in optimizing their work environment, the 5S methodology fosters a culture of continuous improvement by minimizing muda. Moreover, adherence to 5S principles serves as the cornerstone of Total Productive Maintenance (TPM) and plays a critical role within the Toyota Production System (TPS). It establishes a stable foundation for launching Kaizen activities, facilitating ongoing, incremental improvements. As a low-investment, high-impact tool, 5S drives lean manufacturing by empowering workers to take ownership of their workspace, ultimately fostering a culture centred on quality, productivity, and continuous enhancement.

Total Productive Maintenance

Total Productive Maintenance (TPM) can be described as an innovative maintenance strategy aimed at maximizing equipment effectiveness, eliminating breakdowns, and promoting autonomous maintenance by operators through regular, workforce-inclusive activities (Nakajima, 1989). The ultimate objectives of this practice are threefold: zero defects, zero accidents, and zero breakdowns (Willmott, 1994; Noon et al., 2000). TPM implies more than just maintenance procedures: it embodies a philosophy, a culture and an attitude shift toward maintenance. According to Nakajima (1988), the aim of TPM is to create a synergy between production and maintenance that drives continuous improvements in product quality, reliability, safety, capacity and operational efficiency. Because of these reasons, TPM plays a critical role in driving the analysis of lean practices and their effects on operational performance. The issue will be further analysed in the empirical analysis included in the fourth chapter.

1.4. The Role of People in Lean Organizations

People are a crucial component of Lean manufacturing, and lean goals are dependent on the active engagement and continuous improvement mindset. For this reason, organizations must foster a culture where people are empowered, skilled, and motivated to contribute to improvements at every level. There are various aspects encompassing the important role of people in lean organizations, the main ones being:

1. **Leadership**: Leaders are fundamental for the creation of a lean culture. They have the responsibility of guiding teams and communicate the vision, as well as setting expectations for incremental improvements. They must also ensure that the required resources and level of support are put in place for lean practices to succeed.
2. **Employee Involvement**: workers must always be involved in decision-making, problem-solving and continuous improvements. Commitment must be shared by all employees of the organization, regardless of their hierarchical level.
3. **Team Collaboration**: Through cross-functional collaborations, it is in fact possible to identify bottlenecks from the start, eliminate muda and make the production flow. Moreover, team collaborations make the implemented solutions more effective and more sustainable over time.
4. **Training and Development**: In order to foster a culture of continuous improvement, employees must be given the opportunity to strengthen their existing skills and develop new ones. Therefore, investments in training are key. Moreover, insights and ideas coming from employees are a valuable resource for the company and provide new and creative solutions to existing and upcoming challenges.
5. **Empowerment**: thanks to investments in training and development, employees can gain the autonomy to solve problems on their own, without always asking their superiors. A beneficial consequence of this employee empowerment is a proactive workforce that is able to drive lean initiatives forward.
6. **Culture of Continuous Improvement**: Lastly, employees are encouraged to make small incremental changes (Kaizen) on a regular basis through many incentives. Workers must also be adaptable and able to solve problems in different areas of the organization, leading to a more agile company that is more responsive to both external and internal challenges.

1.5. Quality and Lean Manufacturing

In the context of Lean manufacturing, quality management plays a central role in driving efficiency, reducing defects, and enhancing customer satisfaction. Two key methodologies that have shaped modern quality management are **Total Quality Management (TQM)** and **Six Sigma**. TQM is a holistic, organization-wide approach that emphasizes continuous improvement, customer focus, and employee involvement. TQM integrates all parts of the organization, including external stakeholders such as suppliers, to create a culture of quality. It relies heavily on employee experience, qualitative methods, and active participation at every organizational level. The focus is on process management, with an emphasis on customer satisfaction and long-term improvements. The main issue with TQM is its dependence on qualitative methods, which may lack the structured, data-driven approach that is increasingly necessary in today's complex, technology-driven manufacturing environments.

To address these limitations, many firms have shifted to *Six Sigma*, which was introduced in the 1980s by Motorola and popularized by companies like General Electric. Six Sigma provides a more structured, data-oriented framework aimed at reducing process variation and improving efficiency. Unlike TQM, Six Sigma focuses heavily on the financial impact of quality improvements, ensuring that every project is tied to measurable business outcomes. It is defined by its DMAIC (Define, Measure, Analyze, Improve, Control) cycle, which helps organizations systematically tackle inefficiencies and improve processes with precision. Both TQM and Six Sigma have been integral in helping organizations achieve operational excellence. While TQM excels in building a quality-focused culture, Six Sigma's process-driven, quantitative methods provide a more tangible, results-based approach to improving quality. These methodologies will be further explored in the second chapter, where their applications and impacts on operational efficiency will be discussed in greater detail.

1.6. Conclusions

This chapter has thoroughly examined Lean Manufacturing, outlining its evolution from the Toyota Production System (TPS) to its current widespread application. We have delineated the five core principles of Lean—Defining Value, Mapping Value Streams, Implementing Pull Systems, Establishing Flow, and Pursuing Perfection (Kaizen)—and discussed the integration of key techniques such as Just-In-Time (JIT), Kanban, Poka-Yoke, and 5S. These principles and techniques collectively form a systematic approach to eliminating waste, improving efficiency, and fostering a culture of continuous improvement.

Specifically, the integration of Lean techniques creates a cohesive strategy for operational excellence. For example, JIT and Kanban work synergistically to align production with real-time demand, minimizing excess inventory and reducing lead times. The 5S system ensures that work environments are organized and conducive to efficient operations, while Poka-Yoke focuses on error prevention, enhancing product quality and operational reliability. Kaizen drives ongoing improvements by engaging all employees in the continuous refinement of processes, which helps sustain gains and adapt to changing conditions.

Looking ahead to Chapter 2, we will dive into the relationship between Lean Manufacturing and Industry 4.0. This exploration will review how emerging digital technologies - such as the Internet of Things (IoT), artificial intelligence (AI), and advanced analytics - can complement and enhance Lean practices. We will investigate how these technologies can be integrated with Lean methodologies to further reduce waste, optimize processes, and enable data-driven decision-making. This analysis will aim to uncover how Industry 4.0 can build on the foundation of Lean to address contemporary manufacturing challenges and drive innovation.

2. LITERATURE REVIEW

2.1. Introduction to Literature Review and Methodology

This second chapter will be dedicated to a literature review on the integration between Lean Manufacturing and Industry 4.0. As the concept of Lean Manufacturing was broadly addressed in the first chapter of this thesis, the first section of the literature review will be dedicated to Industry 4.0, covering its definition, the enabling technologies and providing an overall theoretical background on the topic. A proper literature review on the interaction between Lean and Industry 4.0 will follow, and the main challenges and opportunities of their integration will be covered. The focus of this chapter will be on the theoretical frameworks and models for the integration as well as on their synergetic interaction. The last part of the chapter will be dedicated to present gap in the literature and future research directions.

To conduct this literature review, databases such as Scopus and Google Scholar were used. The consultation of scientific magazines such as the International Journal of Operations & Production Management and the International Journal of Production Research. In particular, the starting point of this literature review was the article "Beyond Lean Beyond Industry 4.0 – integrating Lean, digital technologies and people" published in 2024 by the IJOPM. To conduct the literature review, roughly fifteen articles were used. They have been first searched by title, abstract and keywords, starting with general terms such as "Industry 4.0" and "Lean manufacturing" and later refining the search. The articles used were published over several years, but particular importance was given to research made in the latest years, from 2017 onwards.

2.2. The concept of Industry 4.0

"Industry 4.0 – also called the Fourth Industrial Revolution or 4IR – is the next phase in the digitalization of the manufacturing sector, driven by disruptive trends including the rise of data and connectivity, analytics, human-machine interaction, and improvements in robotics" is the definition provided by McKinsey in 2022. The term was first introduced at the 2011 Hannover Fair through the announcement of the "Zukunftsprojekt Industrie 4.0" as part of Germany's high-tech strategy, and from this point onward, Germany and later the European Union began pushing for the digitalization of manufacturing processes. Industry 4.0 is now a global phenomenon, and companies worldwide have begun integrating these technologies. Although no definition of Industry 4.0 is universally accepted, the concept revolves around the vision of a manufacturing future where humans and machines are interconnected and capable of communication through extensive networks (Santos et al., 2017). This interconnectedness improves productivity, speed, flexibility, and quality across the entire value chain. (Qin et al., 2016; Tortorella and Fettermann, 2018). The communication was also facilitated by the rise of Smart Factories, that use internet-connected devices, machinery, or production systems that collect, share, and process data to adapt their behavior accordingly (Shrouf et al., 2014). In these facilities, efficient data-sharing IT infrastructures are put in place, as well cyber-physical systems, which integrate the physical and virtual words through decentralized decision-making. This type of integration fosters the diffusion of global supply chains where data is aggregated, stored in cloud systems, and accessible across the value chain (Szozda, 2017). In their paper "The industry 4.0 Opportunities", PwC defined Industry 4.0 as a "new business model focused on exploiting opportunities deriving from technologies", technologies that enable companies to adapt quickly to volatile demand scenarios and mass-produce highly customizable products (Kagermann et al., 2013; Fettermann at al., 2018). The resulting significant changes in production systems also created demand for new jobs.

As for the fundamentals of Industry 4.0, in 2015, Boston Consulting Group identified its nine technological pillars, the core technologies driving the digital transformation of manufacturing. In the following paragraphs, a brief overview of each pillar will be provided.

The first pillar is **Big Data and Analytics**. The growing digitalization of daily life, driven by advanced technologies and smart devices, has resulted in the creation of vast amounts of diverse data, coming in various volumes, formats, and from multiple sources, making data analytics a crucial technology in Industry 4.0 (Lampropoulos et al., 2019). Data is first collected from various sources, both external (e.g. market reports) and internal (e.g. machines), then organized. Lastly, analytics tools are employed to process data and identify relevant trends, optimize production processes and improve decision making.

Industrial Internet of Things is the second pillar of Industry 4.0 and represents all the smart devices that, using their embedded sensors, can collect various types and amounts of data. By connecting industrial assets to the cloud via networks, IoT enables to collect and analyse data, as well as to programme machines so as it is possible to make them take decisions autonomously. These improvements lead to an increased level of productivity, due to higher production efficiency, and consequently a shorter time to market (Lampropoulos et al., 2019).

Lastly, real-time data acquisition and analytics allows companies to react much faster to critical situations, and improve workplace safety at the same time, by making machines handle more dangerous tasks (Sisinni et al., 2018).

The third pillar is **Autonomous Robots**. Robotics has been an integral part of manufacturing for decades, but Industry 4.0 introduces a new generation of autonomous robots. These robots, after the programming phase, are able to perform complex tasks in a completely autonomous manner, as well as to learn from their past actions, thanks to the use of Artificial Intelligence (AI) and Machine Learning (ML). Different tasks can also be performed depending on the context, a consequence of the implementation of IoT. These robots are not only capable of performing tasks independently but can also collaborate with other machines and human operators. Among the effects of worker-robot interactions, particular importance is given to the enhancement of workers' productivity and at the same time a reduction of stress and fatigue (Villani et al., 2018).

Simulation technologies allow companies to create digital models of real-world processes, machines, or products, and they are the fourth pillar of Industry 4.0. These virtual simulations help manufacturers test and optimize production setups before they are implemented in the physical world, reducing time, cost, and errors. They are especially useful in design, R&D, and quality testing, as well as for safety-related tests.

System integration, the fifth pillar of Industry 4.0, refers to the seamless communication and coordination between machines, processes, and departments within an organization (vertical integration) and across different companies within a supply chain (horizontal integration). This integration allows for smoother operations and collaboration, improving production efficiency and adaptability. Indeed, horizontal integration facilitates raw materials and final products delivery, with an effect on operational costs and time to market, while vertical integration helps decision making actions to be less dependent of human intervention by linking together all hierarchical levels of the company (Frank et al., 2019).

The sixth pillar of Industry 4.0 is **Cyber physical systems (CPS)**, systems in which the physical space is integrated with the cyberspace. CPS ensure the real-time transmission of data and information between the elements of the two environments fusing computation, networking and physical processes. This allows for a high degree of synchronization, transparency and efficiency of the supply chain (Ivanov et al., 2019). Considering the nature and constituents of CPS, security is a key component and requirement of CPS, due to the huge amount of sensible data stored and transmitted via internet. Cybersecurity aims at protecting the cyberspace from any cyber threat or attack (Lezzi et al., 2018), ensuring data integrity, confidentiality and availability, while restricting access to designated users only.

Following the diffusion of Big Data, companies needed new ways of storing information. This is the purpose of **Cloud Computing**, the seventh pillar of Industry 4.0. In 2011, the National Institute of Standards and Technology (NIST), defined Cloud Computing as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction". In other words, Cloud Computing is a simple online information and data storage and retrieval platform using web-based applications that require no installation (Oztemel et al., 2020). Unlimited scalability is one of the main benefits of Cloud Computing, since providing elasticity and self-service provisioning allows the company to scale capacity up and down according to current data traffic. Moreover, this technology leads to increased speed and agility, proving also to be a cost-effective solution, since you pay only for cloud-based infrastructure and other computing resources as you use them.

The eighth pillar of Industry 4.0 is **Additive Manufacturing** and refers to the creation of objects by adding successive layers of materials. This technology completely changed the way to do manufacturing, going from traditional machining processes that rely on material removal to additive processes that eliminate any need for components and parts assembly (Kamble at al., 2019). This leads to decreased waste and scrap that previously resulted from activities of cutting and finishing products. With additive manufacturing it is easier to produce custom and complex designs with minimal waste, as well as diminishing costs and lead time. The most used practise by Additive Manufacturing is 3D printing, mainly used for small-batch production, on-demand manufacturing and prototyping. Using 3D printing, an object can be created with a single machine and the use of material is limited only to the required amount, making production more environmentally sustainable and cost efficient. It is important to notice how Additive Manufacturing also presents some disadvantages, such as its high variable costs and high toxicity of materials used for 3D printing. However, exploring these downsides is beyond the scope of this thesis.

Lastly, the ninth pillar of Industry 4.0 is **Augmented Reality (AR)**, a technology to make information interactive by adding an overlay of digital content and relevant information. (Pagliosa et al., 2019). Implementing human vision with the visualization of digital elements enhances users' perception and interaction with the environment, increasing the amount of information available at a time of a particular action. Many uses of AR can be found in manufacturing, from training to simulation, to remote assistance. The latter in particular is important because by providing operators with real-time data and visual guidance, task efficiency and accuracy can be significantly improved.

When discussing about the nine pillars of Industry 4.0, it is important to notice how there is a strong interaction within all these technologies. It was not the single technologies, but rather the connection between them that enabled the digital transformation of the industrial sector, leading to new business models, improved processes, and increased competitiveness, also due to the rise of Smart Factories.

2.3. The scope of Industry 4.0 and the link with Lean Manufacturing

The scope of Industry 4.0 extends beyond mere automation; it involves the complete digitalization of production systems. This transition allows manufacturers to move from a traditional production line to a highly flexible and interconnected production network. More informed decision making, as well as the optimization of internal processes and supply chain interaction are among the benefits brought by the ability to gather and analyse large amounts of data from various sources (Rüßmann et al., 2015). Industries and countries embraced Industry 4.0 at different rates and in different ways. Although among the industries mostly affected by the fourth industrial revolution we can find healthcare, agriculture and banking/finance, we will focus exclusively on the manufacturing sector, which is also the one that was able to capture the most benefits out of Industry 4.0. The transition towards mass customization is also supported by Industry 4.0, and represents an important advantage given the growing demand for highly customized products. The integration of cyber-physical systems and IoT facilitates dynamic reconfiguration of production lines, making it easier for manufacturers to respond to shifts in market demand and customer preferences (Pereira and Romero, 2017). In a globalized economy, Industry 4.0 also plays a crucial role in maintaining competitiveness. As manufacturing becomes increasingly digitized, companies that fail to adopt these technologies risk falling behind. By embracing Industry 4.0, manufacturers can enhance productivity, reduce downtime, and improve the overall quality of their products. This digital transformation is not only a technical challenge but also a strategic imperative, driving the need for new business models and innovation in manufacturing processes (Hermann et al., 2015). Thus, Industry 4.0 represents the convergence of the physical and digital worlds, offering valuable opportunities for manufacturing companies to improve product quality, optimize their processes, and meet changing market demands in real-time. As the foundation for smart manufacturing, it paves the way for more efficient, adaptive, and sustainable production systems, reinforcing its pivotal role in the future of manufacturing.

Having explored the scope of Industry 4.0, it is intuitive to notice how some of the goals it seeks to achieve leveraging digitalization and smart technologies correspond to the ultimate purpose of Lean Manufacturing, that is to maximize customer value while minimizing waste. Other objectives, such as efficiency enhancement and production optimization find a place in both Industry 4.0 and Lean Manufacturing. Given this alignment, it comes naturally to think about how the two concepts could integrate as to amplify their positive effects and reach their shared objectives faster. Indeed, the purpose of the remaining of this chapter is to identify ways and consequences of this valuable but complex integration. From now onwards, the term Lean Automation (LA) will also be used to refer to the integration between Lean Manufacturing and Industry 4.0.

2.4. Challenges and Opportunities in integrating Lean with I4.0

The integration between Lean Manufacturing and Industry 4.0 presents both valuable opportunities and significant challenges for manufacturing companies. While it has been proven that Industry 4.0 technologies enhance the potential for Lean by providing better data management, improving the decision-making process and automating waste reduction, this integration faces many barriers to implementation, especially related to organizational readiness and workforce capabilities.

2.4.1. Challenges

The article “Beyond Industry 4.0 – integrating Lean, digital technologies and people”, published in the International Journal of Operations and Production Management, focuses on two different types of tensions that could be generated when integrating Lean and Industry 4.0. In this paragraph, the main challenges to integration will be presented and a correspondence with the tensions identified in the articles will be provided.

Dialectical tensions can be assimilated to “dialogues” between two opposing entities that struggle to find accommodation (Margherita and Braccini, 2024), and that can be solved only by finding a synthesis that transcends the original observations. The other type of tension is represented by *paradoxical tensions* between organizational elements that cannot coexist. They cannot be solved, and on the contrary, they must be accommodated and embraced through imbalances and dynamics equilibriums (Smith and Lewis, 2011). Four main groups of paradoxical tensions were identified: performing, organizing, learning and belonging.

One of the key challenges in integration is represented by the differences in the underlying principles of Lean Manufacturing and Industry 4.0. Indeed, while Industry 4.0 focuses on complex automation and advanced digital technologies, Lean is more concerned about simplicity, manual processes and human-driven continuous improvements (Pagliosa et al, 2019). This challenge is classified as a performing paradoxical tension that can only be solved through the creation of a new equilibrium deriving from a cultural shift. However, companies that have successfully implemented Lean, due to its nature, could show resistance to the adoption of high-tech solutions, making this cultural shift difficult to achieve (Buer et al., 2018). Another challenge concerns the technological infrastructure needed to implement Industry 4.0 solutions. This is a problem of resource allocation between future smart production and current operations' demand, given the fact that SMEs, in particular, lack the necessary resources and expertise to invest in advanced systems such as IoT or cloud computing (Kolberg and Zühlke, 2015). This situation creates a tension between supply-driven strategies (push) strategies that aim to exploit possibilities as they arise, and demand-driven (pull) strategies focused on meeting current requirements. This struggle is classified as an organizing paradox.
Lastly, Johansson et al. (2024) identified belonging paradoxes and especially learning paradoxes, revolving around the choice between exploitation and exploration during the implementation phase of new technologies and between generalization and specialization of knowledge.

As for the dialectical tensions, Margherita and Braccini (2024) identified four different types following a qualitative single case-study over a 3-year period. The four tensions occurred across different Industry 4.0 adoption phases, and they appear to be all linked to the interaction between workers and machines.

- Robotised vs humanised Industry 4.0 automation. The introduction of new technologies may create feelings of marginalization in workers, replacing them in manual and decision-making tasks. At the same time, automation makes workers more constant and efficient in production. As a synthesis, communication and technology trials can be used to involve workers in the selection of Industry 4.0 technologies.
- Machine vs Worker governed operations. Accumulated knowledge of the workforce is disrupted by new technologies, and workers do not completely embrace a collaborative mindset with machines. As a resolution mechanism, workers must rotate between

traditional and more advanced job positions to develop their skills across different areas, as well as get trained to become supervisors of Industry 4.0 technologies.

- Surveillance vs Self-monitoring. This tension refers to workers who are unsure of how managers use production data, whose traceability enables workers surveillance. To solve the problem, workers should be allowed to manage their teams autonomously and transparency should be ensured.
- Techno-empowerment vs techno-stress. Sometimes workers find it difficult to positively interact with new technologies, so they must train their competences and interfaces of technologies should be created to be easy-to-use and intuitive.

Therefore, the last challenge covered in this work to ensure a positive integration between Lea and Industry 4.0 is represented by workforce readiness. Among the different resolution mechanisms explained in the above paragraph, the common point is the retraining or upskilling of employees, an activity that is essential but at the same time can be resource-intensive and time-consuming (Sanders et al., 2016).

2.4.2. Opportunities

Despite the challenges, integrating Lean with Industry 4.0 presents considerable potential to enhance manufacturing efficiency and fully capitalize on the opportunities offered by both approaches. These paragraphs will focus on the positive effects generate by their convergence, while the detailed interaction at pillar level will be discussed in a following section. First, we will cover the concept of Lean as a foundation for Industry 4.0, later the enabling power of Industry 4.0 for a successful Lean Production, and lastly, some space will be given to their cumulative impact on operational performance.

Lean as a foundation for Industry 4.0

Some researchers claim that Lean Production represent the ideal premise for the implementation of Industry 4.0 technologies. This is most likely due to the alignment of LP and Industry 4.0 objectives, and the fact that digitalization can be viewed as a natural progression for the continuous improvement mindset characteristic of LP. Moreover, this concept of Kaizen, together with critical thinking, enables people to identify the most suitable solutions to solve complex problems. The idea is also supported by research based on surveys conducted by Rossini et al. (2019) on 108 European manufacturing firms, finding that companies with low or high adoption of I4.0 technologies also showed similar patterns in adopting Lean practices. The research also indicated that improved performance metrics are more closely linked to established Lean processes than to I4.0 technologies. The authors suggest that for companies aiming to enhance their operational performance, it is essential to first implement LP principles, solidify their processes, and then introduce I4.0. Following the idea of Nicoletti et al. (2013) that "the automation of an inefficient process does not make it efficient", it is paramount that before introducing new technologies, waste-free efficient processes are already put in place. Given that LM is based on stable and standardized processes and has the reduction of muda as one of its core value, it is easy to observe how Lean can facilitate the implementation of I4.0. A similar reasoning could be applied to streamlined production systems used in Lean environments, that lend themselves to be complemented by I4.0 technologies. An example is represented by IoT sensors that can be easily integrated to monitor machine performance and production metrics, thanks to the existing processes being already optimized for efficiency.

Industry 4.0 as an Enabler for Lean

A significant portion of literature is focused on the different ways in which Industry 4.0 supports LM, enhancing the effectiveness and operations of its practices (Rosin et al., 2019). In other words, LP practices are complemented by real-time functionality and their effectiveness is enhanced by technologies that improve company processes and support the core resources of lean, people. The reason for this relationship can still be attributed to the alignment of objectives between the two methodologies, as explained before. As an example of this goals correspondence, we need to go back to the first chapter, and rethink about the two pillars of Lean: Jidoka and JIT. To enable production efficiency and waste reduction by keeping low inventory levels and safety stocks, effective inventory data management is a requisite. A digitalized supply chain enabled by Industry 4.0 technologies can offer substantial support to successfully implement JIT. (Haynes, Helms, and Boothe, 1991; Zelbst et al., 2014). According to Sanders (2016), JIT is complemented by IIoT through tracking of materials and electronic tagging, which leads to reductions in lead time and optimization of processes. By integrating technologies like sensors and radio frequency identification tags, companies are able to monitor materials and inventory in real time, ensuring that they are delivered exactly when needed, further minimizing waste and delays.

Industry 4.0 also addresses traditional communication and bureaucratic challenges that Lean systems sometimes encounter. The implementation of CPS enables machines to communicate autonomously with one another and send feedback directly to suppliers and operators. This real-time communication ensures that adjustments are made promptly, whether it's redirecting production flows or addressing supply chain disruptions. Such connectivity increases transparency throughout the value chain, aligning with Lean principles of flow and *kaizen* (Kagermann et al., 2013).

Moreover, the *horizontal and vertical integration* of systems facilitated by Industry 4.0 allows for a more holistic view of operations across the entire value chain. Internal processes—from raw materials to finished goods—become more aligned and synchronized, reducing inefficiencies, thanks to vertical integration and the integration of data from multiple sources. At the same time, integration extends promotes enhanced collaboration between suppliers, manufacturers, and customers. This helps achieve Lean's ultimate objective of delivering greater value to the customer (Buer et al., 2018).

One of the key ways in which Industry 4.0 enhances Lean practices is through the use of *Big Data Analytics*. Identifying inefficiencies and bottlenecks within processes is a reliable starting point for continuous improvement. Big Data Analytics plays a critical role here by providing real-time insights into production performance, allowing companies to track key performance indicators (KPIs) such as cycle time, downtime, and machine utilization. This data-driven approach enables faster identification of problem areas enables teams to quickly adjust production schedules or resource allocation based on up-do-date information. The interconnectedness of machines and the real-time data generated through Big Data Analytics empowers companies to make faster, more informed decisions. These practices allow the firm to implement solutions more effectively, supporting Lean's goal of reducing waste and optimizing processes (Buer et al., 2018). At the same time, they lead to increases agility and allow for more responsive, data-driven decision-making (Kolberg & Zühlke, 2015).

Two other I4.0 technologies that closely align with Lean's focus on waste reductio and value maximization are automation and predictive maintenance. Lean seeks to eliminate non-value-adding activities, such as downtime, and to ensure that machines are running at optimal efficiency. According to Tortorella et al. (2018), a*utomation* supports this goal by reducing human error, speeding up production processes, and standardizing operations, leading to more consistent output and fewer defects. Through automation, companies optimize the flow of operations, with less idle time and waiting. On the other hand, predictive maintenance leverages data collected from sensors embedded in machines to monitor their real-time condition. In this way, firms can predict when equipment is likely to fail, and maintenance to be performed before a breakdown occurs. By reducing unplanned downtime and extending the lifespan of machines, predictive maintenance aligns with Lean's focus on minimizing waste, particularly in terms of equipment failures and repair times (Söderberg et al., 2017). This proactive approach directly supports the *Total Productive Maintenance (TPM)* principle, and the two practices combined enable companies to optimize machine performance and operational reliability, driving continuous improvement.

To conclude, we can say that by complementing Lean practices with advanced digital technologies, Industry 4.0 not only improves existing processes but also creates new opportunities for innovation and growth. The result is a more resilient, agile, and efficient production system that is well-positioned to succeed in an increasingly complex and dynamic manufacturing environment.

Effect of Lean-Industry 4.0 integration on Operational Performance

The integration of Industry 4.0 and LM practices has profound implications for improving operational performance in supply chain and manufacturing environments. By combining the principles of waste reduction, process efficiency, and continuous improvement from Lean with the advanced capabilities of Industry 4.0 technologies—such as real-time data analytics, automation, and predictive maintenance—organizations can achieve significant enhancements across key performance metrics, in particular productivity, the most targeted one. This allows for a more agile, responsive, and efficient operational framework, which has direct influence on various aspects of performance. This section will be dedicated to specific operational performance implications found in literature.

Buer et al. (2020) conducted a study showing how companies that combine together Lean and I4.0 practices tend to have better results in terms of operational performance compared to companies implementing Lean and I4.0 practices separately. In their own words: "The true operational performance advantage comes when both domains are implemented; in other words, their concurrent use produces a synergistic effect that is larger than the sum of their individual contributions." The result of their study is illustrated in the image below, in which the two scenarios can be observed.

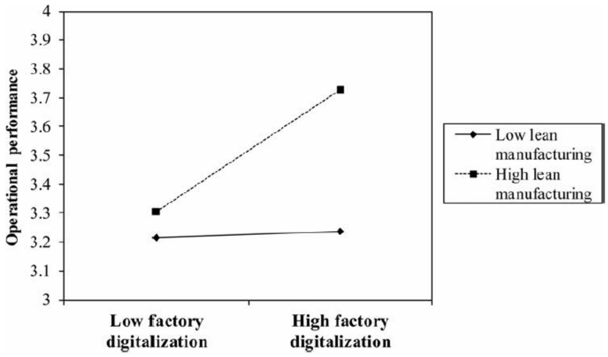


Figure 2: Interaction effect between lean manufacturing and factory digitalisation with lean manufacturing as the moderator

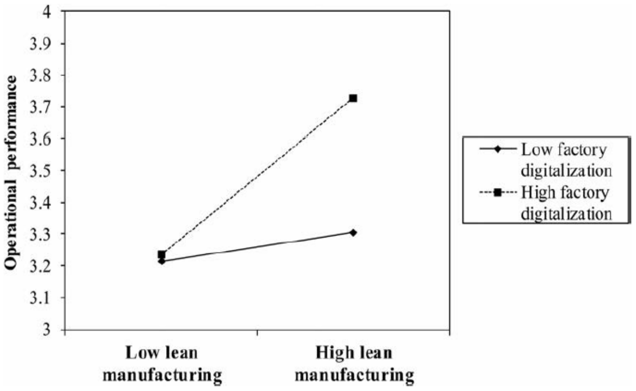


Figure 3: Interaction effect between lean manufacturing and factory digitalisation with factory digitalisation as the moderator

Source: Buer et al., 2020. The complementary effect of lean manufacturing and digitalisation on operational performance

The idea of Lean and I4.0 being mutually reinforcing was reaffirmed by Rafael et al. (2019) who conducted a study on the integration of Lean and Industry 4.0 in the Swiss manufacturing industry. To carry out the research, companies were grouped based on their maturity in both Lean practices and digitalization. The performance of these companies across several metrics was assessed: operational performance (relative performance in cost, quality, and delivery), financial performance (revenue, EBIT, market share), organizational culture, and continuous improvement efforts. The study highlighted how the combination of Lean and digitalization did not result in any conflict. On the contrary, it reinforced the idea of I4.0 as a support for LM, enhancing decision-making and process improvement. The outcome of this integration was a superior result in terms of both efficiency and adaptability.

In their 2021 study, Santos et al. adopted an empirical approach to demonstrate how the integration of Industry 4.0 technologies with Lean practices can significantly improve performance in different industries. The study explored six real-world cases from different sectors: automotive, paper, machine manufacturing, furniture, healthcare, and apparel. The integration was indagated across different levels of the value chains and technologies adopted. These case studies emphasize two key findings:

1. **Performance Benefits**: The integration of Lean with digital technologies enhanced operating performance and enabled companies to streamline their operations and respond more effectively to market demands.
2. **Context-Dependence**: The study stressed the importance of a deep, context-specific analysis before choosing which technologies to adopt. A tailored approach is required on the base of the industry and level of digitalization of the company. Moreover, not all I4.0 technologies fit every Lean process. This highlights how, before implementing digital solutions, companies must necessarily evaluate their unique characteristics.

Ultimately, the study shows that Lean and Industry 4.0 are not contradictory but can mutually reinforce each other, enhancing performance only when properly aligned to the specific context and value chain needs.

Tortorella et al. (2021) studied the difference in the level of Lean Automation implementation between manufacturing companies in emerging and developed countries. Survey-base research was conducted with 249 Brazilian (emerging economy) and Italian (developed economy) firms. The findings indicated that LA implementation is influenced by the socio-economic context in which companies operate. However, it was also shown that achieving higher levels of LA implementation is possible despite certain socio-economic barriers. Additionally, the factors contributing to successful LA implementation vary between emerging and developed economies, emphasizing the need for a deeper understanding of these distinct contexts.

The synergetic relationship between Lean and I.40 is also explained by the image below, where it can be observed how cost reductions can be achieved up to 40%. BCG (2017) also explained how costs related to poor quality could potentially be reduced by 20%, and costs related to WIP by 30% through the combined effect of Lean 4.0. In its article "*When Lean meets Industry 4.0 – The next level Operational Excellence" (2017),* BCG highlights how operational performance is enhanced across the five dimensions of flexibility, productivity, speed, quality, and safety.

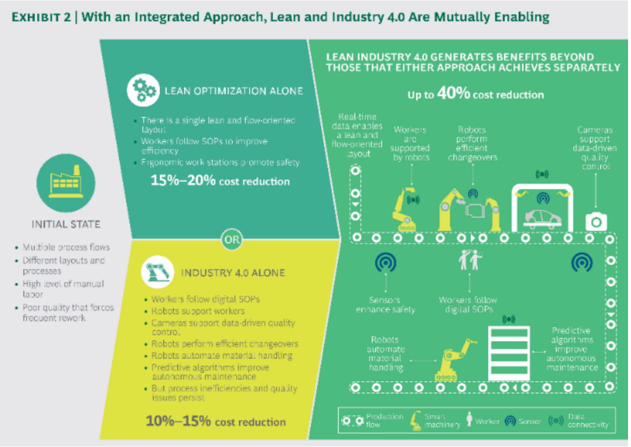


Figure 4: With an integrated approach, Lean and Industry 4.0 are mutually enabling

Source: BCG, 2017. When Lean meets Industry 4.0 – The next level of Operational Excellence

Three of these five dimensions were reaffirmed by Raji et al. (2021). Alongside cost, quality, and workplace safety, customer satisfaction was included in the KPIs that companies can expect to improve by investing and integrating digital technologies with lean practices. costs and lower overall production and inventory costs (Moeuf et al., 2017). Customer satisfaction was also indicated as a relevant KPI to measure operational performance by Tortorella et al. (2019), thanks to the ability of technologies like *IoT* and *real-time analytics* to enable better tracking and faster response to customer demand.

Similar results were achieved by a study conducted by Tortorella and Fettermann (2018) on the implications of I4.0 and LM in underdeveloped countries. 110 Brazilian manufacturing companies were used as base for the analysis and results showed clear benefits for operational performance. Indeed, significant improvements were found in key performance areas such as productivity, delivery service level, inventory management and workplace safety. Overall process efficiency and responsiveness of the manufacturing systems also showed clear improvement.

In the outstanding literature on integration between Lean and I4.0, increased flexibility was the most common reported performance benefit, followed by improved productivity, reduced cost, reduced delivery time, and improved quality (Moeuf et al., 2017).

Rossini et al. (2021) also indagated on the effects of integrating Lean Production and I4.0 on operational performance. A regression analysis included in their article *"Lean Production and Industry 4.0 Integration: How Lean Automation is Emerging in the Manufacturing Industry"* revealed that LA implementation explains about 37.8% of the variance in operational performance, demonstrating the significant role of integrating LP and Industry 4.0 in enhancing operational outcomes. Two primary LA bundles were identified:

1. **Operational Stability (OS) Bundle:** Focuses on improving upstream supply chain efficiency, reducing process variability, and increasing stability. It includes practices like Total Productive Maintenance and Supplier Feedback.
2. **Fast-to-Market (FtM) Bundle:** Enhances downstream supply chain speed and customer responsiveness through flow optimization and reduced setup times.

The research explained how both LA bundles contribute positively to operational performance improvements, particularly in areas such as productivity, delivery service levels, and quality. However, the OS bundle was found to have a more significant impact compared to the FtM bundle due to its focus on process stability.

Bauer et al. (2020) also demonstrated how LA can represent a competitive advantage for a company, since implementing simultaneously many elements of I4.0 and Lean can be difficult for competitors to imitate.

2.5. Synergies between Lean and I4.0 at pillar level

Having explored the mutual benefits of integrating Lean principles with I4.0 technologies, demonstrating how the combination can significantly enhance operational efficiency, minimize waste, and improve responsiveness, we can now focus on their synergetic relationship at pillar levels. This paragraph will provide deeper insights on how specific practices of Lean interact with key Industry 4.0 technologies. The interaction between founding pillars of Lean and I4.0 will be examined, illustrating how the resulting synergies contribute to create a more adaptive, efficient, and data-driven production environment.

Going back to chapter one, we saw how the pillars of Lean include Just-In-Time (JIT), Jidoka, stability and standardization, and respect for people. Each of these pillars has its unique contribution to improving production efficiency and reducing waste. At the beginning of this chapter, instead, we have identified IIoT, Big Data and Analytics, CPS, Autonomous Robots and others as the pillar technologies of Industry 4.0.

Analysing several studies, JIT was found to have the largest weight of synergy with I4.0 pillars (Kassem et al., 2024). Its focus on minimizing inventory and ensuring a prompt delivery is particularly significant in interaction with IIoT, which enables real-time tracking and data collection. The synergy created among the two practices allows for a better synchronization across supply chains and helps maintain lean inventory levels. This revolutionary contribution of IIoT also explains how it is the pillar of I4.0 showing the largest weight of synergy with LP pillars. JIT also shows great correspondence with Big Data and Analytics, that enhance the scheduling and planning capabilities typical of *Heijunka (levelling),* enabling the company to be more reactive to unforeseen changes in demand and production. Lastly, JIT was found to interact significantly also with autonomous robots, a powerful tool to increase flexibility and agility to assembly processes, and simulation, particularly useful for the identification of bottlenecks in production processes and for the improvements of the results achieved with Value Stream Mapping. As it can be seen in figure 4, the synergies created by JIT are mostly reflected in improvements in productivity, but also benefit costs, quality and time in a significant manner.

Jidoka is the second pillar exhibiting significant interaction with Industry 4.0 technologies. Given its inherent focus on automation and quality control, integrating it with IIoT technologies is a natural progression. This integration occurs through both sensors and smart devices, which are among the main developments of IIoT. Sensors, when embedded in machines, have a fundamental role in preventing mistakes and breakages, monitoring processes and detecting defects in real-time. Smart devices, on the other hand, notify operators instantly, regardless of their physical location. This technology significantly reduces the time between the occurrence of the failure and its notification. The synergy created between Jidoka and IIoT mainly results in improved overall efficiency and product quality.

The other two pillars of Lean indagated by Kassem et al., “stability and standardization”, and “respect for people” were found to have a smaller level of interaction with I4.0 pillars. However, they interact with all I4.0 pillars equally. In particular, respect for people is fostered by the introduction of collaborative robots, that can relieve workers from performing repetitive tasks, and by the introduction of Cloud Computing, a useful tool to facilitate the communication along the value chain. Collaborative robots are also a powerful tool in the standardization of work procedures. Lastly, stability is supported by CPS, thanks to which machines are able to monitor themselves and communicate with each other to ensure a smooth and standardized production process.

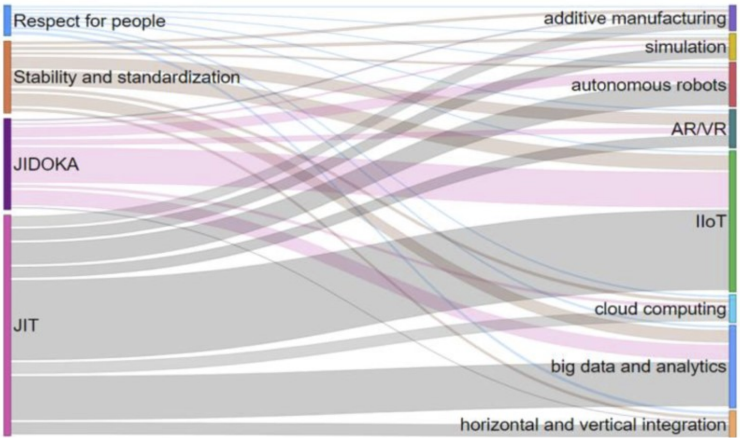


Figure 5: LP and I4.0 interaction

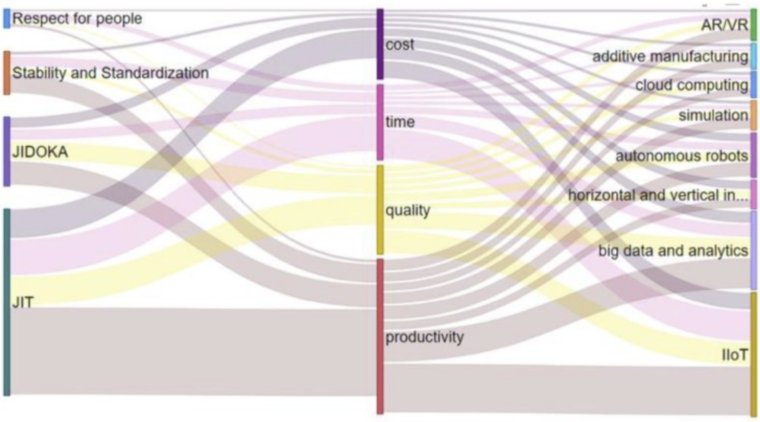


Figure 6: LP and I4.0 interaction on operational performance

Source: Kassem et al., 2024. Lean 4.0: a systematic literature review on the interaction between lean production and industry 4.0 pillars

After having explored the main synergies created by the integration of Lean and I4.0 pillars, it must be said how the research on this topic is still limited. In fact, most of the studies have a strong conceptual focus and lack empirical validation. Moreover, research was carried out mainly in a qualitative way, with very few evidence of quantitative improvements on operational performance. Therefore, further empirical and quantitative research is needed to fully understand the potential of integrating Lean and Industry 4.0 technologies.

2.6. Theoretical Frameworks and Models for Lean-Industry 4.0 Integration

The integration of Lean manufacturing principles with Industry 4.0 technologies has led to the development of several theoretical frameworks and models attempting to provide a path for their combined implementation. These models typically aim to align the waste-reduction focus of Lean with the advanced technological capabilities of Industry 4.0. However, the existing literature remains limited, with most models being theoretical rather than empirically validated. Furthermore, these frameworks are often too general to offer concrete guidance, leaving practical applications underdeveloped and rarely explored in real-world settings. As a result, while the potential synergies are well-documented, there is a clear need for more specific and applied frameworks to bridge this gap. In this section, we will review some of these models in chronological order.

Sony et al. (2018) developed a theoretical model for the integration of LA in their article *"Industry 4.0 and Lean Management: A Proposed Integration Model and Research Propositions"*. In the article, three types of integration are proposed:

1. **Vertical Integration:** Connecting all hierarchical subsystems within an organization for a more flexible and reconfigurable manufacturing.
2. **Horizontal Integration:** Promoting collaboration across organizations in the supply chain for improved efficiency and value creation.
3. **End-to-End Engineering Integration:** Starting from the analysis of customer needs, creating customized products and services using CPS.

The study also proposed 15 research propositions to guide future empirical studies on the integration of LM and Industry 4.0, such as using Lean principles to optimize integration mechanisms and ensuring continuous improvement.

Similar studies were previously conducted and tries to provide a roadmap for both researchers and firms to explore and implement this integration. However, they were still too general to provide concrete implementation practices contingent on organizations' unique circumstances. The following frameworks, developed in the last two years, try to fill this gap and provide concrete guidance for firms wanting to enter a Lean Automation journey.

In 2024, Manjallore et at. conducted a study on the integration of Lean and I4.0 in SMEs, with a particular focus on the Indian context. The authors presented a conceptual framework, known as the “Shuriken Framework," designed to help SMEs to implement Lean and I4.0 approaches together.

While the benefits of both Lean practices and I4.0 technologies are well-demonstrated, Indian SMEs often struggle with their implementation due to limited resources and knowledge, as well as lack of expertise. These impediments, typical of emerging economies, are addressed in the proposed framework as the core tenets, needed to enable the integration.

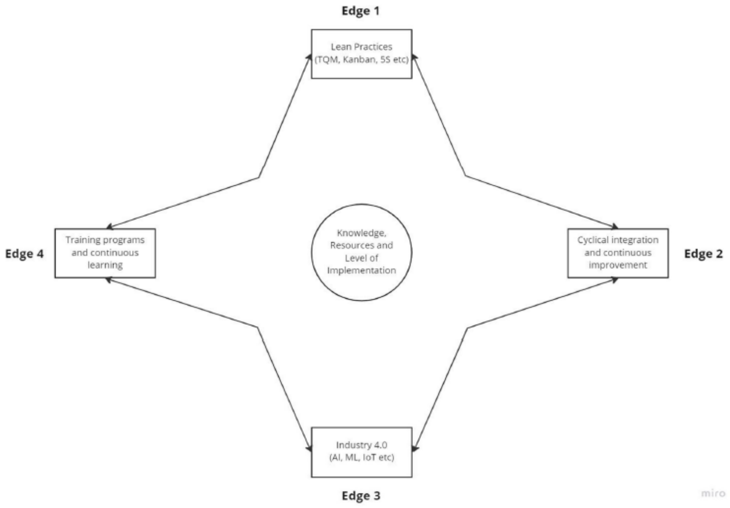


Figure 7: Conceptual model of integration between Lean and I4.0

Source: Manjallore et al., 2024. Conceptual Framework for Lean and Industry 4.0 Implementation in SMEs (Shuriken Framework)

The Shuriken Framework includes three core tenets:

1. **Knowledge**: Employees must possess the necessary understanding of Lean and Industry 4.0 and use this knowledge to effectively guide and implement the systems.

2. **Resources**: SMEs need both the required financial resources to buy the technologies and tools, and the human resources to implement them.
3. **Level of Implementation**: This involves assessing the current state of technology and Lean practices within an organization to tailor the framework's application.

Additionally, the framework emphasizes the importance of continuous learning and improvement, concepts derived from the Agile Methodology. Lean practices must be added in increments within each process, so that employees have time to get familiar with them, and regular meetings to discuss feedback are organized. Indeed, to ensure the proper implementation of practices, a culture of retrospection must be promoted by the company.

On the other hand, the lack of knowledge can be filled by fostering a culture of continuous learning. Training programmes must be financed, in order for employees to expand their existing skills and develop new ones. The end result should be a cross-functional team filled with domain experts.

Different ways of implementing the framework lead to different social and environmental implications. Regardless of specific contexts, the most common ones are:

- **Job Displacement**: The implementation of Lean and I4.0 could eliminate or automate some tasks, leading to job displacement. At the same time, however, new roles could emerge in the fields like data analysis.
- **Skill Development**: The need for employees to develop new skills can be an opportunity for career advancement. However, some employees may be unwilling or unable to learn, leading to the presence of skills gaps within the workforce.
- **Inequality:** Organizations must consider the aspect of inequality, that could emerge in the workforce, particularly for individuals having difficulties to adapt to the new technologies or for groups that are more likely to be exposed to job displacement.

The adoption of this framework could provide substantial help for SMEs to bridge the existing hindrances between technology availability and practical implementation of LA, to drive efficiency, productivity and competitiveness.

Another valuable contribution for the integration of Lean and I4.0 in SMEs of emerging countries was provided by Vargaset al. (2023) in their article *"A Framework for the Prioritization of Industry 4.0 and Lean Manufacturing Technologies Based on Network Theory"*. The data-based framework proposed is designed to assist manufacturing firms in adopting both Lean and I4.0 technologies, is cantered on network theory and applies practical visualization tools to support decision-making. Network theory is used to analyse technology adoption patterns, providing visual representations known as "technology networks." These networks reveal the relationships and co-adoption trends of different manufacturing technologies, revealing how certain technologies are more commonly adopted together across six industrial segments (e.g., vehicles, food, clothing).

The technical functioning of network theory will not be explored, as it is beyond the scope of this thesis, however its application represents a powerful tool for companies to visualize and prioritize technology adoption. It simplifies complex decision-making processes by providing clear, data-driven insights into which technologies to invest in, based on existing adoption rates and industry trends. The framework is particularly suitable for SMEs, offering a structured approach to face the complex integration between Lean and I4.0 for companies usually having limited resources. However, the framework could also be applied and useful to larger organizations, thanks to its customizable and practical nature. Like said before, it can be applied to multiple industries, for companies of different sizes and with different levels of technological maturity. The data collection approach also enables to take decision on the base of the firm's specific circumstances.

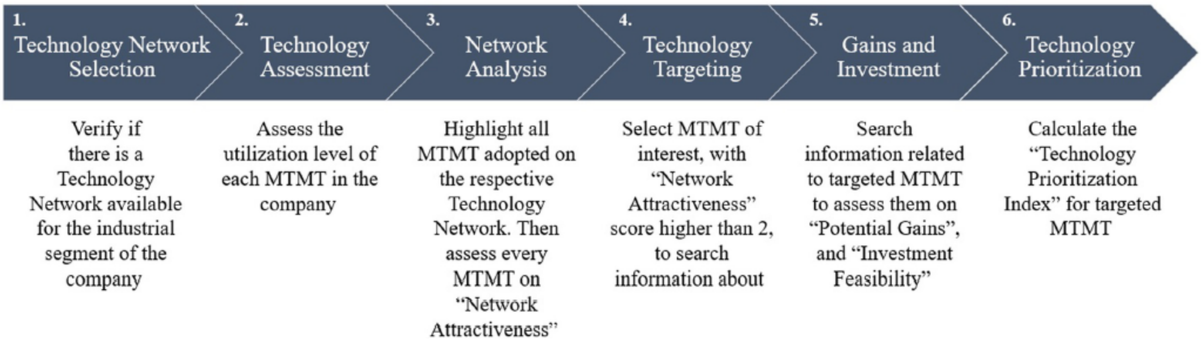


Figure 8: Framework for the prioritization of manufacturing technologies, methods and tools (MTMT)

Source: Vargas, 2023. A framework for the prioritization of industry 4.0 and lean manufacturing technologies based on network theory

Komkowski et al. (2024) explored the integration of LM with I4.0 using a Dynamic Capabilities (DC) model, which focuses on how companies integrate, adapt, and reconfigure their internal and external competencies to face dynamic environments. The study was grounded in empirical research based on a survey conducted among 256 experts of German manufacturing companies. The aim of the research was to provide a comprehensive operational framework designed to guide firms in executing this integration effectively. The framework uses the DC model, which focuses on how organizations adapt, integrate, and reconfigure their internal and external competencies to meet changing environmental demands.

The framework validates 43 practices organized into six core dimensions: initiating, sensing, seizing, transforming, resources, and capabilities.

- **Initiating** represents a novel contribution to the DC theory and includes the early-stage practices that trigger and streamline the subsequent phases of integration. This dimension emphasizes the need for setting target states, developing long-term principles, and strong leadership engagement. An internal momentum should be created as to facilitate the occurrence of later stages, helping the firm visualise change before it fully engages in it.
- The **sensing** dimension focuses on the organization's ability to identify opportunities and changes in both the external and internal environments. The framework highlights the importance of complementing traditional external monitoring (e.g., market trends) with internal reflections (e.g., employee interviews).
- **Seizing** refers to the firm's capacity to act upon opportunities identified during the sensing phase. In this framework, seizing is split into two categories: *governance* (promoting communication of progress, leadership involvement, and fostering a training culture) and *transparency* (monitoring progress through KPIs and reporting systems).
- The dimension of **transforming** focuses on the firm's ability to reconfigure its processes and resources to realize the changes captured in the earlier stages. The transforming dimension is further divided into two sub-categories: *execution* (e.g., using digital tools and alternating implementation steps between LM and I4.0 technologies) and *culture and change management* (e.g., fostering continuous improvement and workforce involvement).
- The **resources** dimension highlights the importance of allocating dedicated resources for continuous development, such as forming dedicated change teams and exploit external expertise. These resources ensure that the integration is sustainable, and that critical skills and tools are available for successful implementation.
- **Capabilities** represent the final dimension emphasizes the importance of developing the leadership's ability to promote openness to new practices, along with their foundational understanding of LM and I4.0. The necessity of training at all levels of the organization is also stressed, to ensure complete adaptability to the implementation of new integrated practices.

In other words, the study stresses the importance of early planning for a successful implementation of LP and I4.0. Effective governance and monitoring systems shall be put in place to track progress with measurable metrics. Cultural readiness, including employee involvement and digital knowledge, enables Lean and I4.0 to be understood and supported across all levels of the organization. Lastly, a strong leadership and dedicated resources are key to sustaining these efforts and driving innovation.

In conclusion, this framework represents a valuable tool in the field of Operations Management as it provides empirical evidence on essential practices for effectively integrating Lean with Industry 4.0. Additionally, the research accentuates the significance of Dynamic Capabilities as a mean to comprehend and manage the complex relationship between these two approaches.

2.7. Conclusions

In this chapter, we have seen how the integration of Lean principles with Industry 4.0 technologies has a great potential for modern manufacturing. By leveraging technologies like the IIoT, Big Data, and Cyber-Physical Systems (CPS), Lean practices such as JIT, Jidoka, and Kaizen can reach new levels of efficiency and flexibility. Different views of the relationship between the two practices have been explored, considering both the perspective of Lean Manufacturing as a necessary premise for digitalization and of Industry 4.0 as a way to further exploit the benefits of Lean. Operational performance implications have also been indagated. Synergetic interaction at pillar level have also been highlighted. JIT, for example, benefits from IoT's capacity to track inventory and production in real time, reducing waste and increasing supply chain synchronization. Jidoka is amplified by smart sensors and devices that enable immediate defect detection, improving product quality and reducing downtime. Similarly, Kaizen is enriched by Big Data and predictive analytics, which allow for quicker identification of process inefficiencies and the acceleration of continuous improvement initiatives.

These synergies, however, do not come without challenges. The literature review identified several key challenges to the implementation of LA. One significant finding is the presence of *paradoxical tensions*, particularly in the coexistence of Lean's simplicity and human-driven improvements with the complexity and automation of Industry 4.0 technologies. This challenge is particularly evident in the context of workforce readiness and organizational resistance to technological change. Similarly, *dialectical tensions* arise in the interaction between human workers and machines, such as the tension between robotized versus humanized automation, where new technologies could marginalize workers while simultaneously enhancing production efficiency.

Moreover, while some Lean pillars show clear, mutually beneficial relationships with I4.0 technologies, other pillars such as "Respect for People" and "Stability and Standardization" exhibit more limited, less obvious interactions. These areas require further exploration to uncover how innovative technologies can support Lean's goals of stability, standardization, and human-centered work environments. Further research should also be conducted on frameworks for the practical implementation of Lean Automation, some of which have been presented in this review. These frameworks provide valuable guidance for companies seeking to navigate the complex journey of integrating Lean and Industry 4.0 technologies but remain underdeveloped in terms of empirical validation and industry-specific applications.

Lastly, the literature review also addressed the gap in empirical evidence. Despite the theoretical benefits regarding the integration of Lean and Industry 4.0, there is a lack of quantitative research measuring the operational performance improvements that result from this integration. The potential gains from automation and digitalization have been thoroughly analysed (Tortorella et al., 2021) but no concrete financial data has been provided. For instance, Gangaraju et al. (2023) point to operational benefits like improved delivery performance and customer waiting time but fails to show numerical effects on operational performance metrics. In the following chapter, we seek to fill this gap by examining the impact of different configurations of Lean practices and I4.0 technologies on financial outcomes.

3. EMPIRICAL ANALYSIS: METHODS

3.1. Research question

The previous chapters covered the concepts and main uses of application of Lean Production and Industry 4.0. As anticipated, an analysis of the existing literature suggests a synergistic relationship between the two practices. However, a significant gap remains due to the lack of empirical evidence supporting this theory. With this study, we aim to address this issue, as well as challenge the widespread assumption that integrating all types of Industry 4.0 technologies with Lean practices automatically leads to positive financial results. Indeed, we argue that many organizations continue to face challenges in implementing I4.0 (Forth et al., 2020) due to an insufficient knowledge on how to effectively align specific combinations of Lean practices with I4.0 technologies. In the rest of the thesis, these specific combinations will be addressed as “bundles”. The breakdown of the bundles will be explained in 3.2.1.

Therefore, the goal of this study is to measure how different bundles of lean and I4.0 technologies can match to produce an impact on financial performance. To do this, we used a survey investigating the levels of adoption of such practices and linked them with financial data from different firms.

The first necessary step is to consider the managerial aspects adopted within companies. Indeed, as explained in Chapter 2, Lean production can enable the development of Industry 4.0 while maintaining its primary focus on achieving high performance. In this thesis, performance is measured using Return on Assets (ROA).

After having assessed the level of operational excellence, the degree of technological adoption must be indagated. By examining different dimensions of Industry 4.0, we aim to gain knowledge of how well digital technologies are implemented, creating a foundation for more effectively analyse their financial impact, especially in combination with Lean practices.

Connecting the dots, our aim is to understand how a firm can get the best out of these two practices, and which are the most potentially profitable configurations to have a higher ROA.

Consequently, the research question is: which are the configurations of Lean practices and digital technologies than lead to superior performance?

The integration between I4.0 and Lean production is still a fresh topic to indagate, and results are not always observable yet. However, it is possible to analyse how current companies combine various elements of this new approach, and whether they are performing as expected.

The idea behind this analysis is to break down Lean management and I4.0 technologies into different components (bundles) and see how they can be combined to achieve superior performance. In this way, the integration between Lean and I4.0 is approached from a critical point of view. Studying different companies allows us to identify the most effective cases of integration, and at the same time highlight instances where the proposed principles fail to enhance operational performance. This approach uncovers the limitations and raises questions about the overall effectiveness of integrating these two practices.

3.1.1. Qualitative Comparative Analysis

To address the research question proposed, Qualitative Comparative Analysis (QCA) was identified as the most appropriate methodology, due to its hybrid nature combining qualitative and quantitative approaches. QCA allows to capture and analyse the relationships between various combinations and levels of condition implementation for a given outcome (Ragin, 2008). To analyse phenomena, a contemporary configurational approach (Fainshmidt et al., 2020) is used, breaking down a scenario into its constituent attributes or causal conditions. Cases – derived from the various attribute combinations – are described by a membership score based on their degree of belonging to each causal condition.

In this study, cases refer to firms. They are characterized as sets of conditions that drive the outcome, in this thesis financial performance. Each case – firm – is described by the absence or presence of each of the conditions identified, scored from full membership to non-membership. Through this process, several configurations can be identified. According to Meyer et al. (1993), they are the combinations of conditions that are minimally required and/or sufficient to produce a specific outcome.

In contrast with regression models, which are suitable to evaluate the net impact of a single variable on an outcome, QCA operates on the principle of conjunctural causation. This implies that it is not possible to isolate the influence of a condition on an outcome because its effect depends on how it interacts with other conditions. In other words, a condition that generates the desired outcome in a configuration might have a different (or null) effect when considered in isolation (Ragin, 2008). This feature allows to better explore the complex interdependencies among different causal conditions (Fiss, 2007).

Qualitative Comparative Analysis is particularly effective for studying phenomena in which multiple aspects work together to create or not create an outcome, rather than attributing causality to a single variable. The focus is on identifying which are the configurations that lead to an outcome. It does not permit to identify whether – among the different conditions – there is one with the strongest correlation to the outcome.

A key feature of QCA is the assumption of equifinality. This acknowledges that there are multiple paths to achieve the same outcome, none inherently more effective than the others. This allows researchers to better account for the complexity of causal relationships within social phenomena (Bell et al., 2014) and the differences across configurations in a detailed way, defining the relevance of an attribute based on how it combines with others.

Qualitative Comparative Analysis also considers asymmetrical relationships. This means that if a particular configuration results in an outcome, this does not imply that the absence of the same configuration leads to the absence of the same outcome (Woodside, 2013).

The choice of QCA as a suitable approach is also explained by the two following reasons. First, while it can accommodate very large sample sizes (e.g., Witt & Jackson, 2016), it was originally developed for use with small sample sizes, far below those required for standard regression analysis. QCA is generally suitable for sample sizes of 12 or more, with the minimum size depending on the number of causal conditions in the model (Marx, 2006). For instance, QCA with four causal conditions requires a minimum sample size of 12, while models with seven causal conditions need a sample size of around 30 (Marx, 2006).

On a second note, performing a QCA allows to use a small number of causal conditions, since it avoids omitted variable bias, unlike regression analysis. Indeed, in regression analysis, omitting relevant independent variables reduces explanatory power and, if the missing variable is correlated with those included, biases the estimates by absorbing part of the missing variable's effect. In QCA, excluding a relevant condition may reduce the model's explanatory power but does not result in an omitted variable bias, as it relies on Boolean algebra rather than correlations. This means QCA does not require control variables, a point that is essential for readers evaluating QCA-based studies (Fainshmidt, 2020).

This approach, therefore, is well-suited to investigate all possible combinations of Lean practices and I4.0 technologies that improve operational performance.

QCA is rooted in Boolean algebra, which enables binary analysis of numbers. There are two types of qualitative comparative analysis: crisp set QCA and fuzzy set QCA. The Crisp set uses dichotomous variables to denote the presence or absence of a condition in each configuration. If the value is present, a value of 1 is associated; on the contrary, in case of absence, the value associated is 0. In contrast, the fuzzy set QCA incorporates fuzzy set theory (Zadeh, 1965), allowing for a continuous measurement of each condition's degree of presence, ranging from 0 to 1. To answer the research question of this thesis, a fuzzy set qualitative comparative analysis was used.

The result is a set of configurations that lead to an outcome. To evaluate the quality of these solutions, two main measures are used: coverage and consistency, both ranging from 0 to 1.

Coverage assesses how well the configurations account for the observed outcomes (Ragin, 2006), their empirical relevance. Essentially, it assesses the likelihood that repeating the analysis with different data on the same conditions would yield similar configurations to those already identified. This measure can be interpreted similarly as the coefficient of determination (r^2) in statistical analysis (Woodside, 2013). Since more than one configuration can lead to the same outcome, raw coverage indicates the extent of empirical overlap of conditions across different configurations associated with the same outcome, while unique coverage informs on the relative importance of each particular configuration associated with the same outcome (Fiss, 2007). In QCA, coverage is determined by comparing the number of pathways leading to the identified solution with the total number of possible configurations across all conditions. For the sufficient relationship, the coverage value can be calculated as follow:

$$Coverage\ (Xi \leq Yi) = \frac{\sum(\min(Xi, Yi))}{\sum(Xi)}$$

where “min” represents the lower of the two values, Xi indicates the membership scores in a configuration of conditions and Yi represents the membership scores in the outcome. The formula also explains how coverage for inconsistent results is not a significant indicator (Schneider & Wagemann; 2007).

Consistency refers to “the degree to which instances of an outcome agree in displaying the causal condition” (Ragin, 2008). In other words, it explains the degree to which the terms of the solution and the solution as a whole are subsets of the result (Ragin, 2006). In fuzzy set theory, a subset relationship exists when the membership scores of one set (i.e. a condition or a combination of conditions) are consistently lower or equal to the membership scores of another set (i.e. the outcome) (Zadeh, 1965). As explained before, the membership score is the value between 0 and 1 that indicate the degree to which a condition is present in an observed configuration. For instance, if the membership scores for a combination of conditions are consistently less than or equal to their corresponding scores in the outcome, a subset relationship is indicated. This supports a sufficiency claim. Consistency thus quantifies this subset relationship by measuring how sufficient a condition or configuration is in producing the outcome, showing the connection between cause and outcome. A consistency score of 1, for instance, would indicate that whenever the outcome is observed, the condition is also present.

The following formula can be used to calculate the consistency measure for the sufficiency relationship.

$$Consistency\ (Xi \leq Yi) = \frac{\sum(\min(Xi, Yi))}{\sum(Xi)}$$

where “min” represents the lower of the two values, Xi indicates the membership scores in a configuration of conditions and Yi represents the membership scores in the outcome.

In summary, consistency indicates how effectively a solution leads to the outcome, while coverage reflects the solution’s empirical relevance, showing the likelihood of achieving the same result if the experiment is repeated. While a higher level of coverage is generally better, there is no universally accepted minimum threshold that a QCA must meet for the results to be considered valid (Fainshmidt et al., 2020). On the contrary, the consensus seems to be that consistency levels should at least be ‘0.75’ or higher (Ragin, 2008).

3.2. Data Collection

The sample for this analysis consists of manufacturing firms located in Northern Italy, a highly industrialized region housing more than 30 percent of Italy’s manufacturing firms. The choice was driven by geographical proximity. This allowed for a continuous exchange of data and information fundamental for the construction of the dataset. The dataset is composed of data obtained through surveys carried out on some manufacturing companies in northern Italy between November 2023 and October 2024.

3.2.1. Structure of the surveys

The purpose of this analysis is to study how practices of Lean Production and adoption of digital technologies can be combined within companies in order to identify the superior performing configurations.

The first step is to isolate each element individually to assess and quantify the extent to which each condition is present within a firm. The two elements of Lean Production and Industry 4.0 technologies were divided into their own sub-categories. Each of these sub-categories – bundles – was indagated and measured through a series of questions contained in a survey. Therefore, the first section of the survey concerned the level of Lean practices utilized by the company, while the second section aimed to rate the level of adoption of digital technologies.

Both sections consist of a series of statements. For each statement, respondents were asked to indicate their degree of agreement on a 7-point Likert scale, where 1 represents complete disagreement, 7 represents complete agreement, and 4 represents indifference.

The time to complete the survey is approximately 15 minutes, and a general understanding of the managerial practices and technologies adopted in the plant is required to answer accurately. The language of the questions is precise, with many statements focusing on the adoption of specific techniques.

The survey begins with some demographic questions, such as identifying the average age of employees, the type of production process of the firm (choosing between one-piece flow, small batch production, and large batch production), and the percentage of Italian workers.

The first section, dedicated to operational excellence, starts with some questions on Total Quality Management (TQM) practices, exploring the use of Andon boards within departments, quality measurement practices employed by managers, and the extent of statistical analysis used for these measurements.

The second causal condition studied within operational excellence is Just-in-Time (JIT), a prominent lean management practice. This section examines the adoption of pull production logic, the use of kanban systems, delivery punctuality, and supply chain relationships, aiming to evaluate the company's progress toward a lean, flexible, demand-driven production system.

Total Productive Maintenance (TPM) is the third and last condition analysed in the operational excellence section. The questions address fault analysis, equipment upgrades, and the inspection and monitoring of equipment conditions.

The second part of the survey explores the adoption of digital technologies, with a table assessing the use of advanced technologies like collaborative robots, 3D printing, IoT, and virtual/augmented reality. Questions also examine the digital integration of processes both within the company and with the supply chain, along with the use of nanotechnology and adaptive materials. This section further investigates digital management systems, including ERP, MES, general digital infrastructure, and cloud data storage. Additionally, the survey assesses advanced logistics technologies used in procurement, including RFID, GIS, and GPS, which support optimized product tracking in logistics operations. It also examines the application of artificial intelligence algorithms and human-machine interfaces.

Each of these conditions was measured using a range of statements derived from validated questionnaires. This research is inspired by prior work by Andrea Furlan and Ambra Galeazzo (Furlan et al., 2019; Galeazzo & Furlan, 2018), who analysed these elements separately. A clearer breakdown of the survey sections, alongside examples of the statements, can be seen in Table 1, while the reasoning behind the choice of causal conditions is explained in Chapter 4.

Dimension	Construct Element	Examples of item-questions	Studies
Lean Bundles	Total Quality Management (TQM)	• Information on quality levels is provided to staff in a timely manner • The production processes in our plant are designed to avoid errors	Galeazzo & Furlan, 2018
	Just-In-Time (JIT)	• Our suppliers operate by filling our containers (kanban), rather than by purchasing orders. • Our customers receive "just in time" deliveries from us	
	Total Productive Maintenance (TPM)	• Workers understand the cause and effect of equipment deterioration. • We estimate the lifespan of our equipment, so we can plan for repair or replacement.	
I4.0 Bundles	Data acquisition and processing technologies (T1)	• Level of adoption of Industrial Internet of Things (IIoT)? • Level of adoption of Big Data and Analytics?	Benitez et al., 2020 Cifone et al., 2021 Tortorella et al., 2019
	Integrated communication technologies (T2)	• Level of adoption of Vertical Integration? • Level of adoption Horizontal Integration?	
	Human-Machine interaction technologies (T3)	• Level of adoption of Collaborative robots (cobots)? • Level of adoption of 3D printing (Additive Manufacturing)?	

Table 1:Construct element and items used to measure lean and I4.0 technologies

Source: Acqui-Caceres M., Furlan A. (2024), "Industry 4.0 technologies and lean: a configurational approach", Euroma Conference 2024

3.2.2. Sample composition

To obtain the required data for the qualitative comparative analysis, we focused on firms that adopt lean manufacturing practices. Additionally, to evaluate the configurations generated by the QCA from a performance perspective, it was deemed useful to select companies with a single production plant. Around 30 manufacturing firms were contacted by email and phone to assess their willingness to participate. In total, 17 firms agreed to take part in the research project. This number is in line with the requirements for a QCA analysis; it is not necessary to have a big sample in order to obtain significant results. The sample obtained can be seen is Table 1.

Data was collected by using an assessment tool in the form of a survey completed by plant managers or supervisors. This questionnaire evaluates the maturity level of I4.0 technologies and lean practices adoption. To minimize response bias and ensure content validity, the companies were asked to identify two plant managers or supervisors – who had at least one-year working experience working in those positions – to fill in the questionnaires. This allowed for the verification of the information provided by one respondent through the answer of the second one. Secondary data on financial performance metrics was collected from the AIDA database (developed by Bureau Van Dijk with information on around 300.000 Italian firms).

Firm	NACE code	Sector	No. of respondents	No. of employees	Average age of employees	Revenues 2022 (mln $)	Type of production
Firm 1	1623	Manufacture of other builders' carpentry and joinery	2	33	31-45	8,59	Small batch
Firm 2	1330	Finishing of textiles	2	25	31-45	4,79	Small Batch
Firm 3	1320	Weaving of textiles	2	63	46-60	13,41	Small Batch
Firm 4	1310	Preparation and spinning of textiles fibres	2	69	46-60	12,33	Small Batch
Firm 5	2562	Machining	2	15	31-45	2,82	Small Batch
Firm 6	1320	Weaving of textiles	2	71	46-60	15,37	Small Batch
Firm 7	2893	Manufacture of machinery for food, beverage and tobacco processing	2	104	31-45	25,32	One-piece Flow
Firm 8	3100	Manufacture of furniture	2	71	31-45	13,79	One-piece Flow
Firm 9	1061	Manufacture of grain mill products	2	31	31-45	11,8	Large Batch
Firm 10	3101	Manufacture of office and shop furniture	2	36	31-45	8,57	Small Batch
Firm 11	2751	Manufacture of domestic electric appliances	2	844	31-45	452,24	Small Batch
Firm 12	2821	Manufacture of kilns, furnaces and burners	2	25	31-45	7,69	One-piece Flow
Firm 13	2511	Manufacture of metal structures and parts of structures	2	70	31-45	17,24	Small Batch
Firm 14	2894	Manufacture of equipment and machines for laundries	2	131	31-45	40,67	One-piece Flow
Firm 15	4321	Installation of electrical systems in buildings or other building works	2	36	31-45	5,4	Small Batch
Firm 16	1520	Manufacture of footwear	2	31	31-45	4,3	Small Batch
Firm 17	2611	Manufacture of electronic components	2	12	46-60	2,62	Small Batch

Table 2: Sample composition

3.2.3. Performance Outcomes

As anticipated before, this research project aims to evaluate configurations based on performance; specifically, to identify fits and misfits between Lean practices and Industry 4.0 technologies. For these practices to be valuable for entrepreneurs, they must demonstrate profitability, making financial performance an essential measure in this context.

Given the inclusion of operational excellence practices among the variables, ideal financial indicators for this thesis would be those influenced by such practices. Some studies have suggested that – when mitigating specific contingencies – lean practices have a positive impact on ROA (Return On Assets). Indeed, companies adopting operational excellence practices often show higher ROA compared to non-adopters (York & Miree, 2004; Demeter & Matyusz, 2011; Hofer et al., 2012; Swink & Jacobs, 2012). Moreover, Yu (2022), in a systematic review, concludes that ROA is the most commonly used measure of firm performance in the literature. For these reasons, the ROA index is used as a performance indicator in this study. The ROA value for each company was acquired thanks to the AIDA databased, using the formula: "net income over total assets".

We considered the average ROA for the last three years for each company. This value was then normalized according to the average ROA of the relevant sector. Firms were assigned to sectors based on their European NACE code (codes were obtained from the AIDA database).

This approach, called calibration, allowed for a comparison of ROA values across companies in different sectors, without considering structural differences inherent to each industry. This issue is further explored in section 3.4.

3.3. Preliminary Analysis

A preliminary analysis was carried out on the data gathered through the surveys. The first step was to create a database containing all the companies' responses, with each statement corresponding to a score between 1 and 7. As explained before, said score represents the respondent's level of agreement with each statement.

To convert the score of each causal condition into the format required for the fsQCA, it is necessary for each condition to be associated with a unique value for each company in the sample, resulting in a dataset where the 17 companies are each assigned a single value for every condition indagated.

To achieve this, multiple-item scales for each condition were aggregated at the firm level by averaging the score of the two respondents from the same firm, following established theoretical foundations and empirical research (Galeazzo and Furlan, 2018).

Before proceeding, it is necessary to ensure that the average value accurately represents the survey data. This can be done through a consistency analysis. In our case of average, consistency means that even if we increase the sample size used for calculation, it continues to reliably reflect the population.

Since the survey gathered objective data on the presence or absence of specific lean practices and digital technologies within each firm, a "true value" should exist, one that ideally both respondents for each company would select independently.

To evaluate the level of agreement between the two respondents we used an inter-rater reliability index, which can be assessed in several ways. For the purpose of this thesis, we selected the intraclass correlation coefficient (ICC) as the consensus index. Specifically, the ICC measures the similarity between responses given by two individuals, making it well-suited for continuous data. A threshold of 0.6 (Cicchetti, 1994) was applied to determine an acceptable level of consistency in the responses.

Database internal consistency was further assessed using Cronbach's alpha (α) with a minimum threshold of 0.7 (Hair et al., 2006). This indicator measures the correlation between various items related to the same condition. In this study, Cronbach's alpha was calculated for each condition examined within each company in the sample.

All ICC and Cronbach's alpha values exceeded the necessary threshold, so it was possible to proceed with the calculation of averages and the construction of the final dataset used in the fsQCA.

3.4. Calibration

Following the calculation of averages, one last step is necessary to create the database required for the fsQCA. Given that QCA operates on Boolean algebra, requiring all values to fall between 0 and 1, and the fact that the calculated average values are between 1 and 7 (reflecting the scores given following a 7-point Likert scale), a transformation is needed. This transformation process is called calibration.

Different ways can be used to calibrate values. The simplest method consists in adjusting values according to the Likert scale, where a score of 1, indicating the absence of a condition, is converted to 0, and a score of 7, indicating full presence, is converted to 1, with intermediate values adjusted accordingly. However, this method has some limitations. Indeed, if most values for a condition all cluster around the same value, internal variability within the distribution is reduced. To better capture variability of data and avoid biases linked to specific conditions, calibration can be performed according to the observed distribution of values. This thesis follows this approach since it enable more accurate comparisons and often leads to solutions with a higher overall consistency and coverage, due to the increased variability of the conditions examined.

It is important to notice how the ROA, our performance outcome, was derived from published financial statements and did not go through a reliability analysis. However, calibration is still required.

To ensure comparability across sectors, ROA values were assessed relative to their sector's ROA distribution. To do this, for each industry, the 25th, 50th, 75th and 90th percentiles of the ROA distribution were identified. High ROA was calibrated using the 75th percentile of the ROA distribution within the relevant industry as the threshold for full membership scores, the 50th percentile as the crossover point, and the 25th percentile as the cut-off for full non-membership. Low ROA was defined as the absence of High ROA.

Following these assumptions and calibrations, the final dataset used for the fsQCA was created, as shown in table 3:

	TQM	**JIT**	**TPM**	**T1**	**T2**	**ROA**
Firm 1	0,64	0,52	0,46	0,14	0,50	0,75
Firm 2	0,56	0,50	0,67	0,17	0,79	0,95
Firm 3	0,45	0,57	0,64	0,56	0,83	0,45
Firm 4	0,64	0,49	0,76	0,44	0,96	0,45
Firm 5	0,72	0,63	0,83	0,11	0,42	0,75
Firm 6	0,62	0,49	0,59	0,19	0,33	0,25
Firm 7	0,58	0,69	0,56	0,86	0,63	0,75
Firm 8	0,60	0,62	0,67	0,78	0,88	0,75
Firm 9	0,39	0,46	0,64	0,83	0,79	0,45
Firm 10	0,45	0,61	0,52	0,39	0,50	0,75
Firm 11	0,76	0,76	0,49	0,56	0,79	0,95
Firm 12	0,39	0,55	0,54	0,28	0,67	0,95
Firm 13	0,49	0,34	0,40	0,50	0,67	0,95
Firm 14	0,74	0,59	0,85	0,50	0,67	0,95
Firm 15	0,46	0,48	0,58	0,61	0,58	0,75
Firm 16	0,62	0,60	0,66	0,67	0,67	0,95
Firm 17	0,85	0,81	0,75	1	1	0,75

Table 3: Final dataset for QCA

3.5. Data Analysis

The goal of this thesis is to identify configurations of selected conditions related to the outcome of interest (ROA). To do this, a fuzzy set qualitative comparative analysis was conducted using the fsQCA 4.1 software.

The Quine-McCluskey algorithm employed by the software allowed to examine different configurations and determine which conditions are associated with the outcome and in what manner. However, the association is not correlational; instead, the link exists only within the context of whole configuration. This approach also recognizes that different configurations may lead to the same outcome (equifinality), assuming asymmetry in causal relationships at the same time. Additionally, no hierarchy is imposed among the resulting configurations, meaning that each provides a valid pathway to the outcome, without one being more probable than another (Greckhamer et al., 2008; Ragin, 2008).

In QCA, conditions can be classified as either necessary or sufficient for the outcome. Necessary conditions are those that must be present for the outcome to occur. However, their presence alone is not sufficient for the outcome to occur. Conversely, sufficient conditions are enough for generating the outcome but are not uniquely necessary – multiple sufficient conditions may exist, each independently capable of producing the outcome. To conduct the QCA, two analyses must be carried out: the first to analyse necessary conditions, the second to identify sufficient conditions. They are both included in the functions of the software used.

As anticipated, the outcome's presence implies the presence of a necessary condition. This relationship is measured by consistency, using a threshold of 0.9 to indicate necessity. After calculating the consistency level for each condition, those with a value exceeding this threshold are classified as necessary conditions.

To identify sufficient conditions, a "Truth Tables Analysis" is used. The truth table calculates every possible configuration that might arise, providing 2^k rows, where k is the number of predictors for the outcome, and each row represents a unique combination. In this context, a sufficient condition encompasses all elements within a configuration collectively rather than any single element acting alone.

Each individual causal condition within a configuration is formally called an INUS condition – an Insufficient but Necessary part of an Unnecessary but Sufficient condition. An INUS condition may be required to be present, absent, or indifferent for the configuration to achieve sufficiency. "Present" means that the INUS condition's presence is essential for the sufficiency of the configuration, "absent" means its absence is necessary, and "indifferent" means the presence or absence of the condition is irrelevant for the sufficiency of the configuration to generate the outcome. (Wu et al., 2014).

INUS conditions are categorized as either core conditions or peripheral conditions. Core conditions are those consistently present across all configurations that yield the same outcome in the same solution; if a core condition meets the necessary threshold, it can also qualify as a necessary condition. Peripheral conditions, on the contrary, appear in only some configurations leading to the same outcome within the solution (Fiss, 2011).

In this study, both truth table analysis and necessity analysis were conducted. The next chapter provides a detailed discussion of the results, including the choice of causal conditions, the configurations identified and the classification of conditions as necessary, core, or peripheral.

4. CONFIGURATIONS FOR EFFIENCT LEAN-I4.0 INTEGRATION

4.1. The choice of causal conditions

A fundamental aspect necessary to conduct a qualitative comparative analysis is the choice of causal conditions that will be included in the final configurations obtained. Our sample size of 17 firms is in line with the minimum sample size (12 cases) required to perform a QCA (Marx, 2006). For a sample size of 17 firms, a number of causal conditions between 4 and 6 is accepted (Fiss, 2009).

In order to identify the most performing configurations for the integration between Lean Manufacturing and Industry 4.0 technologies, both the aspects must be thoroughly represented in the choice of causal conditions. Their specific breakdown is explained in the following paragraphs.

Lean production was defined as a comprehensive, multidimensional approach that integrates a series of managerial practices into a cohesive system (Shah & Ward, 2003). The ultimate goal is to allow these practices to work synergically to build a high-quality production process, delivering finished products that maximize customer value with minimal waste. Shah & Ward (2003) were the first to classify Lean practices in 4 bundles: Total Quality Management (TQM), Just-In-Time (JIT), Total Preventive Maintenance (TPM) and Human Resource Management (HRM).

JIT is one of the most commonly used practices in Lean Management and is designed to make production flexible and responsive to demand by shifting from a traditional "push" system to a "pull" one. By triggering production only when there is actual demand, JIT helps reducing waste and increasing efficiency. The effective implementation of JIT is subordinated to the presence of synchronized practices adopted throughout the supply chain. As an example, materials used must be immediately replenished and *kanban* tags are often used to signal reorder needs. This methodology minimizes inventory, resulting in lower costs and improved financial performance (Cua et al., 2001; Shah & Ward, 2003; Mackelprang & Nair, 2010). TQM refers to a comprehensive approach aimed at delivering high-quality products and processes. To prevent errors and endure quality at every stage of production, it includes practices such as statistical process control to monito and maintain process standards, error-proofing methods to reduce mistakes and visual management tools to identify deviations from quality benchmarks.

Through the use of these practices, TQM seeks to continuously improve quality, as well as to reduce variability and enhance reliability (Kaynak, 2003; Jayaram et al., 2010). TPM aims at minimizing downtime and boost workplace stability. Through proactive actions like involving operators in routine maintenance, implementing safety measures and scheduling regular preventive maintenance, TPM prevents unexpected breakdowns and extends equipment lifespan. Moreover, it promotes continuous improvement and teamwork. Lastly, HRM focuses on actively involving employees and enhancing their skills, as well as to ensure the support of top management. Training and developing programs to build competencies and fostering an engaged work culture are only a few of the practices applied to create a collaborative environment that supports continuous improvement (Cua et al., 2001; Furlan et al., 2011b).

While the idea of a classification of Lean Manufacturing in 4 bundles has gained widespread acceptance among scholars (Van Assen & de Mast, 2019; Ciano et al., 2020), research investigating the integration between Lean practices and I4.0 technologies often focuses on only 3 of these 4 bundles. Specifically, studies tend to highlight the interactions and synergies of JIT, TQM and TPM with digital technologies. According to Kamble et al. (2020) and Rossini et al. (2019), these 3 bundles have a more direct effect on production processes, quality, and equipment efficiency, aligning well with the objectives of digital transformation. On the contrary, HRM, though important for the overall success of Lean Management, is generally treated as an enabling factor rather than a core focus in the integration process. As literature rarely explores the direct interaction between HRM and I4.0 technologies, HRM is viewed as a background enabler, while JIT, TPM and TPM are considered the main Lean bundles having direct relationships with I4.0. Consequently, the QCA focuses only on these 3 bundles.

As for the section related to Industry 4.0, we selected I4.0 technologies with the potential to optimize manufacturing processes (Kolberg et al., 2017; Cifone et al., 2021) or to contribute to the product development and innovation (Wan et al., 2015). Technologies are therefore classified as:

- T1 – Data acquisition and processing technologies
- T2 – Integrated communication technologies
- T3 – Human-machine integration technologies

The technologies considered in T1, namely Big Data and Analytics, Cloud computing and IIoT aim to manage the collection of data, as well as handle its storage, analysis and simulation.

Integrated communication technologies (T2) include both practices of vertical and horizontal integration. To assess the level of horizontal integration within the companies analysed, we focused on the degree of implementation of Electronic Data Interchange (EDI) systems. These are used to exchange information between organizations in a standardized format and are a fundamental tool to streamline supply chain operations, as they enable better communication with clients and suppliers. Vertical integration, on the other hand, was evaluated on the degree of presence of Enterprise Resource Planning (ERP) and Manufacturing Execution System (MES). ERP is an integrated software system used by organizations to manage and streamline processes across different departments by creating a centralized database, in which it is possible to share and update information in real time. A famous example of ERP is SAP. MES is instead a software solution to manage, coordinate and monitor production activities in real time, ensuring that manufacturing operations are performed efficiently and according to standards. MES acts as a bridge between physical production equipment and ERP.

Lastly, we analysed human-machine interaction technologies (T3). These have the goal to improve the interaction between workers and machines through the use, among others, of collaborative robots (cobots), addictive manufacturing (3D printing) and tools of Augmented Reality (AR), Virtual Reality (VR) and simulation.

Despite the analysis being conducted on all 3 I4.0 technologies, it was not possible to work with the third bundle (T3), since the results of the surveys reveal a very low level of implementation within the firms considered. This is not a surprising result, as existing literature has indicated that these technologies remain in the early stages of adoption, with most SMEs yet to implement them. (Jalo et al., 2022).

In conclusion, the causal conditions used to conduct the QCA analysis, that will appear in the resulting configurations are TQM, JIT, TPM, T1 and T2. The exclusion of T3 does not represent an issue for the analysis, since the final number of causal conditions (5) is still in line with the requirements (Fiss, 2009).

4.2. Presence of necessary conditions

In order to identify which factors are essential to produce the desired outcome, the assessment of necessary conditions is required. The consistency of each condition was calculated by the software fsQCA 4.1 and the results can be seen in the following table.

Analysis of Necessary Conditions

Outcome Variable: ROA

Causal conditions:	Consistency
TQM	0,7410
JIT	0,7362
TPM	0,7569
T1 (Data acquisition and processing)	0,6143
T2 (Integrated communication)	0,7960

Table 4: Analysis of necessary conditions

As explained in the previous chapter, consistency measures the strength of the relationship between each causal condition and the outcome (ROA in our case). In other words, consistency reflects the likelihood of a condition being present in the configurations that lead to the desired outcome.

The analysis of necessary conditions (Table 4) reveals that neither Lean bundles nor I4.0 technologies bundles are strongly associated with a high ROA, as the consistency ranges between 0.614 and 0.796. Indeed, none of the consistencies exceeds 0.9, which is the value identified by the Quine-McCluskey algorithm as the threshold for a sufficiently high consistency. Although the result is not surprising, since none of these factors represents a fundamental element for a company to generate high operational performance (Jayaram et al., 2008; Nawanir et al., 2013), it may be noticed how all the bundles present a significant degree of consistency. The implications of these findings will be indagated in the following paragraph.

4.3. Analysis of sufficient conditions: configurations emerged

The second analysis performed – to identify sufficient conditions – involves the truth table algorithm, a core component of qualitative comparative analysis. The analysis was performed using the fsQCA 4.1 software, which automatically generates the possible configurations of causal conditions. This method enables to understand which mix of conditions leads to the desired outcome and gives an insight on how these conditions interact with one another.

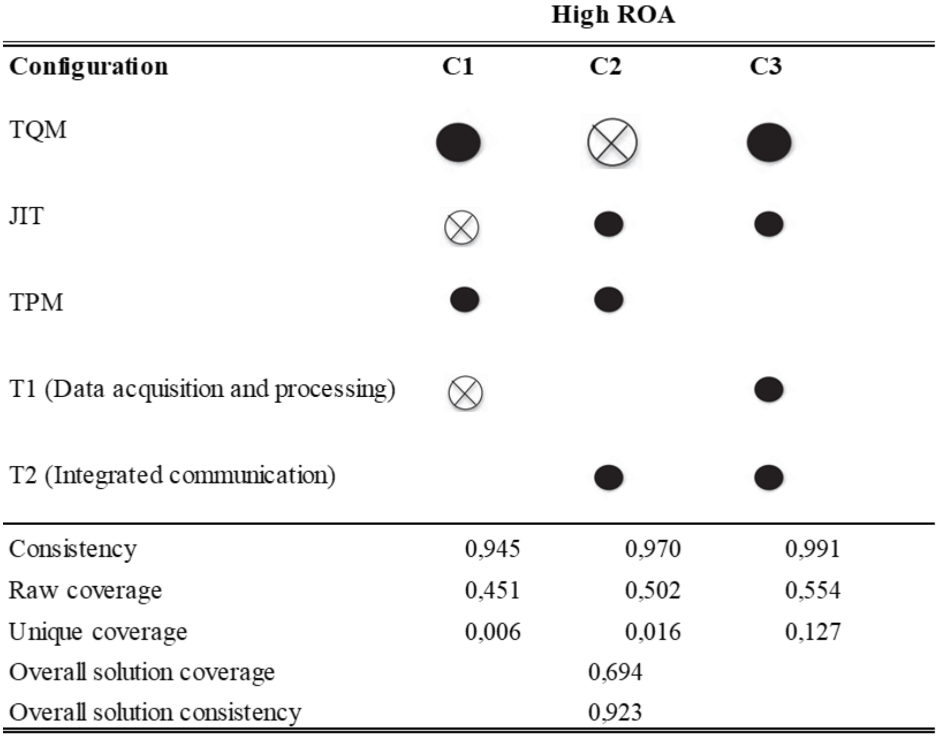
Alongside the proposed configurations, the software also presents their respective consistency and coverage. On the base of these two values, less significant configurations are filtered out, ensuring that only the most meaningful one are selected for further examination.

For the purpose of this thesis, and to better grasp the relationship between causal conditions – two truth table analyses were performed, one having High ROA as the performance outcome, and one having Low ROA. As explained before, we define Low ROA as the absence of High ROA. Both the analyses were performed using all the selected causal conditions: TQM, JIT, TPM, T1 and T2. In the following sections, all configurations for both the performance outcomes will be discussed.

Notice how in the tables, each column represents a configuration proposed. Within each configuration, each condition is represented by a symbol. Black circles indicate the presence of a condition that leads to the outcome (i.e. the condition must be present for the outcome to occur). Crossed-out circles indicate the absence of a condition for the generation of the outcome (i.e. the condition must be absent for the outcome to occur). In addition, big circles represent core conditions, while small circles indicate conditions that are peripheral. Lastly, blank spaces indicate "do not care", meaning that the presence or absence of the condition is not relevant in the configuration.

4.3.1. Discussion of results – configurations for High ROA

In accordance with the principle of equifinality, three different configurations to have a High ROA are represented in the figure below.



		High ROA	
Configuration	**C1**	**C2**	**C3**
TQM	⬤	⨂	⬤
JIT	⊗	●	●
TPM	●	●	
T1 (Data acquisition and processing)	⊗		●
T2 (Integrated communication)		●	●
Consistency	0,945	0,970	0,991
Raw coverage	0,451	0,502	0,554
Unique coverage	0,006	0,016	0,127
Overall solution coverage		0,694	
Overall solution consistency		0,923	

Figure 9: Configurations for High ROA

The overall consistency of 0.923, significantly exceeding the accepted threshold of 0.80 (Fiss, 2011), ensures the validity of the results. Moreover, we can notice an overall solution coverage of 0.694, meaning that the three configurations combined account for about 70% of membership in the outcome. Lastly, the value of raw coverage for each configuration is greater than 0.45 and demonstrate goodness of fit (Woodside, 2013).

Before going more in depth with the single configurations, notice that we have considered T1 – data acquisition and processing technologies – as base technologies of I4.0, which also have the ability to reinforce integrated communication technologies.

The first configuration (C1) is characterized by the presence of TQM and TPM and by the absence of JIT and T1. The presence of T2 is indifferent. This solution suggests that a significant implementation of Lean practices (2 out of the 3 bundles are present) does not require the adoption of T1 to lead a superior ROA.

The result supports the hypothesis of a potential misalignment between Lean principles and could be linked to the tensions researched by Margherita and Braccini (2024) and explained in chapter 2. Indeed, while T1 is defined by a data-driven problem-solving approach that detects deviations from standards, deviation detection in Lean practices mainly occurs through the observation of actual process abnormalities and human judgement. T1 technologies, while beneficial for decision-making, may unintentionally limit employees' engagement in decisional processes. The increased use of automation, indeed, reduce the opportunity for workers to apply their knowledge and critical thinking skills to identify root causes of potential issues. One implication is that employees may experience a sense of marginalization, feeling increasingly detached from active involvement in production processes. This hypothesis is supported by Romero et al. (2020), who highlighted that numerous I4.0 technologies place greater emphasis on data analytics and artificial intelligence over human insights, potentially diminishing the significance of employee expertise and intuition in Lean operations. This imbalance between workers and machines could be solved by initiatives such as improved communication and involvement of employees in the selection and implementation of I4.0 technologies. In this way, companies could try to establish a complementary human-machine relationship as opposed to a conflictual one.

Lastly, the absence of JIT in this configuration suggests that the lean practice of emphasizing on-time delivery and minimizing stock is not always fundamental to achieve superior performance, especially when TQM and TPM are strongly in place. This idea aligns with studies that considered TQM and TPM as highly effective, both in isolation and paired together (Shah & Ward, 2007; Ho et al., 2020).

The second configuration (C2) includes the absence of TQM and the presence of JIT, TPM and T2, with T1 being indifferent. This implies that the adoption of integrated communication technologies can support processes of Lean Manufacturing, leading to a superior ROA. This supports the hypothesis of I4.0 technologies as enablers of Lean.

The reason at the base of this positive effect on ROA could be linked to the creation of an improved information flow among departments and between companies. This represents a critical advantage for Lean practices, as they rely on seamless communication and coordination. In fact, as explained in chapter 1, Value Stream Mapping (VSM) is a fundamental tool to identify value-adding and non-value-adding activities. VSM involves the coordination and collaboration across several functions and companies (Fukuzawa, 2020). This collaboration, for example, can be enhanced by T2 technologies like ERP systems, which improve data sharing and visibility across the organization, allowing for more streamlined operations (Bieg, 2018). This is particularly important in today's interconnected business environment, where real-time data and coordination can provide a significant competitive advantage (Tortorella & Fettermann, 2018).

Finally, the absence of TQM may suggest that companies could prioritize operational efficiency over quality activities in specific settings, especially when JIT and TPM are already implemented. In other words, this configuration supports the idea that while TQM is often associated with superior performance, in some contexts, the combination of JIT and TPM, enhanced by I4.0 technologies, can still be sufficient to have a high ROA.

Following this reasoning, we could consider TPM as a substitute for TQM, given the fact that in both C2 and C3 they do not appear together, yet the outcome of High ROA is still achieved. This idea is supported by Konecny and Thun (2011), whose studies found no clear benefits from combining TPM and TQM, suggesting that different combinations of Lean bundles can yield successful outcomes.

The last configuration emerged to obtain an improvement in operational performance is C3. It is characterised by the presence of all causal conditions, except for TPM, whose presence is indifferent.

This result is in line with our previous findings about a synergetic relationship between Industry 4.0 technologies and Lean practices. Technologies of T1 like Big Data and IIoT allow companies to monitor performance in real time, offering insights that enable a faster and more informed decision-making, as well as proactive problem solving (Wang et al., 2020). The overall integration of operation is further enhanced by the presence of T2 technologies such as ERP systems. In turn, the effect of this bundle of technologies is also reinforced by the presence of T1.

Note that among the different configurations, C3 was the one including the highest ROA value. Thus, the combination of TQM, JIT, T1 and T2 generates a powerful synergy that leads to superior operational efficiency and quality, while also leveraging digital technologies to streamline data flow, create predictive insights and strengthen overall system integration. This also represents a valuable source of competitive advantage as organizations become more responsive, agile and efficient in meeting customer needs and optimizing their internal processes.

Lastly, the fact that all causal conditions are present except for TMP, which is irrelevant, suggests that this practice might not be a key factor in driving operational improvements when other JIT and TQM are implemented. This supports the previous hypothesis of TQM and TPM as substitutive bundles and reflects the idea that some Lean practices can be substituted by others depending on the organizational context and objectives. This highlights the need to customize Lean strategies to fit specific operational goals and challenges, as opposed to rigidly apply a prescribed set of practices.

4.3.2. Discussion of results – configurations for Low ROA

When Low ROA was used as a performance outcome, the software generated one configuration only (Figure 10)

	Low ROA
Configuration	**C4**
TQM	⊗
JIT	
TPM	●
T1 (Data acquisition and processing)	●
T2 (Integrated communication)	●
Consistency	0,799
Raw coverage	0,752
Unique coverage	0,752
Overall solution coverage	0,752
Overall solution consistency	0,799

Figure 10: Configuration for Low ROA

As seen in the figure, the consistency value obtained is 0.799, which is just below the threshold of 0.80 required for the solution to be considered fully valid. Nonetheless, we have decided to accept the result, as it is sufficiently close to the cutoff to be relevant for our analysis. Again, goodness of fit is secured by a raw coverage of 0.752.
Moreover, considering all the configurations for High ROA and Low ROA, we can say that they are all "neutral permutations", since they share the same core condition – TQM – and only differ in their peripheral conditions.

The last configuration (C4) – the only one for a Low ROA – is characterized by the presence of TPM, T1 and T2, and the absence of TQM. JIT is irrelevant. In this solution, the degree of implementation of Lean practices is very low, as only one of the three bundles is present. The configuration reveals that the joined adoption of T1 and T2 without a strong Lean foundation leads to poor operational performance.
The idea of implementing Lean practices before embarking on a digital transformation journey is well-supported in academic literature. The rationale is that Lean can create a disciplined, waste-free environment and I4.0 technologies could amplify the benefits derived from this environment. Research by Powell et al. (2021) aligns with the concept of Lean as a groundwork for successful digitalization and even proposes a framework to: "*Lean first… then Digitalize*" for SMEs. Nicoletti et al. (2013) argued that: "an inefficient process that is automated is still inefficient", explaining how the premature adoption of digital technologies can aggravate existing inefficiencies if the underlying processes are not correctly optimized. Supporting research was also provided by Lorenz et al. (2019). According to their studies, Lean is essential to realize the full potential of digital technologies and the integration between the two methodologies allows companies to develop a more holistic approach to operational excellence. Moreover, Ejsmont et al. (2020) defines digitalization as an "evolutionary step" able to elevate Lean practices, and advocates at the same time that I4.0 technologies need Lean practices as a prerequisite to exploit their full potential.
Regarding the practical implications, we can conclude that organizations, in particular SMEs with few resources, should carefully manage the sequencing of Lean and I4.0 adoption. By implementing Lean practices as a first step, these companies could optimize operations and stive for continuous improvement, creating a solid foundation to address the complex nature of digitalization without critical repercussions on the existing processes (Powell et al., 2021; Lorenz et al., 2019).
In conclusion, Lean is not only a complementary practice but a necessary precondition to successful I4.0 implementation. According to Buer et al. (2018), many companies still struggle

to fully implement Lean Manufacturing despite its demonstrated benefits in terms of waste reduction and performance improvement. This implies that Industry 4.0 technologies are most effective when integrated in an established Lean culture.

4.4. Limitations and opportunities for future research

Despite trying to fill an existing gap in literature regarding the best fits of Lean practices and I4.0 technologies resulting in superior performance, this thesis suffers from some limitations. These limitations represent valuable paths for future research, in order to deepen our understanding of Lean-Industry 4.0 integration in different organizational contexts.

First, while our sample size of 17 firms complies with the minimum requirement for the fuzzy-set qualitative comparative analysis, greater insights could be generated by expanding the sample to include SMEs with advanced technological development. For instance, the inclusion of firms that have adopted complex I4.0 technologies – such as 3D printing, collaborative robots, Augmented Reality (AR) and Virtual Reality (VR) – would enable us to consider also the third technological bundle identified (T3 – human-machine interaction technologies) as a causal condition in the QCA. As anticipated in chapter 3, these technologies often present challenges in the alignment with Lean's processes for problem-solving, which are fundamentally human-cantered. Indeed, an expanded sample size could also be useful to understand how this tension can be balanced.

The second limitation of our research project is the exclusive focus on Italian companies, which may hamper the transferability of our findings. The ways companies implement I4.0 technologies and Lean practices is influenced by the economic and industrial characteristics of the country of belonging, and it is likely that these factors are different across other regions and sectors. For instance, it could be interesting to expand the sample to various companies in different cultural and economic environment, as well as with different regulatory policies, to see how these elements affect the effectiveness of Lean Automation. In this way, a more global framework for the correct integration could be developed.

Lastly, our study only limited to manufacturing companies, excluding service industries where Lean implementation takes on a distinct character. Unlike manufacturing, where Lean emphasizes process optimization, waste reduction, and efficiency, in service sectors such as banking, healthcare and customer service, the focus is on service delivery, customer satisfaction, and employee engagement. In these contexts, waste is often defined in terms of resource allocation and time and Value Stream Mapping (VSM) is focused on workflows and customer experience (Radnor et al., 2012). Because of this, Lean tools and practices must be adapted to fit the less tangible aspects of service delivery. For example, implementing Lean in healthcare may involve streamlining patient flow or improving the accuracy of service delivery rather than reducing inventory.

Expanding studies to include these additional factors – more advanced technological capabilities, broader cultural and regional diversity, and service sector applications – would allow to refine the theoretical models and provide more generalizable conclusions on the integration between Lean practices and Industry 4.0. By addressing these limitations, future research could develop a holistic view of Lean-I4.0 integration, identifying best practices suited to diverse industry sectors and technological contexts.

CONCLUSIONS

This thesis explored the integration of Lean Manufacturing and Industry 4.0, with a focus on identifying optimal configurations of Lean practices and digital technologies that maximize operational and financial outcomes for manufacturing companies. Lean, originating from the Toyota Production System, focuses on maximizing value and minimizing waste through practices like Just-In-Time (JIT), Total Quality Management (TQM), and Total Predictive Maintenance (TPM). Its principles revolve around continuous improvement, simplicity, and a people-centric approach to optimize processes. In contrast, Industry 4.0 – representing the fourth industrial revolution – introduces advanced digital technologies such as Big Data analytics, cyber-physical systems, and the Industrial Internet of Things (IIoT), which enable smart, interconnected factories capable of real-time data analysis and automation.

The literature on Lean and I4.0 integration reveals multiple dimensions of potential synergy but also highlights significant implementation challenges. On the one hand, Lean's JIT, Jidoka (automation with a human touch), and Kaizen (continuous improvement) principles align with I4.0 capabilities in real-time data analytics, defect detection, and process optimization. This synergy can result in improved quality, shorter lead times, and minimal inventory waste. On the other hand, several paradoxical tensions arise, primarily due to the cultural and structural differences between Lean's human-centered approach and I4.0's automation-driven nature. The emphasis on simplicity and human-driven solutions sometimes conflicts with I4.0's technological complexity, resulting in resistance from employees not used to digital systems and an increased demand for specialized skills within the workforce.

In response, recent studies have proposed theoretical frameworks to facilitate the integration between the two. For example, Sony et al. (2018) suggest vertical, horizontal, and end-to-end integration as means to align organizational hierarchies, enhance supply chain coordination, and better serve customer needs through customization. Additionally, frameworks like the "Shuriken Framework" focus on adapting Lean and I4.0 in resource-limited environments, such as small- and medium-sized enterprises (SMEs), where the barriers to technology adoption are often greater due to resource constraints. While provide a foundation, the empirical research measuring the operational and financial outcomes of Lean-I4.0 integration remains limited. With our analysis, we tried to fill this gap of empirical evidence in the literature.

The critical research question we aimed to answer is: *which configurations of Lean practices and digital technologies lead to superior performance?*

This question explores whether specific combinations of Lean and I4.0 technologies yield quantifiable financial benefits, in our case regarding Return on Assets (ROA), and seeks to identify the conditions under which these benefits manifest. Using a fuzzy set Qualitative Comparative Analysis (fsQCA) approach, the study systematically examines various configurations across a sample of manufacturing firms, revealing key patterns in how Lean and I4.0 technologies interact to influence performance outcomes. Different resulting configurations provided different insights according to the fits and misfits between Lean and I4.0 bundles. Interesting findings were obtained on the following areas:

1. **Lean also works well alone:** Lean practices, such as TQM and TPM, can be highly effective when combined with limited use of data acquisition technologies. This configuration supports controlled, waste-reducing processes while avoiding the complexities and costs of full-scale digitalization. It is important to notice how Lean organizations are able to achieve superior performance without the need to rely on digital tools.
2. **Integrated Communication and Information Flow**: Integrated communication technologies enable real-time data sharing across departments, facilitating smooth information flow, which aligns well with Lean's focus on waste reduction and streamlined operations. This configuration produced significant financial benefits by enabling better alignment and responsiveness, essential to Lean principles, through Industry 4.0's digital connectivity.
3. **Human-Centric and Data-Driven Synergy**: The study found that Lean's focus on human-centric improvement is complemented by Industry 4.0's data-driven approach. Big Data analytics, for instance, enables real-time tracking of performance metrics, supporting the Kaizen approach to continuous improvement. This configuration allows companies to capitalize on data insights while maintaining Lean's emphasis on people-led, adaptive improvements.
4. **Lean Foundations as Essential Prerequisites**: The analysis underscored that certain Industry 4.0 technologies are most beneficial when Lean practices have already established stable, waste-minimized processes. In companies where Lean foundations were lacking, digital initiatives were less effective, suggesting that Lean serves as a critical precondition for the adoption of I4.0 technologies.

Our findings have significant implications for both theory and practice. The configurations underscore the concept of *equifinality*, meaning that there are multiple ways to achieve superior performance. This insight challenges traditional assumptions that comprehensive Lean or I4.0

implementation alone will yield optimal results, instead supporting a more nuanced view that specific combinations are required. From a theoretical perspective, this supports configurational thinking, acknowledging that in complex organizational environments, success depends on the alignment of multiple, interdependent factors.

These configurations provide guidance into how manufacturing firms can achieve high ROA through customizable Lean-I4.0 integration. It is important for companies to avoid direct adoption of I4.0 technologies without assessing their fit with existing Lean practices. For example, companies with established TQM and TPM frameworks may not need to invest heavily in data processing technologies if they can leverage communication-focused I4.0 tools to achieve similar performance gains. Additionally, the findings emphasize the importance of organizational readiness, specifically in the form of workforce training and alignment between Lean's human-centered philosophy and I4.0's digital infrastructure. Firms are encouraged to foster a culture of continuous learning to support employees as they adapt to the new technology landscape, thereby addressing resistance to change and enhancing overall readiness for LA adoption.

Despite the interesting findings, some limitations were identified in the study. The sample size, limited to manufacturing firms in Northern Italy, may restrict the generalizability of findings across industries or geographic regions with different economic structures and technological adoption rates. Future studies could expand this research by incorporating a broader range of sectors and geographic contexts, which would enhance the robustness of the configurations identified. Additionally, while ROA provides a valuable financial measure of performance, other metrics such as customer satisfaction, employee engagement, and operational flexibility could provide a more comprehensive assessment of Lean-I4.0 integration's impact.

Another promising direction for future research is the exploration of dynamic configurations, examining how the effectiveness of Lean-I4.0 integration evolves over time. As firms progress in their digital transformation journeys, new configurations may emerge that align with the changing technological landscape and organizational capabilities.

This thesis contributes to the growing literature on Lean-I4.0 integration, providing empirical evidence on the configurations of Lean practices and I4.0 technologies that lead to superior performance in manufacturing firms. By employing a configurational approach, the study reveals that specific combinations of Lean and I4.0 elements—rather than individual practices or technologies—drive superior financial outcomes, highlighting the critical importance of strategic alignment in LA adoption. The results demonstrate that manufacturing firms can achieve high ROA through thoughtfully selected configurations, validating the potential for

Lean-I4.0 integration to enhance both operational efficiency and financial performance. As manufacturing firms continue to navigate the challenges of digital transformation, this study provides a valuable roadmap, emphasizing the need for strategic alignment, organizational readiness, and an adaptable approach to Lean-I4.0 integration.

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