UNIVERSITÀ DEGLI STUDI DI PADOVA | DIPARTIMENTO DI SCIENZE ECONOMICHE E AZIENDALI "MARCO FANNO"

UNIVERSITA' DEGLI STUDI DI PADOVA

DIPARTIMENTO DI SCIENZE ECONOMICHE ED AZIENDALI "M.FANNO"

CORSO DI LAUREA MAGISTRALE IN ENTREPRENEURSHIP AND INNOVATION

MASTER THESIS

Enhancing Lean Manufacturing Systems with Industry 4.0 Technologies: A Systematic Literature Review

Supervisor:
Professor Andrea Furlan

Student:
Sahar Khalilzadeh (2049626)

Academic Year 2023 – 2024

Declaration of Authenticity

Il candidato dichiara che il presente lavoro è originale e non è già stato sottoposto, in tutto o in parte, per il conseguimento di un titolo accademico in altre Università italiane o straniere.

Il candidato dichiara altresì che tutti i materiali utilizzati durante la preparazione dell’elaborato sono stati indicati nel testo e nella sezione “Riferimenti bibliografici” e che le eventuali citazioni testuali sono individuabili attraverso l’esplicito richiamo alla pubblicazione originale.

The candidate declares that the present work is original and has not already been submitted, totally or in part, for the purposes of attaining an academic degree in other Italian or foreign universities. The candidate also declares that all the materials used during the preparation of the thesis have been explicitly indicated in the text and in the section "Bibliographical references" and that any textual citations can be identified through an explicit reference to the original publication.

Sahar Khalilzadeh

To those who fight quietly in the shadows, their eyes fixed on the promise of dawn. This thesis is dedicated to the resilient women of my homeland—those who face every challenge with grace and unyielding courage. Their battles, though often unsung, forge paths toward light and liberation. May their spirits continue to inspire and shape a world where every voice that whispers hope is heard and cherished.

Acknowledgment

I would like to express my sincere gratitude to Professor Andrea Furlan for his invaluable guidance, support, and insightful mentorship throughout my research journey. His expertise has significantly shaped my work, and I am deeply appreciative of his contributions.

I am also deeply thankful to my family and friends, whose unwavering support has been a source of strength during my academic pursuit. Their love, motivation, and belief in me have provided the foundation for my success.

Sahar Khalilzadeh

Abstract

Lean Manufacturing (LM) streamlines production by eliminating waste and enhancing quality through continuous improvement. Industry 4.0 (I4.0) technologies—such as IoT, AI, Big Data Analytics, Cyber-Physical Systems, and Additive Manufacturing—offer opportunities to elevate LM practices. Integrating LM with I4.0, termed Lean 4.0, combines waste-reducing principles with advanced technologies for superior operational performance.

This thesis investigates the synergy between LM and I4.0 through a Systematic Literature Review from 2016 to 2024, following PRISMA guidelines, and bibliometric analysis using Python and Bibliometrix. Key findings highlight I4.0 technologies that enhance LM practices, including Just-in-Time inventory management, Total Productive Maintenance, Value Stream Mapping, Kanban systems, and continuous improvement initiatives. Seven major themes emerged: phased technology implementation, impacts on efficiency and performance, integration challenges, development of decision-making frameworks, sustainability practices, sector-specific variations, and leadership and regulatory considerations.

The integration offers significant benefits—improved efficiency, quality, flexibility, and sustainability—but presents challenges like technical complexities and organizational resistance. To address these, the study proposes practical frameworks emphasizing strategic leadership to assist organizations in navigating the integration process. By providing updated insights into the integration of LM and I4.0, this research highlights Lean 4.0's potential for sustainable competitive advantage in manufacturing. It offers guidance for practitioners seeking to implement these practices.

Keywords: Lean Manufacturing, Industry 4.0, Lean 4.0, Operational Efficiency, Sustainability, Digital Transformation

Table of contents

Figures:

Tables:

1. Introduction

1.1 Background and Motivation

In today's rapidly evolving manufacturing landscape, firms are under increasing pressure to enhance operational efficiency, reduce costs, and minimize waste to remain competitive. Lean Manufacturing (LM), derived from the Toyota Production System (TPS), emerged in post-war Japan as a response to resource scarcity and the need for flexible production systems. Pioneered by Taiichi Ohno and Eiji Toyoda, the TPS introduced core principles aimed at reducing waste (*muda*), minimizing overburden (*muri*), and eliminating unevenness (*mura*) in production processes, while emphasizing continuous improvement (*kaizen*) and Just-in-Time (JIT) production (Imai, 1986; Ohno, 1988). These methodologies have transformed Toyota into a global manufacturing leader and have been widely adopted across various industries worldwide.

Lean Manufacturing principles are now applied in manufacturing and healthcare, logistics, and services sectors. By eliminating non-value-adding activities and optimizing value streams, Lean practices have significantly improved operational performance, leading to increased productivity, cost reduction, and enhanced product quality (Shah & Ward, 2003; Womack & Jones, 1996). A survey of global manufacturing trends 2023 highlighted that over 80% of firms applying Lean principles reported reduced operational costs and improved production efficiency (Fortune Business Insights, 2023).

However, the complexity of modern manufacturing presents new challenges that traditional Lean methods may not fully address. The Fourth Industrial Revolution, or Industry 4.0 (I4.0), has emerged as a critical driver of manufacturing innovation, characterized by the integration of digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data analytics, and Cyber-Physical Systems (CPS). These technologies enable the creation of "smart factories," where interconnected systems and machines communicate and optimize production processes in real-time (Lasi et al., 2014; Schwab, 2016).

The global smart factory market reflects this technological shift, projected to reach around **USD 564.38 billion by 2029**, growing at a compound annual growth rate (CAGR) of approximately **9.74%** from 2024 onwards (Mordor Intelligence, 2023). The adoption of advanced technologies, energy efficiency, and the integration of IoT across manufacturing processes drives this growth. The increasing demand for automation and data exchange in manufacturing environments underscores the significance of digital transformation in the sector.

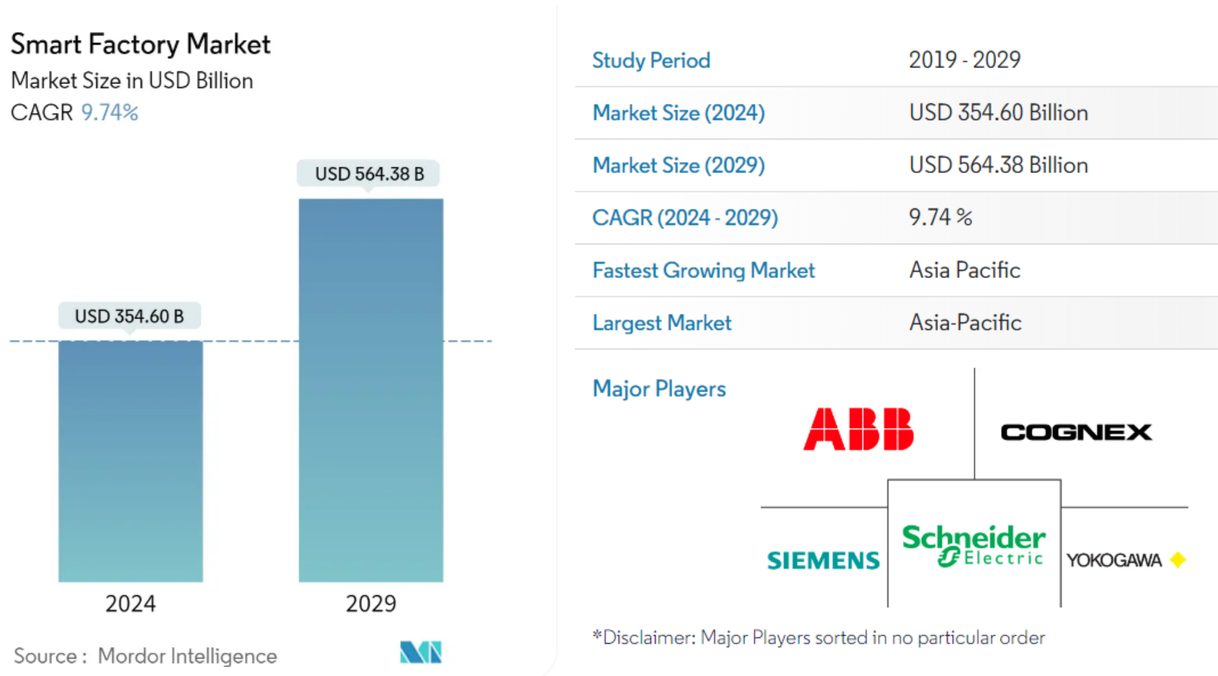

Figure 1: Smart Factory Market - Mordor Intelligence, 2023

The convergence of Lean Manufacturing and Industry 4.0, often termed "Digital Lean" or "Lean 4.0," marks a significant shift in how firms approach operational efficiency. Manufacturers can enhance agility, responsiveness, and sustainability by combining Lean's focus on waste reduction and continuous improvement with Industry 4.0's data-driven capabilities (Buer et al., 2018). This integration is critical in addressing modern pressures such as customization, demand variability, and resource optimization in a globalized market.

1.2 Problem Statement

While previous studies have explored the relationship between LM and I4.0, there is a lack of recent research that captures the latest developments and provides practical guidance for integration. Notably, seminal works by Buer et al. (2018) and Pagliosa et al. (2019) do not cover the rapid changes that have occurred since 2016. Given the fast-paced evolution of technologies and market demands, six years can lead to significant shifts in trends, applications, and best practices.

Moreover, recent studies focus on specific technologies or tools, such as blockchain in supply chain management (Jackson et al., 2023), without providing a holistic view of the integration process across various I4.0 technologies and LM practices. There is a need for updated research that addresses these gaps by providing a comprehensive analysis of the integration of LM and I4.0, identifying key technologies, impacted LM practices, and the benefits and challenges associated with this integration.

1.3 Research Objectives and Questions

The primary objective of this study is to investigate the integration of Lean Manufacturing systems with Industry 4.0 technologies to enhance operational efficiency and sustainability in manufacturing. The study aims to:

- Identify the key Industry 4.0 technologies applied in Lean Manufacturing systems.
- Determine which Lean Manufacturing technical solutions are most impacted by Industry 4.0 integration.
- Explore the benefits and challenges of integrating Industry 4.0 technologies into Lean Manufacturing systems.
- Develop a practical decision-guide framework and a conceptual model to assist practitioners in effectively integrating LM and I4.0 technologies.

Based on these objectives, the following research questions are formulated:

RQ1: What are the key Industry 4.0 technologies applied in Lean Manufacturing systems?

RQ2: Which Lean Manufacturing technical solutions are most impacted by Industry 4.0 integration?

RQ3: What benefits and challenges are reported from integrating Industry 4.0 technologies into Lean Manufacturing systems?

1.4 Significance of the Study

This study contributes to the academic literature by providing an updated and comprehensive analysis of the integration of LM and I4.0 technologies, covering recent developments from 2016 to 2024. By addressing the identified gaps in previous research, this study offers valuable insights into emerging trends, key technologies, and the evolving relationship between LM and I4.0.

From a practical perspective, developing a practical decision-guide framework and a conceptual model provides practitioners with actionable guidance for effectively integrating LM and I4.0 technologies. This framework considers organizational maturity, resources, and sector-specific factors and emphasizes dynamic capabilities, allowing organizations to adapt and reconfigure resources in response to changing environments.

Furthermore, the study explores the environmental, social, and economic dimensions of sustainability associated with Lean 4.0 practices, highlighting the potential for organizations to achieve sustainable growth by aligning technological advancements with Lean principles and sustainability goals.

1.5 Scope and Limitations

The study focuses on integrating LM and I4.0 technologies within the manufacturing sector, although insights may apply to other industries such as healthcare and services. The research employs a systematic literature review (SLR) following PRISMA guidelines and includes publications up to 2024, ensuring that recent developments and emerging trends are captured.

A limitation of the study is the reliance on the Scopus database for literature sourcing, which may exclude relevant studies indexed in other databases. Additionally, the study acknowledges potential publication bias and the exclusion of non-English publications, which may affect the comprehensiveness of the findings.

1.6 Structure of the Thesis

The thesis is organized as follows:

Chapter 2: Literature Review provides an overview of Lean Manufacturing and Industry 4.0, exploring their principles, tools, and the existing body of knowledge on their integration.

Chapter 3: Methodology outlines the research design, including the systematic literature review process, data extraction, and analysis methods.

Chapter 4: Findings and Results presents bibliometric analysis and the findings organized around seven major themes, incorporating critical analysis, case studies, and the development of practical frameworks.

Chapter 5: Conclusion summarizes the key findings, discusses the contributions to theory and practice, acknowledges limitations, and provides recommendations for future research.

2. Literature Review

Building upon the foundational concepts introduced in Chapter 1, this chapter delves deeper into the literature surrounding Lean Manufacturing and Industry 4.0, examining their evolution, core principles, and the implications of their integration. The manufacturing landscape has evolved dramatically in recent decades, driven by globalization, fluctuating market demands, and rapid technological advancements. Firms are under increasing pressure to enhance operational efficiency, reduce costs, and respond swiftly to market shifts. Two key paradigms have emerged to address these challenges: Lean Manufacturing and Industry 4.0.

2.1 Lean Manufacturing: Concepts, History, and Evolution

2.1.1 Definition and Origins

Lean Manufacturing is a systematic approach to production that focuses on maximizing customer value while minimizing waste. Originating from the Toyota Production System (TPS) developed by Taiichi Ohno and Shigeo Shingo in post-World War II Japan, Lean Manufacturing emerged as a response to Japan's economic challenges and resource scarcity at the time (Ohno, 1988). The TPS emphasized reducing waste ("muda"), increasing efficiency, and ensuring the smooth flow of materials and production. Key principles such as Just-in-Time (JIT) production and jidoka (automation with a human touch) were central to TPS.

Lean Manufacturing gained international recognition with the publication of *The Machine That Changed the World* by Womack, Jones, and Roos (1990). This seminal work introduced the concept of Lean to a global audience based on research from the International Motor Vehicle Program at MIT. The authors detailed how Toyota outperformed its global competitors by focusing on customer value and eliminating non-value-added activities. They asserted, "The fundamental ideas of lean production are universal—applicable anywhere by anyone" (Womack et al., 1990). Furthermore, they emphasized that "Lean production is a superior way for humans to make things. It provides better products in wider variety at lower cost."

In their follow-up book, *Lean Thinking*, Womack and Jones (1996) provided a detailed framework for implementing Lean principles across industries. They articulated the five core principles of Lean—Value, Value Stream, Flow, Pull, and Perfection—which have become foundational to the modern understanding of Lean Manufacturing.

2.1.2 Key Principles and Lean Tools

The five core principles of Lean Manufacturing are:

Value: Identifying what the customer values most and ensuring that all activities contribute directly to delivering this value (Womack & Jones, 1996).

Value Stream: Mapping the entire value stream to identify all steps required to bring a product from concept to customer, eliminating any steps that do not add value (Rother & Shook, 1999).

Flow: Ensuring the smooth flow of products through the production process by eliminating bottlenecks and interruptions (Liker, 2004).

Pull: Utilizing a pull system where production is driven by actual customer demand rather than forecasts, minimizing overproduction and excess inventory (Ohno, 1988).

Perfection: Continually striving for zero defects and maximum efficiency through ongoing improvements in processes and production systems (Imai, 1986).

A central aspect of Lean Manufacturing is the elimination of waste. Taiichi Ohno identified seven types of waste ("muda") that impede efficient production, encapsulated in the acronym **TIMWOOD** (Ohno, 1988):

Transportation: Unnecessary movement of materials or products between processes.

Inventory: Excess stock of materials or products that are not being processed.

Motion: Unnecessary movement by employees within the workspace.

Waiting: Idle time when workstations are not operating due to delays.

Overproduction: Producing more than is needed, leading to excess inventory.

Overprocessing: Doing more work or using more resources than required.

Defects: Producing products that do not meet quality standards, leading to rework.

The TIMWOOD framework is central to Lean because it provides a structured way to identify and address the inefficiencies that plague traditional manufacturing systems.

To implement these principles effectively, Lean Manufacturing relies on tools and techniques designed to target specific inefficiencies. **Table 1** provides an overview of key Lean tools commonly used across industries.

Table 1: Key Lean Manufacturing Tools and Techniques

No.	Lean Tool	Application

1	Value Stream Mapping (VSM)	Visualizes and analyzes the flow of materials and information to identify bottlenecks and waste, improving the efficiency of the value stream (Rother & Shook, 1999).
2	Kanban	A visual system for managing workflow and limiting work in progress (WIP), promoting smoother workflows and reducing overproduction (Gross & McInnis, 2003).
3	Poka-Yoke	Error-proofing techniques are designed to prevent defects by eliminating mistakes in production processes and improving product quality (Shingo, 1986).
4	Just-in-Time (JIT)	Ensures materials and products are produced and delivered only when needed, reducing inventory costs and minimizing waste (Ohno, 1988).
5	Kaizen	Fosters a culture of continuous improvement by involving employees at all levels in identifying inefficiencies and implementing incremental improvements (Imai, 1986).
6	Andon	Uses visual signals to notify workers and managers of production problems, enabling immediate corrective action and continuous improvement (Liker, 2004).
7	Single Minute Exchange of Dies (SMED)	Reduces setup times in manufacturing, improves flexibility, allows quicker changeovers, and increases productivity (Shingo, 1985).
8	5S	A methodology for organizing and standardizing the workplace to improve efficiency, safety, and cleanliness, fostering a culture of continuous improvement (Hirano, 1996).
9	Jidoka	Combines automation with human oversight, allowing machines and operators to detect abnormalities and stop production to prevent defects and ensure quality (Ohno, 1988).

10	Total Productive Maintenance (TPM)	Involves all employees in maximizing equipment effectiveness through proactive maintenance, reducing breakdowns, and improving efficiency (Nakajima, 1988).
11	Heijunka	Smooths production demand by leveling fluctuations, reducing variability, and ensuring consistent production flow (Liker, 2004).

2.1.3 Evolution and Global Adoption

Lean Manufacturing has evolved and expanded beyond its automotive roots. Its adaptability has led to widespread adoption across various industries, including healthcare, electronics, and services, as firms seek to reduce operational inefficiencies, lower costs, and improve quality (Shah & Ward, 2007).

"The fundamental ideas of lean production are universal—applicable anywhere by anyone" (Womack et al., 1990). This universality has allowed Lean principles to be applied successfully in diverse contexts. For instance, in the electronics sector, companies like Samsung and Apple have utilized Lean tools such as Value Stream Mapping and JIT to synchronize production with consumer demand, minimize excess inventory, and reduce lead times (Chiarini & Vagnoni, 2015).

Lean has been adopted in the healthcare sector to improve patient care by reducing wait times, eliminating bottlenecks, and increasing staff efficiency. The Virginia Mason Medical Center in Seattle implemented Lean tools like Kaizen and 5S, significantly improving patient flow and care outcomes (Toussaint & Berry, 2013).

2.2. Industry 4.0: Concepts, Key Technologies, and Implications for Lean Manufacturing

2.2.1 Overview of Industry 4.0

Industry 4.0, or the Fourth Industrial Revolution, represents a transformative shift in manufacturing driven by integrating digital technologies into traditional production systems. First introduced at the Hannover Fair in 2011, Industry 4.0 emphasizes the fusion of physical and digital systems through technologies such as the Internet of Things (IoT), Big Data Analytics, Artificial Intelligence (AI), Cyber-Physical Systems (CPS), and Cloud Computing (Kagermann et al., 2013). These technologies enable the development of smart factories, where machines, products, and systems are interconnected and communicate in real-time, allowing for enhanced decision-making, predictive maintenance, and optimized production processes (Lasi et al., 2014).

Industry 4.0 is not merely an extension of automation—it represents a new era of digitization, where every part of the production process is monitored, analyzed, and optimized based on real-time data. This enables manufacturers to adapt quickly to changes in demand, improve production efficiency, and reduce costs, all while increasing the customization of products to meet specific customer needs (Xu et al., 2018).

2.2.2 Key Technologies of Industry 4.0

The core technologies driving Industry 4.0 have far-reaching implications for manufacturing processes, particularly when integrated with Lean Manufacturing systems. **Table 2** overviews the most prominent Industry 4.0 technologies and their applications in Lean Manufacturing.

Table 2: Key Industry 4.0 Technologies and Their Application in Lean Manufacturing

No.	Industry 4.0 Technology	Application in Lean Manufacturing	Source
1	Internet of Things (IoT)	Enables real-time monitoring of production lines, inventory levels, and equipment performance, facilitating precise control over Lean systems and supporting JIT production.	Sanders et al., 2016
2	Cyber-Physical Systems (CPS)	Integrates digital and physical systems, automating processes and providing real-time data to optimize flow, reduce bottlenecks, and enhance overall production efficiency.	Kolberg & Zühlke, 2015
3	Big Data Analytics	Identifies inefficiencies, optimizes production processes, and supports data-driven decision-making, enhancing Lean's focus on waste reduction and continuous improvement.	Wamba et al., 2015

4	Cloud Computing	Enables real-time data sharing and collaboration across departments, improving transparency, coordination, and decision-making in Lean Manufacturing systems.	Xu, 2012
5	Simulation	Allows manufacturers to model and test production scenarios virtually, optimizing processes and minimizing disruptions in real-world operations.	Wagner et al., 2017
6	Digital Twin	Provides virtual representations of physical systems, enabling real-time monitoring and predictive maintenance, improving overall equipment effectiveness in Lean environments.	Tao et al., 2018
7	Machine Learning (ML)	Enables automated decision-making and continuous process optimization by analyzing production data, supporting Lean's focus on reducing waste and improving quality.	Lee et al., 2018
8	Augmented Reality (AR)	Supports Lean Manufacturing by providing real-time guidance for workers on the factory floor, improving training, maintenance, and quality control tasks.	Mourtzis et al., 2020
9	Additive Manufacturing (AM)	Enables rapid prototyping and production of customized products, reducing waste and improving process flexibility.	Gao et al., 2015
10	Radio Frequency Identification (RFID)	Helps track inventory and materials in real-time, ensuring efficient management of resources in line with Lean's JIT principles.	Kwok & Wu, 2009

2.2.3 Implications for Lean Manufacturing

Integrating Industry 4.0 technologies with Lean Manufacturing principles enhances eliminating waste, improving quality, and increasing flexibility. Real-time data collection and analysis allow for immediate identification of inefficiencies, enabling proactive decision-making and continuous improvement (Sanders et al., 2016).

For example, IoT devices can monitor equipment performance to predict maintenance needs before a breakdown occurs, aligning with Lean's Total Productive Maintenance (TPM) goals (Lee et al., 2015). Similarly, Big Data Analytics can identify patterns and trends in production processes that may not be apparent through traditional Lean tools, offering deeper insights into waste reduction opportunities (Wamba et al., 2015).

2.3. Timeline and Evolution of Lean Manufacturing and Industry 4.0

The convergence of Lean Manufacturing and Industry 4.0 technologies marks a transformative era in manufacturing. Lean's focus on eliminating waste, optimizing processes, and continuous improvement has merged with Industry 4.0's data-driven tools, automation, and real-time analytics, creating what is now referred to as Lean 4.0.

2.3.1 Key Milestones in Lean Manufacturing

Historical Foundations and Global Expansion (1890s–2000s): Lean Manufacturing's roots can be traced back to Sakichi Toyoda's invention of the automatic loom in the 1890s, followed by the development of the Toyota Production System in the 1950s (Ohno, 1988). Over the next few decades, Lean principles expanded globally, becoming integral to improving workflow, reducing waste, and optimizing production systems (Womack et al., 1990).

Environmental and Social Impact (1990s–2020s): By the 1990s, Lean began to intersect with environmental sustainability efforts, contributing to reduced material waste and energy consumption (EPA, 2003). Recent studies have explored the synergy between Lean practices and environmental sustainability, termed "Green Lean," highlighting how Lean tools can support environmental objectives (Garza-Reyes, 2015).

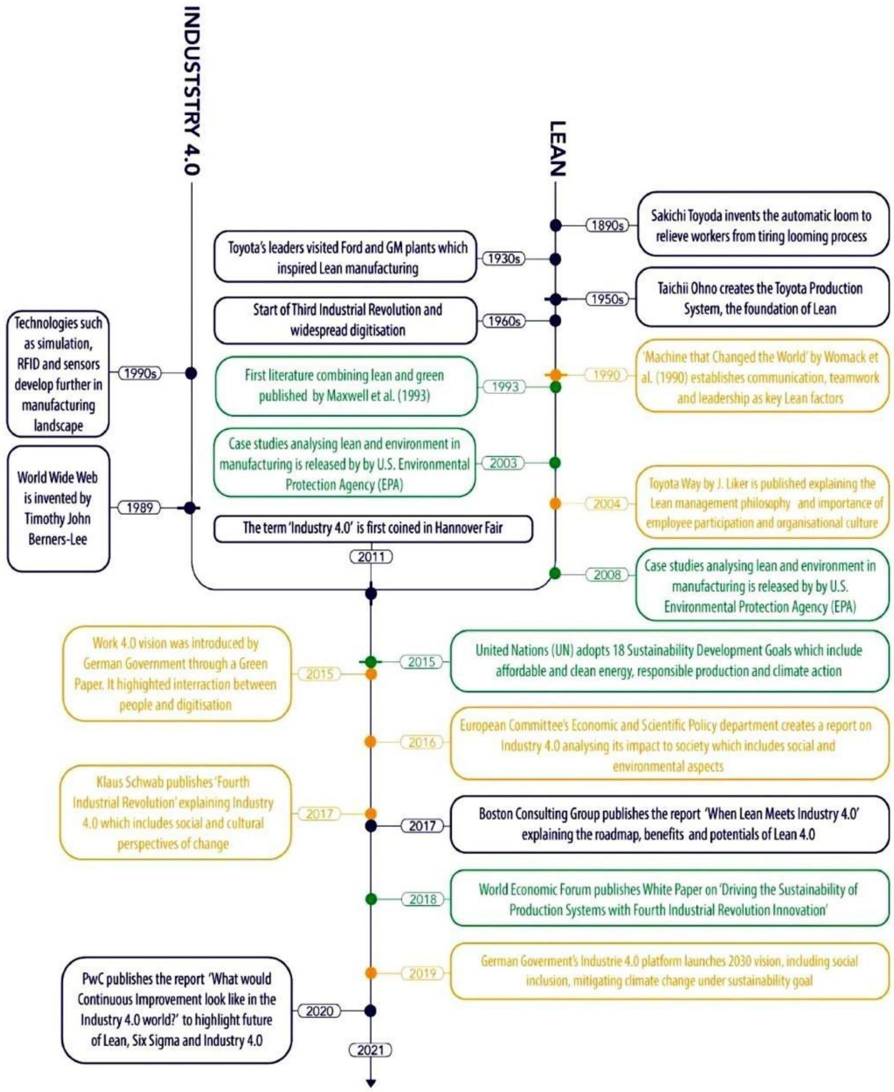

Figure 2: Timeline of Lean 4 and Industry 4.0 evolution with operational, social, and environmental focus (Yilmaz et al., 2022)

2.3.2. Key Milestones in Industry 4.0

Technological Milestones and Digitalization (2000s–2010s): The advancement of digital technologies such as IoT, CPS, and AI laid the groundwork for Industry 4.0. In 2011, the concept of Industry 4.0 was formally introduced in Germany as part of the High-Tech Strategy 2020 Action Plan, aiming to enhance the manufacturing sector's competitiveness through digital transformation (Kagermann et al., 2013).

Global Adoption and Standards Development (2010s–2023): Industry 4.0 has gained global traction, with countries developing their initiatives like China's "Made in China 2025" and the United States' "Advanced Manufacturing Partnership." Standardization efforts have been made to ensure interoperability and security in Industry 4.0 systems (Lu, 2017).

2.4. Convergence: Lean 4.0

The convergence of Lean Manufacturing with Industry 4.0 signifies the integration of Lean's focus on waste reduction and process optimization with Industry 4.0's advanced technologies.

Operational Synergy: Lean 4.0 allows real-time production monitoring through IoT and CPS, optimizing workflows and reducing production variability (Kolberg & Zühlke, 2015). For instance, Bosch implemented Lean 4.0 in their production systems, resulting in increased efficiency and flexibility (Posada et al., 2015).

Environmental Benefits: Combining Lean's waste reduction focus with Big Data Analytics and predictive maintenance leads to greater resource efficiency and energy savings (Verrier et al., 2016). Chiarini et al. (2020) found that Lean 4.0 contributes to environmental sustainability by reducing emissions and energy consumption.

Social Impact: Lean 4.0 fosters a more engaged workforce by promoting employee autonomy through digital tools like AR, improving workplace safety, and creating opportunities for upskilling (Buer et al., 2021). Companies like Siemens have invested in training programs to equip employees with the skills needed for digital manufacturing environments (Siemens, 2018).

2.5. Previous Systematic Literature Reviews in the Field

Multiple systematic reviews have been undertaken on integrating Lean Manufacturing with Industry 4.0. Previous SLRs have delivered important insights and identified areas needing further exploration, which this study aims to address. Table 3.1 encapsulates the key SLRs previously conducted in this domain.

Table 3: Summary of Previous Systematic Literature Reviews

Authors	**No. of Reviewed Papers**	**Period**	**Objectives**
Buer et al., 2018	21	Until Aug 2017	Examine the effects of Industry 4.0 and Lean Manufacturing integration on performance indicators.

Pagliosa et al., 2019	93	Until 2018	Establish connections between Industry 4.0 technologies and Lean Manufacturing tools.
Bittencourt et al., 2019	33	2011–2019	Explore Lean's role in industrial production via Industry 4.0 automation.
Ejsmont et al., 2020	87	2011–2019	Investigate research trends and future areas in Lean 4.0.
Jackson et al., 2023	202	2023	Examine Blockchain Technology in SCM for Lean Automation; develop a waste taxonomy and future research agenda.

The existing SLRs, such as those by Buer et al. (2018) and Pagliosa et al. (2019), are among the field's most cited and comprehensive studies. However, they have not covered recent developments since 2018. In today's fast-changing environment, technology and the market evolve rapidly, and six years can lead to considerable differences in trends and applications (Upadhyay et al., 2023). For instance, the earlier studies could not access a large dataset that could reveal emerging patterns in integrating Lean Manufacturing and Industry 4.0.

More recent works like Jackson et al. (2023) focus on particular tools of new technologies, such as blockchain, and do not cover a broader range of technologies or their integration with Lean practices. This narrow focus leaves a gap in understanding the implications and potential of integrating various Industry 4.0 technologies with Lean Manufacturing.

2.6. Research Gaps and Critical Perspective

Despite significant advancements in understanding the integration of Lean Manufacturing and Industry 4.0, several research gaps persist.

2.6.1. Inadequate Exploration of Long-Term Sustainability

There is a lack of research on the long-term sustainability of Lean 4.0, particularly concerning environmental impacts and the ability of small and medium-sized enterprises (SMEs) to maintain the benefits over time (Müller et al., 2018). While short-term benefits such as increased productivity are documented, the long-term effects on sustainability and continuous improvement require further investigation.

Additionally, some studies indicate that implementing Industry 4.0 technologies can lead to increased energy consumption due to the continuous operation of digital devices, potentially offsetting the environmental benefits of Lean practices (Bonilla et al., 2018). Research is needed to develop strategies that balance the energy demands of digital technologies with sustainability goals.

2.6.2. Limited Focus on Workforce Adaptation and Organizational Culture

Strategies for overcoming workforce resistance to change and bridging the skills gap required for Industry 4.0 technologies are underdeveloped (Buer et al., 2021). The human factor is critical in Lean 4.0 implementation, as employees need to adapt to new technologies while maintaining the Lean culture of continuous improvement.

Research should focus on developing training programs and organizational change management strategies that facilitate the integration of digital skills with Lean principles (Sony & Naik, 2019). This includes exploring how leadership styles and organizational structures impact the successful adoption of Lean 4.0.

2.6.3. Sector-Specific Challenges and Adaptations

While Lean 4.0 has been studied in sectors like automotive and electronics, other industries remain underrepresented. For example, the construction industry faces unique challenges in adopting Lean 4.0 due to its project-based nature and fragmented supply chains (Sacks et al., 2018). Similarly, the healthcare sector must navigate regulatory constraints and data privacy concerns when implementing digital technologies (Dalenogare et al., 2018).

Further research is needed to explore sector-specific adaptations of Lean 4.0, developing tailored frameworks that address the unique operational constraints of different industries.

2.6.4. Gaps in Understanding the Full Synergy between Lean and Industry 4.0

Current literature primarily focuses on how Industry 4.0 technologies can enhance specific Lean practices, but fewer studies explore how Lean principles can enhance the effectiveness of Industry 4.0 technologies. The bidirectional relationship between these paradigms is underexplored.

For instance, Lean principles such as value stream thinking can inform the development of digital tools by focusing on value creation and waste elimination in the design of Industry 4.0 systems (Rossini et al., 2019). Research should examine how Lean methodologies can guide the implementation of digital technologies to maximize their effectiveness.

2.6.5. Lack of Longitudinal Studies

The absence of longitudinal studies examining the impact of Lean 4.0 over time is a significant gap. Most research focuses on short-term case studies or initial implementation phases. Longitudinal studies could provide valuable insights into how firms adapt to Lean 4.0 technologies over several years, how benefits evolve, and what challenges emerge in the long term (Mrugalska & Wyrwicka, 2017).

2.6.6. Ethical Considerations in Digital Transformation

An emerging area that requires attention is the ethical implications of digital transformation in manufacturing. Issues such as data privacy, cybersecurity, and the potential displacement of workers due to automation need to be addressed (Stankovska et al., 2020). Ethical considerations should be integrated into the implementation strategies of Lean 4.0 to ensure responsible and sustainable adoption.

2.6.7. Methodological Approaches in Studying Lean 4.0

There is a need to expand the methodological approaches used in studying Lean 4.0. While case studies provide valuable insights, incorporating quantitative methods, simulation models, and cross-industry comparative analyses can enhance the robustness of research findings (Sony et al., 2021). This multifaceted approach can provide a more comprehensive understanding of Lean 4.0 implementation.

This chapter has thoroughly reviewed the literature on Lean Manufacturing and Industry 4.0, exploring their historical evolution and foundational principles and highlighting the transformative potential of their integration. Significant research gaps persist despite promising operational flexibility, customization, and sustainability opportunities. These include challenges related to long-term sustainability, workforce adaptation, sector-specific issues, achieving full synergy between Lean processes and Industry 4.0 technologies, and ethical and methodological concerns.

The following chapters will extend this exploration with a systematic literature review and bibliometric analysis to delve deeper into these issues. The overarching aim of this thesis is to address these research gaps and provide an updated and comprehensive analysis of the most current literature, extending through 2024. It will expand the scope to include a broader array of Industry 4.0 technologies and their integration with Lean practices.

This thesis will develop a conceptual framework based on this refreshed overview to guide practitioners in effectively integrating Lean Manufacturing with Industry 4.0 technologies, thus contributing to academic knowledge and practical applications in the manufacturing sector.

3. Methodology

This chapter delineates the research methodology, outlining the framework, data collection techniques, and search strategy used to construct an article dataset examining digital technology integration in Lean Manufacturing systems. It describes the systematic approach to gathering and analyzing data, setting the foundation for effectively addressing the research questions. This methodology is crucial for deriving insights that demonstrate how these technologies can be seamlessly combined to enhance manufacturing processes, thereby contributing to the broader goals of the thesis.

3.1. Research Design

A systematic literature review (SLR) was conducted to address the research questions. An SLR is a rigorous method of identifying, evaluating, and synthesizing existing research to answer specific questions (Tranfield et al., 2003). This approach ensures a comprehensive and unbiased overview of the literature, allowing for the identification of patterns, themes, and gaps in the research.

3.1.1. Rationale for Using a Systematic Literature Review

Adopting a Systematic Literature Review (SLR) in this research is underpinned by its methodological rigor, which offers distinct advantages over traditional narrative literature reviews. Firstly, SLRs are designed to provide comprehensive coverage by systematically identifying all relevant studies that meet pre-defined eligibility criteria, thereby minimizing selection bias and enhancing the scope and depth of the analysis. This structured approach ensures a methodical examination of literature and supports reproducibility and transparency in research processes (Tranfield et al., 2003).

Moreover, one of the significant advantages of SLRs is that the researcher's subjective opinions influence them and follow a structured protocol, which provides a less biased overview of the research field and objectives (Kitchenham & Charters, 2007).

The advantages of an SLR include offering a thorough and unbiased overview of existing research and facilitating a holistic understanding of the field. A rigorous methodological framework also strengthens the validity of conclusions drawn from the research. It helps identify research gaps, thus directing future research efforts and innovations in the field.

However, SLRs can be time-consuming and require substantial resources, which may limit their feasibility under certain constraints. The reliance on predefined criteria might lead to excluding relevant studies that do not fit the stringent inclusion parameters. Additionally, SLRs face potential publication bias, with studies reporting positive findings more likely to be published and thus more readily included in the review.

3.2. Application of the PRISMA Framework

For the data collection step, we used the PRISMA framework. An international group of experts developed the PRISMA statement to help improve the reporting quality of systematic reviews and meta-analyses. PRISMA consists of a 27-item checklist and a 4-phase flow diagram to guide transparent reporting. The checklist covers critical information that should be reported in the title, abstract, introduction, methods, results, discussion, and funding sections. The flow diagram depicts the flow of information through the phases of a systematic review, from identification of records to screening, assessing eligibility, and final inclusion. (Moher et al., 2009)

PRISMA aims to help authors improve the reporting of systematic reviews by providing an evidence-based minimum set of reporting items. It can be used to report systematic reviews of interventions and synthesize other evidence. Journals and editorial groups have widely endorsed PRISMA to encourage its adoption. An Explanation and Elaboration paper provides the rationale and examples for each checklist item. (Moher et al., 2009)

While PRISMA focuses on improving reporting, it does not assess the quality of systematic reviews. It provides a basis for assessing review reports by ensuring clear, complete, and transparent reporting. PRISMA is an important, internationally developed standard that authors should follow to ensure their choices are reported fully and transparently (Page et al., 2021).

3.3. Data Collection and Search Strategy

3.3.1. Database Selection

The Scopus database was selected as the primary source for literature retrieval due to its extensive coverage of peer-reviewed journals and conference proceedings across multiple disciplines, including engineering, business, and technology (Harzing & Alakangas, 2016). Scopus offers robust indexing and citation tracking, making it ideal for identifying high-impact research relevant to integrating Lean Manufacturing and Industry 4.0.

3.3.2. Keyword Selection

Keywords were carefully chosen to capture the breadth of relevant literature. The selection was based on authoritative sources (e.g., Buer et al., 2018; Kipper et al., 2020) and frequently cited terms in seminal articles (Benitez et al., 2020). The keywords were grouped into three categories: Lean Manufacturing, Industry 4.0, and Integration Terms.

Table 4: Keywords Used for Literature Search

Category	Keywords
Lean Manufacturing	"Lean Manufacturing", "Lean Production", "Lean Systems", "Lean Management", "Lean Practices", "Lean Thinking", "Lean Strategies", "Toyota Production System", "Kaizen", "Just-in-Time", "Waste Reduction", "5S"
Industry 4.0	"Industry 4.0", "Fourth Industrial Revolution", "I4.0", "Industrie 4.0", "Industrial Internet", "Industrial Internet of Things", "Industrial IoT", "Smart Manufacturing", "Smart Production", "Smart Factory", "Cyber-Physical Systems", "Cyber-Physical Production Systems", "4IR", "Fourth IR", "IoT", "Big Data", "Artificial Intelligence", "Machine Learning", "Automation", "Advanced Robotics", "Additive Manufacturing", "3D Printing", "Cloud Computing", "Simulation", "Digital Twin", "5G", "Augmented Reality", "Cybersecurity", "Blockchain", "Edge Computing", "Virtual Reality", "Data Analytics",
Integration Terms	"Digital Lean", "Lean 4.0", "Lean Automation", "Smart Factories", "Digital Transformation", "Sustainability", "Circular Economy"

3.3.3. Search Query Construction

The search query was formulated using Boolean operators to combine the keywords effectively—the query aimed to capture studies that specifically address the integration of Lean Manufacturing and Industry 4.0 technologies.

Search Query:

(TITLE-ABS-KEY("Lean Manufacturing" OR "Lean Production" OR "Lean Systems" OR "Lean Management" OR "Lean Practices" OR "Lean Thinking" OR "Lean Strategies" OR "Toyota Production System" OR "Kaizen" OR "Just-in-Time" OR "Waste Reduction" OR "5S")

AND

TITLE-ABS-KEY("Industry 4.0" OR "Fourth Industrial Revolution" OR "I4.0" OR "Industrie 4.0" OR "Industrial Internet" OR "Industrial Internet of Things" OR "Industrial IoT" OR "Smart Manufacturing" OR "Smart Production" OR "Smart Factory" OR "Cyber-Physical Systems" OR "Cyber-Physical Production Systems" OR "4IR" OR "Fourth IR" OR "IoT" OR "Big Data" OR "Artificial Intelligence" OR "Machine Learning" OR "Automation" OR "Advanced Robotics" OR "Additive Manufacturing" OR "3D Printing" OR "Cloud Computing" OR "Simulation" OR "Digital Twin" OR "5G" OR "Augmented Reality" OR "Cybersecurity" OR "Blockchain" OR "Edge Computing" OR "Virtual Reality" OR "Data Analytics"))

AND

TITLE-ABS-KEY("Digital Lean" OR "Lean 4.0" OR "Lean Automation" OR "Smart Factories" OR "Digital Transformation" OR "Sustainability" OR "Circular Economy")

3.3.4. Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were established to ensure the selected studies' relevance and quality.

Table 5: Summary of Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Studies explicitly address the integration of Lean Manufacturing and Industry 4.0 technologies.	Articles focusing solely on Lean Manufacturing or Industry 4.0 without integration.
Peer-reviewed journal articles.	Non-peer-reviewed publications (e.g., editorials, opinion pieces).
Publications in English.	Studies not related to Business, Management, Accounting, Economics, Econometrics, and Finance.
Studies published between until 2024.	Not final published papers.

3.3.5. Study Selection Process

The study selection process (Figure 3) followed the PRISMA 2020 flow diagram (Page et al., 2021), ensuring a transparent and systematic approach.

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework is an evidence-based set of guidelines designed to improve systematic reviews' transparency and reporting quality. First published in 2009, PRISMA was developed as an evolution of the earlier QUOROM (Quality of Reporting of Meta-analyses) statement, which focused specifically on reporting meta-analyses of randomized controlled trials (RCTs). However, as systematic reviews became more widely used across different types of studies and disciplines, a broader and more comprehensive framework was required, leading to the development of PRISMA (Moher et al., 2009).

PRISMA consists of a 27-item checklist and a four-phase flow diagram. The checklist includes essential items that should be reported in systematic reviews, covering sections such as the title, abstract, introduction, methods, results, discussion, and funding sources. The flow diagram illustrates the literature selection process, from identifying records to screening, assessing eligibility, and final inclusion of studies. This structured approach ensures that systematic reviews are reported with sufficient clarity and detail to allow for replication and critical assessment (Page et al., 2021).

Since its introduction, PRISMA has been widely adopted across multiple disciplines, contributing significantly to the standardization of systematic review reporting. Its influence is particularly notable in the health sciences but has increasingly been recognized in social sciences, management, and engineering. While PRISMA primarily focuses on improving reporting transparency, it also indirectly supports the quality of systematic reviews by ensuring that all critical aspects of the review process are documented and reported. The PRISMA guidelines are widely endorsed by academic journals, research institutions, and editorial boards, making it a key standard for systematic reviews across various fields, including health sciences, social sciences, and management studies (Page et al., 2021).

3.3.6. Limitations of PRISMA:

Although PRISMA significantly enhances transparency and reporting quality, it does not address the quality of the individual studies included in a systematic review. Therefore, while PRISMA helps ensure a comprehensive and transparent review process, additional tools and criteria are necessary to assess the quality and reliability of the included studies. Recognizing these limitations, this study incorporates complementary quality assessment tools to ensure that the included studies meet transparency standards and adhere to high-quality research practices.

3.3.7. Application of PRISMA in This Study:

This study employed the PRISMA framework during the data collection phase to ensure a comprehensive and methodologically sound selection of relevant literature. The framework's four-phase flow diagram was particularly useful in documenting the process of identifying, screening, and including studies in the systematic review.

Identification: The initial search yielded 508 records from Scopus.

Screening: After removing 13 non-English studies, 492 records remained. Titles and abstracts were screened for relevance, excluding 273 studies that did not meet the inclusion criteria.

Eligibility: The full texts of the remaining 213 studies were assessed against the inclusion and exclusion criteria. During this phase, 143 studies were excluded due to a lack of focus on integration, inadequate methodological rigor, or irrelevance to the manufacturing sector.

Inclusion: The final analysis included 72 studies, of which the full texts 63 were found and analyzed.

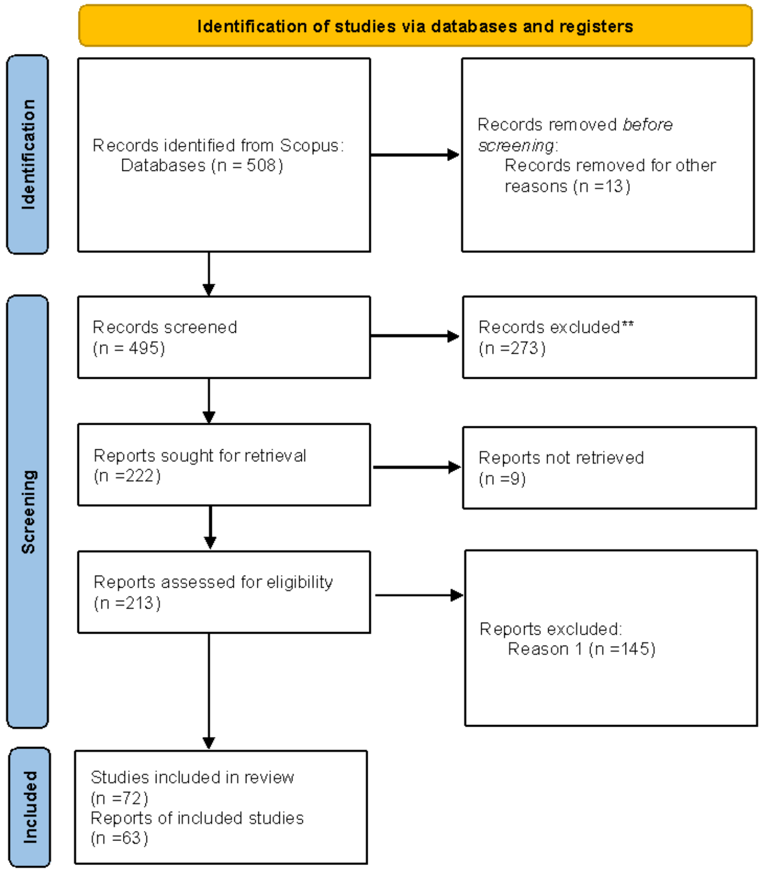

Figure 3: PRISMA 2020 Flow Diagram (http://www.prisma statement.org/ org/)

3.4. Data Extraction and Analysis

3.4.1. Data Extraction

Data was extracted using a standardized form to ensure consistency and comprehensiveness across the gathered information. This extraction process included citations, bibliographic information, abstracts and keywords, and funding specifics.

The standardized data extraction form was developed based on guidelines from the Cochrane Handbook for Systematic Reviews (Higgins et al., 2020) and included predefined categories to capture relevant information systematically. To enhance reliability, the extraction was performed independently by two researchers. Any discrepancies between the researchers were resolved through discussion and consensus, ensuring inter-rater reliability (Gough et al., 2017). This process minimized the risk of bias and errors in data collection.

Additionally, bibliometric data were obtained from Scopus, encompassing various elements, including:

Authors, author IDs, titles, publication years, source titles, volumes, issues, page numbers, citation counts, DOIs, and links.

Affiliations, abstracts, author keywords, index keywords, funding details, references, document type, publication stage, open access status, and EID.

3.4.2. Data Analysis

Given the focus on bibliometric analysis, the study utilized the following quantitative assessment tools, with the associated codes available in Appendix A:

Python (version 3.12) for data manipulation and visualization.

Bibliometrix (R package) is used for detailed bibliometric analysis (Aria & Cuccurullo, 2017).

The choice of Python was driven by its wide-ranging utility and comprehensive ecosystem, which boasts a plethora of libraries specifically designed for data analysis. With its user-friendly syntax and efficient processing capabilities, Python is ideally suited for managing the intricate details of bibliometric evaluations. Unlike other programming environments such as R or MATLAB, Python facilitates an integrated data manipulation and visualization approach, which is crucial for analyzing extensive datasets typical in exhaustive literature reviews.

Libraries like Pandas and Matplotlib play a critical role in this framework. Pandas allow straightforward handling of complex data structures, enabling easy data manipulation and analysis. Matplotlib provides advanced visualization tools that aid in revealing trends and patterns within the data, thereby enhancing the precision and effectiveness of the bibliometric assessments (McKinney, 2017, Chapters 5 & 9).

Moreover, Python is increasingly recommended for graduate students and professionals in entrepreneurship and data science, equipping them with the skills to harness data-driven insights and analytics for a competitive edge in the contemporary data-focused business landscape (Grus, 2019, Chapter 1).

In addition to Python, this research employed Bibliometrix, an R-based software package designed for bibliometric analysis. Bibliometrix streamlines the bibliometric study process, incorporating an established workflow with various analytical and mapping tools. This package facilitates automated analysis within the R environment, allowing for the examination of citation networks, co-authorship networks, and keyword co-occurrence networks, among other features (Aria & Cuccurullo, 2017).

To mitigate potential publication bias and ensure a comprehensive analysis, strategies such as searching multiple databases and including grey literature were considered (Siddaway, Wood, &

Hedges, 2019). However, due to resource constraints, the study focused on Scopus, acknowledging that this may limit the inclusion of some relevant studies. This limitation is addressed in the critical evaluation section, where the potential impact on findings is discussed.

The data analysis also involved assessing the risk of bias in individual studies. While conducting the bibliometric analysis, attention was given to the quality of journals, citation counts, and the authors' H-index to gauge the sources' reliability (Bornmann & Daniel, 2007). The study aimed to enhance the conclusions' validity by combining quantitative metrics with critical appraisal.

The analysis included:

Publication Trends: Analysis of annual scientific production to identify trends over time.

Citation Analysis: Evaluation of citation counts and trends to assess the impact of publications.

Correlation Analysis: Examination of the relationship between publication year and citations.

Journal Impact: Identification of key journals and their bibliometric indices (H, G, and M).

Geographical Distribution: Analysis of contributions by country and collaboration patterns.

Keyword Analysis: Investigating keyword trends, co-occurrence networks, and thematic mapping.

4. Findings and Results

This chapter presents the findings from the systematic literature review on enhancing Lean Manufacturing (LM) systems with Industry 4.0 (I4.0) technologies. The aim is to address the research as mentioned earlier questions:

RQ1: What are the key Industry 4.0 technologies applied in Lean Manufacturing systems?

RQ2: Which Lean Manufacturing technical solutions are most impacted by Industry 4.0 integration?

RQ3: What benefits and challenges are reported from integrating Industry 4.0 technologies into Lean Manufacturing systems?

4.1. Data Analysis and Findings

The dataset consists of 72 academic publications focused on integrating Industry 4.0 and Lean Manufacturing within the manufacturing sector, spanning from 2016 to 2024. This period is significant as it aligns with rapid technological advancements and a global shift towards digital transformation in manufacturing. The growing interest in this area reflects the increasing recognition of the potential benefits of combining Lean methodologies with Industry 4.0 technologies to create smarter, more sustainable manufacturing practices.

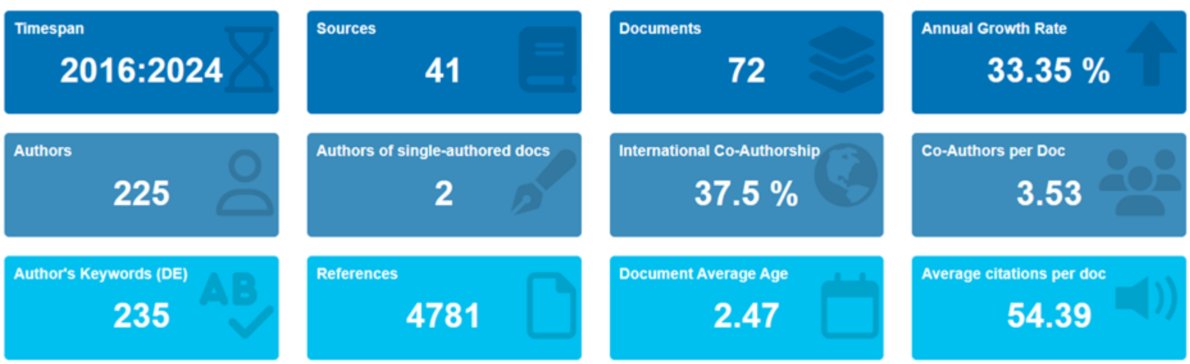

Figure 4.1: Data Analysis and Findings, Bibliometrix Tool

4.1.1. Correlation Analysis: Citations vs. Year of Publication

Exploring the relationship between the year of publication and the number of citations helps to assess the scholarly impact within the domains of Industry 4.0 and Lean Manufacturing. This correlation analysis sheds light on how citation trends influence research articles' visibility and perceived impact.

The dataset's correlation coefficient calculated between 'Citation' and 'Year' is -0.58. This moderate negative correlation indicates that, generally, more recent publications receive fewer citations than older ones. This trend underscores the temporal dynamics of citation accumulation; older articles have had more time to garner citations. This pattern aligns with findings from bibliometric studies, such as those by Larivière et al. (2008), which suggest that in rapidly evolving fields like Industry 4.0, it often takes time for new research to accumulate citations. As the field develops and newer studies gain recognition, their citation counts are expected to increase, thus enriching the academic dialogue on these subjects. With this understanding, we will continue with the citation analysis in the following section.

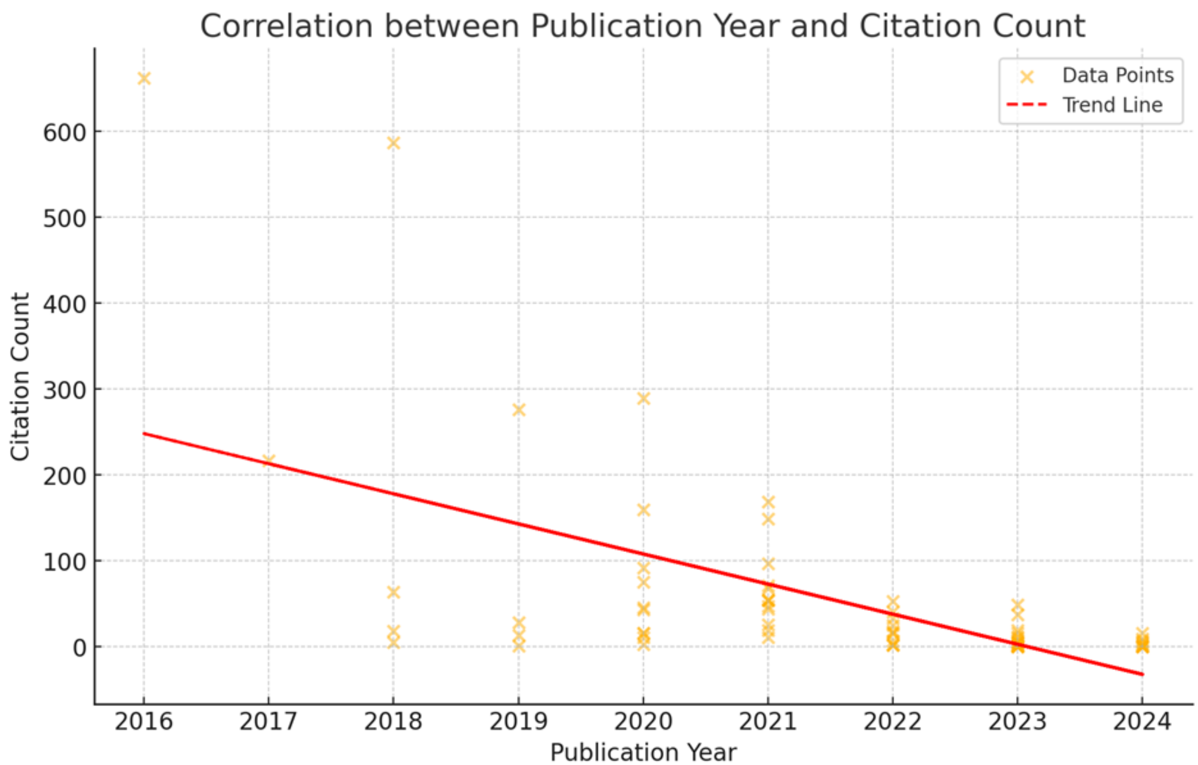

Figure 4.2: Scatter Plot of Citations vs. Year of Publication

4.1.2. Trends in Annual Scientific Production

Analyzing average citations annually reveals valuable insights into the scholarly impact and thematic evolution within Industry 4.0 and Lean Manufacturing. Citations, shown in Figure 4.3, reflect a publication's influence and its relevance to ongoing academic discussions.

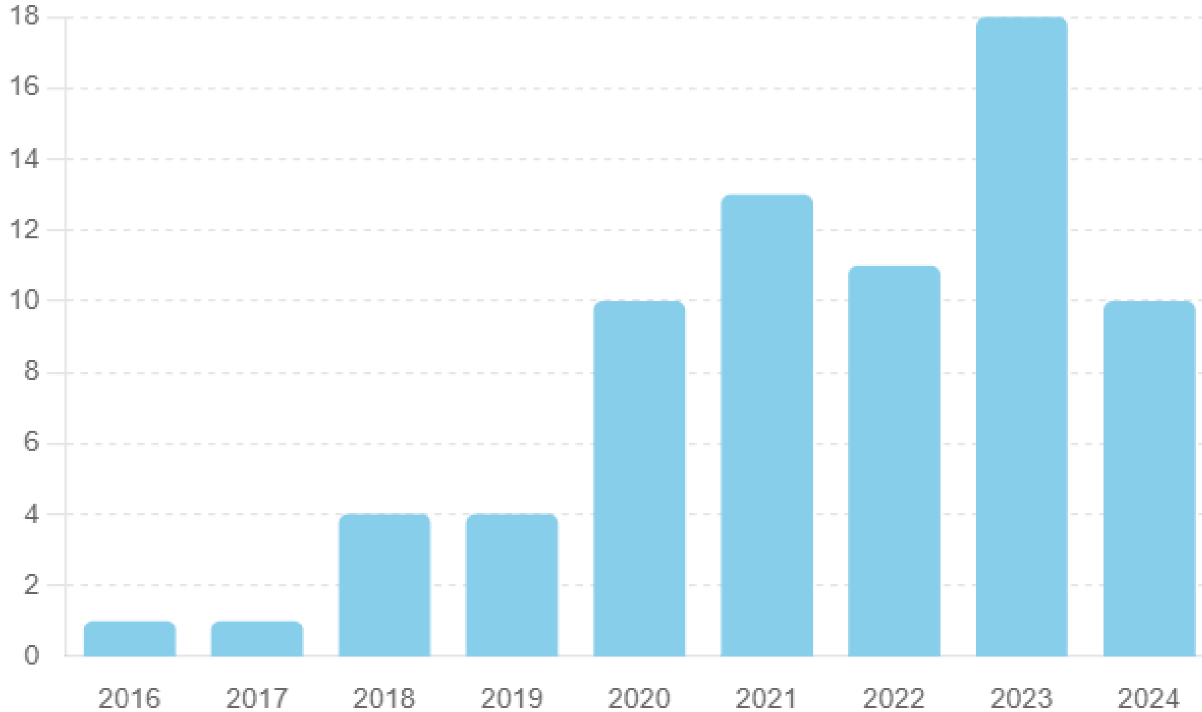

Figure 4.3: citation landscape from 2016 to 2024,

As shown in Figure 4.3, the citation landscape from 2016 to 2024 shows noticeable fluctuations, with 2021 standing out as the peak year, garnering 864 citations. This peak correlates with the rapid adoption of Industry 4.0 technologies highlighted in Chapter 2, particularly the increasing deployment of cyber-physical systems and IoT in manufacturing during the Growth Period (2018–2020). The substantial rise in citations during this period aligns with the broader global trend of technological integration, supported by government initiatives like the EU Horizon 2020 program, which was the European Union's flagship research and innovation funding initiative from 2014 to 2020. With a budget of €80 billion, it promoted scientific research, technological development, and innovation in areas like Industry 4.0, fostering collaboration and addressing societal challenges such as sustainability and digital transformation.

4.1.3. Trends in Total Citations

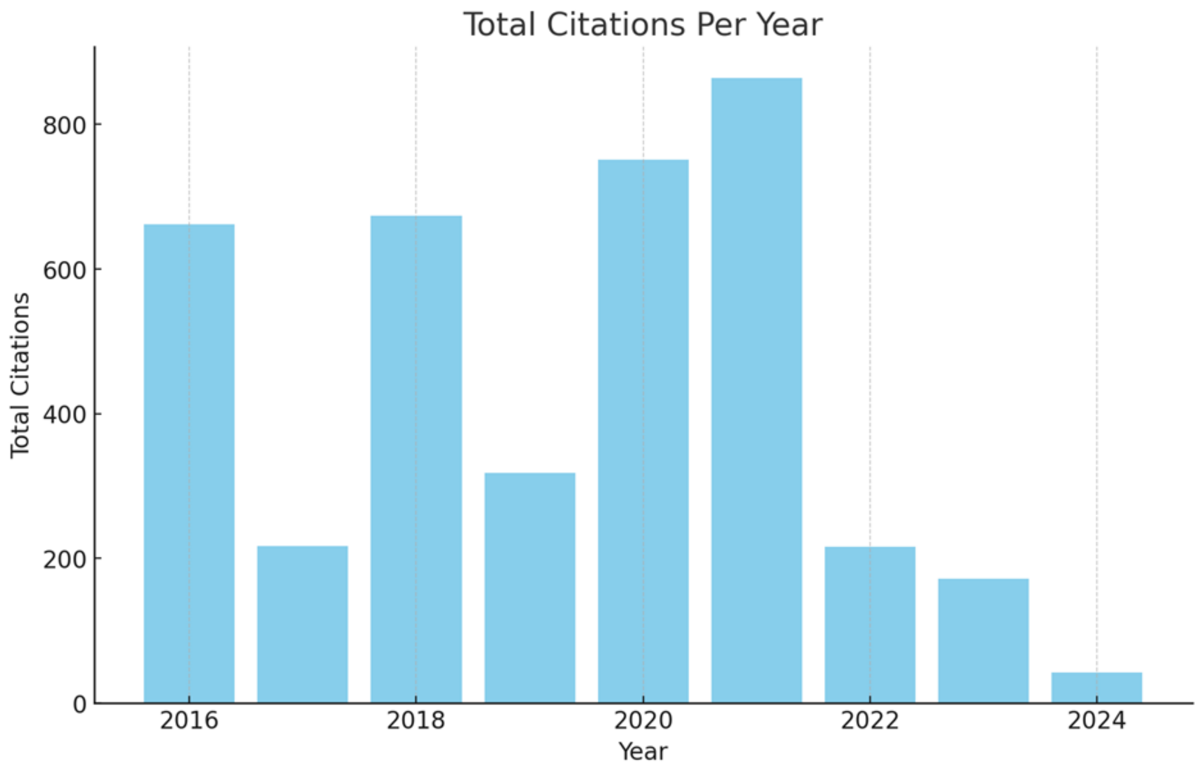

Figure 4.4: Total citation per year,

The lower citation numbers in 2024 do not necessarily indicate declining interest but likely reflect the early stages of citation accumulation. It is well-documented that research publications often reach peak citation rates approximately two years post-publication. Therefore, the citation count for 2024 studies is expected to rise as these studies begin to influence the field. This trend aligns with findings from Kalsoom et al. (2021), who observed a significant increase in citation rates within two years of publication in IoT and digital transformation areas. Such patterns underscore the importance of considering publication and citation delays when analyzing the impact of recent research.

4.1.4. Thematic Evolution and Citation Patterns

In the early years (2016–2018), research focused on foundational themes such as Cyber-Physical Systems, IoT, and Lean Manufacturing, reflecting early explorations into how emerging Industry 4.0 technologies could enhance traditional Lean principles. This phase, consistent with the Initial Research Activity (2016–2017) discussed in the timeline, laid the groundwork for subsequent integration of these technologies into manufacturing systems.

As research progressed, newer themes such as Digital Transformation and Circular Economy gained prominence, reflecting the transition into the Growth Period (2018–2020). This thematic shift mirrors broader technological advancements and the maturation of Industry 4.0 technologies, which by 2020 had become central to discussions on sustainability and efficiency. These themes expanded the research focus from technological integration to interdisciplinary concerns like environmental sustainability.

The relatively low citation numbers in 2024 reflect the early stages of citation accumulation. As highlighted earlier, it is typical for research to gain citations approximately two years post-publication (Kalsoom et al., 2021). Therefore, the true impact of 2024 publications will become clearer in the next few years, and the current data should not be seen as indicative of declining interest.

4.1.5. Keyword Trends and Topic Analysis

The evolution of keywords within Industry 4.0 and Lean Manufacturing provides a window into shifting research priorities. We can trace the field's transition from foundational topics to more complex interdisciplinary themes by examining keyword trends. (Figure 4.5)

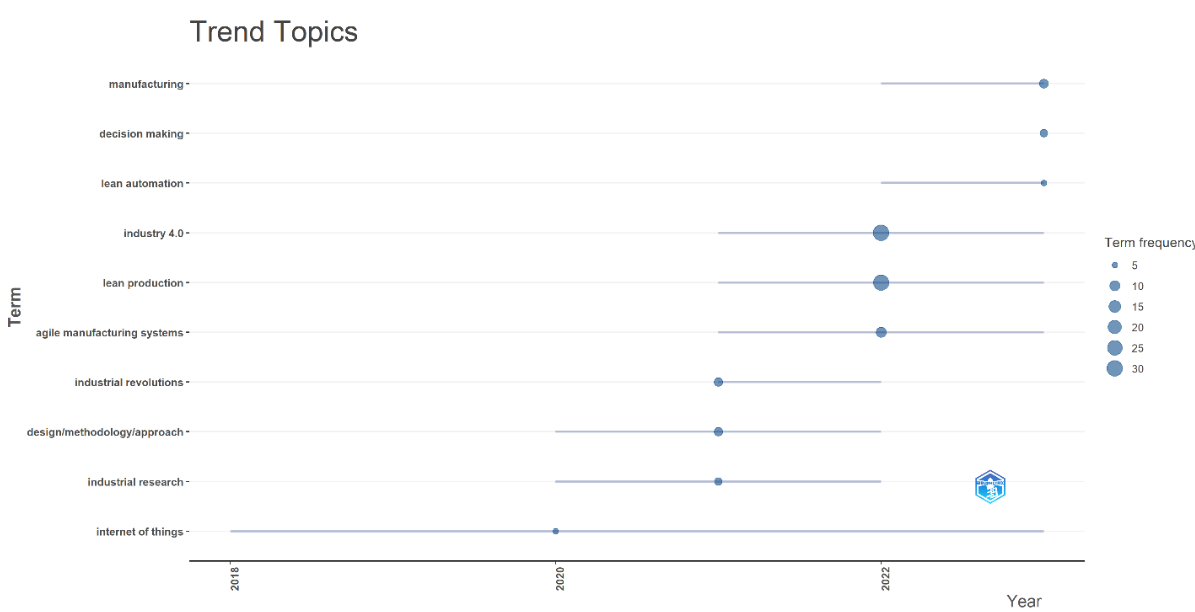

Figure 4.5: Trend topics, Bibliometrix tool

4.1.6. Trend Analysis of Keywords Over Time

As mentioned earlier, the timeline helps contextualize the rise of key terms over time. Industry 4.0, appearing consistently from 2018 onward, underscores the central role of digitalization in manufacturing. This term's dominance aligns with the Technological Milestones (1989–2011), where the increasing digitization of industries laid the foundation for smart manufacturing systems.

Similarly, Lean Manufacturing remains a stable focus throughout the years, mirroring its long-established importance in manufacturing efficiency, as described in the Historical Foundations and Global Expansion of Lean Manufacturing (1890s–2000s) in Chapter 2. The prominence of IoT in 2022 marks a pivotal shift towards incorporating advanced connectivity into manufacturing processes, aligning with the broader global push towards Smart Factories and digital connectivity highlighted in the timeline.

By 2023–2024, keywords such as Circular Economy and Sustainability will emerge, reflecting the integration of environmental policy and sustainable development into manufacturing, consistent with the growing focus on green manufacturing noted in Environmental and Social Impact (1993–2015) in the evolution timeline mentioned earlier.

4.1.7. Quantitative Analysis of Keyword Relevance

Quantitative keyword analysis further highlights the enduring relevance of Industry 4.0 and Lean Production. These terms, frequent in recent years, reflect the field’s ongoing focus on enhancing efficiency and integrating digital technologies. Terms such as Agile Manufacturing Systems and Automation became more prominent during the Growth Period (2018–2020), highlighting the industry’s focus on flexibility and reducing reliance on manual processes, as outlined in Chapter 2’s Technological Milestones.

Emerging terms like embedded systems and digital twins are closely tied to the realization of smart manufacturing solutions that are integral to the Industry 4.0 vision discussed in the timeline. The presence of keywords such as Design/Methodology/Approach across studies suggests that researchers continue to explore strategic frameworks for integrating Industry 4.0 technologies with Lean practices.

4.1.8. Integration of Technology and Lean Practices

Over time, the increasing integration of advanced technologies with Lean practices has become a dominant trend. This is reflected in the rise of terms like Lean Automation, Digital Twin, and

Smart Manufacturing, particularly during the Peak Activity (2023). The industry's move toward leveraging technology for enhanced operational efficiency aligns with the growing complexity of manufacturing systems. The broadening of keywords from core concepts like Lean Production and Industry 4.0 to more advanced themes such as Sustainability and Circular Economy reflects a clear shift toward addressing broader global challenges.

4.1.9. Key Journals and Their Impact on Research

Analyzing leading journals provides valuable insights into the dissemination and influence of research on Industry 4.0 and Lean Manufacturing. These journals are critical in shaping scholarly discourse, guiding research priorities, and setting future study agendas. The distribution of articles among leading journals is shown in the Figure below.

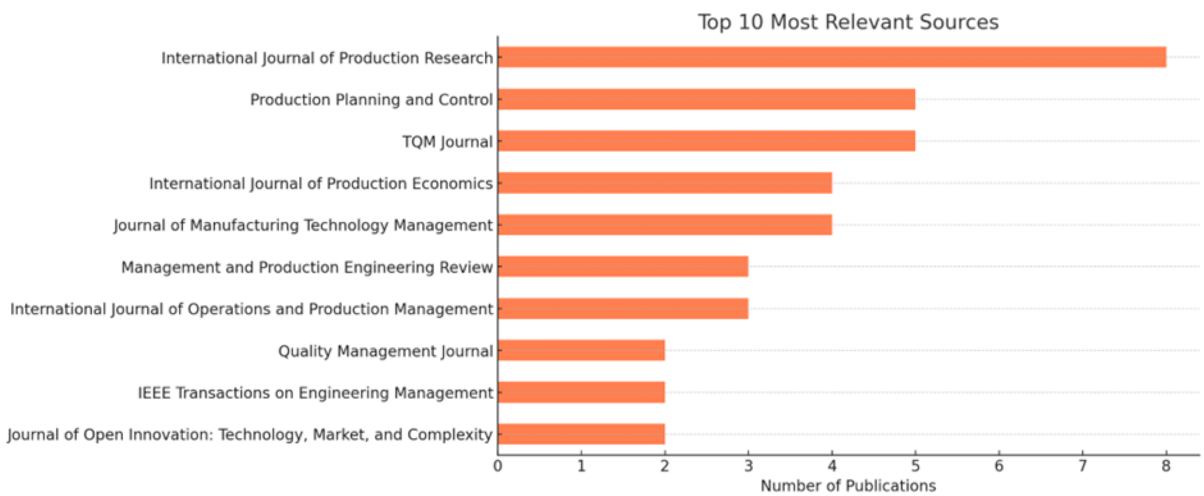

Figure 4.6: Most Relevant Sources

4.1.10. Leading Journals and Publication Patterns

International Journal of Production Research (IJPR): IJPR stands out as the most significant contributor, with eight articles published on integrating Industry 4.0 technologies with Lean methodologies. IJPR has consistently been at the forefront of publishing cutting-edge research, particularly in automating production processes and utilizing cyber-physical systems. Its high impact factor and extensive reach make it a key publication for researchers in the field.

Production Planning and Control (PPC): With five contributions, PPC focuses on the operational intricacies of manufacturing. The journal emphasizes how Industry 4.0 technologies like data analytics and IoT can streamline production planning and enhance supply chain management.

TQM Journal: The TQM Journal also contributes five articles. It specializes in quality management within the Lean Manufacturing framework, particularly as it intersects with Industry 4.0 technologies. Research published in this journal often explores the application of machine learning and advanced data analytics to improve quality control processes.

4.1.11. Trends in Journal Output Over Time

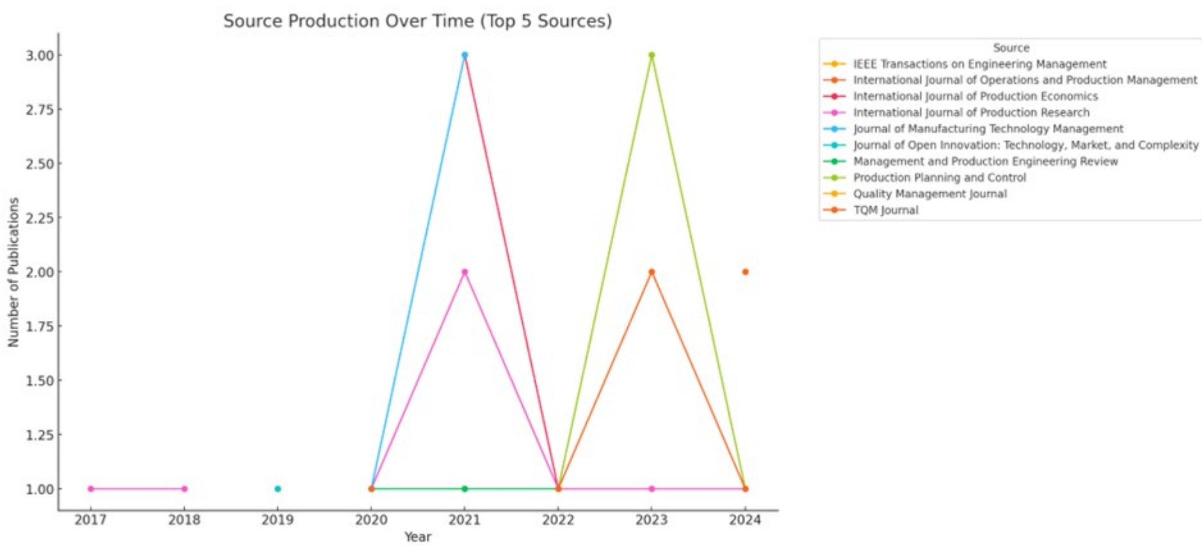

Figure 4.7: Source Production Over Time

This line graph traces the publication output across the top journals from 2017 to 2024. The sharp peaks, particularly in the *Journal of Manufacturing Technology Management* in 2023, suggest periods of concentrated research activity, likely driven by technological innovations and industry demands during those times.

4.1.12. Editorial Influence and Industry Resonance

Special Issues and Thematic Focus: The journals highlighted often release special issues that delve into specific aspects of Industry 4.0, such as the integration of robotics or the shift toward sustainable manufacturing. These thematic issues can significantly influence the research agenda by drawing attention to emerging areas of interest.

Reflecting Industry Innovations: The peaks and trends in publication output often correspond with significant technological advancements or shifts in industry needs. This alignment between academic research and industry innovation underscores the importance of these journals in bridging the gap between theory and practice.

4.1.13. Implications for Researchers and Practitioners

Monitoring the output and trends within these key journals is essential for researchers aiming to contribute to or stay informed about the latest advancements in Industry 4.0 and Lean Manufacturing. The evolving focus of these publications also provides practitioners with insights into the future direction of these critical fields, highlighting where innovation and research are likely to intersect.

4.1.14. Application of Bradford's Law to the Dataset

4.1.14.1. Understanding Bradford's Law

Bradford's Law, introduced by Samuel C. Bradford in 1948, is a key bibliometric principle that describes the distribution of articles on a specific topic across various journals. According to this law, a small journal core will contain the most significant articles in any given field. In contrast, an exponentially larger number of journals will contain fewer articles. This distribution is crucial for researchers and librarians in identifying the most impactful journals for their work, thereby ensuring focused and efficient access to critical literature. (Brookes, 1969)

4.1.14.2. Applying Bradford's Law

In the context of Industry 4.0 and Lean Manufacturing, journals have been categorized into three zones based on their contribution to article and citation counts:

Core Journals (Zone 1): These journals contribute a significant portion of articles and citations and are central to the field:

- International Journal of Production Research
- Journal of Industrial Engineering and Management
- Journal of Manufacturing Technology Management
- International Journal of Operations and Production Management

- International Journal of Production Economics
- TQM Journal
- Production Planning and Control

Secondary Journals (Zone 2): These journals contribute fewer articles but are still significant:

- Technological Forecasting and Social Change
- Management and Production Engineering Review

Peripheral Journals (Zone 3): These journals publish the fewest articles, focusing on niche aspects of the field.

The application of Bradford's Law underscores the concentration of scholarly communication within a few key journals and guides researchers in effectively navigating the literature landscape of Industry 4.0 and Lean Manufacturing.

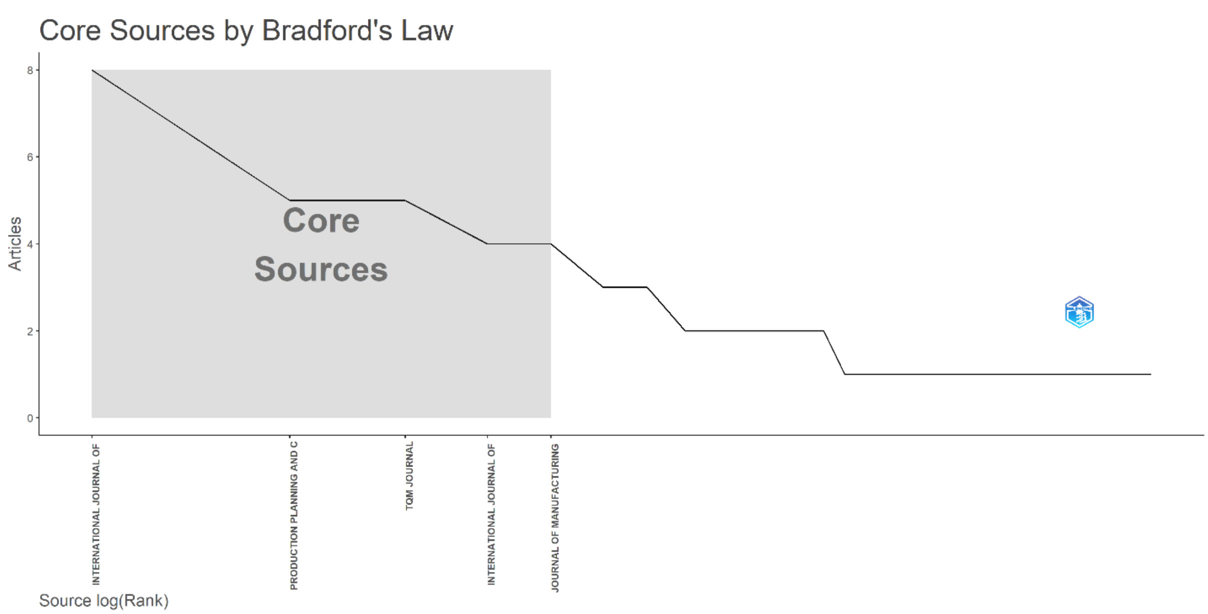

Figure 4.8: Bradford's Law Applied to the Dataset

The figure demonstrates the cumulative distribution of articles across journals. The steep initial curve represents the Core Journals (Zone 1), responsible for most of the research output. As the curve flattens, it indicates increasing journals in the Secondary (Zone 2) and Peripheral (Zone 3) zones, contributing progressively fewer articles.

4.1.15. Sources' Local Impact

Bibliometric indices such as the H-index, G-index, and M-index are essential tools for assessing scholarly journals' academic influence and research output.

H-index: Measures both the productivity and citation impact of the publications of a scholar or journal (Hirsch, 2005). A higher H-index suggests that a journal has many highly cited papers.

G-index: Builds on the H-index by giving additional weight to highly cited articles (Egghe, 2006). It highlights journals that may publish fewer articles but have a significant impact due to high citation counts.

M-index: Normalizes the H-index by accounting for the years a journal has been active (Bornmann & Daniel, 2007). A higher M-index suggests rapid recognition and prominence in its field.

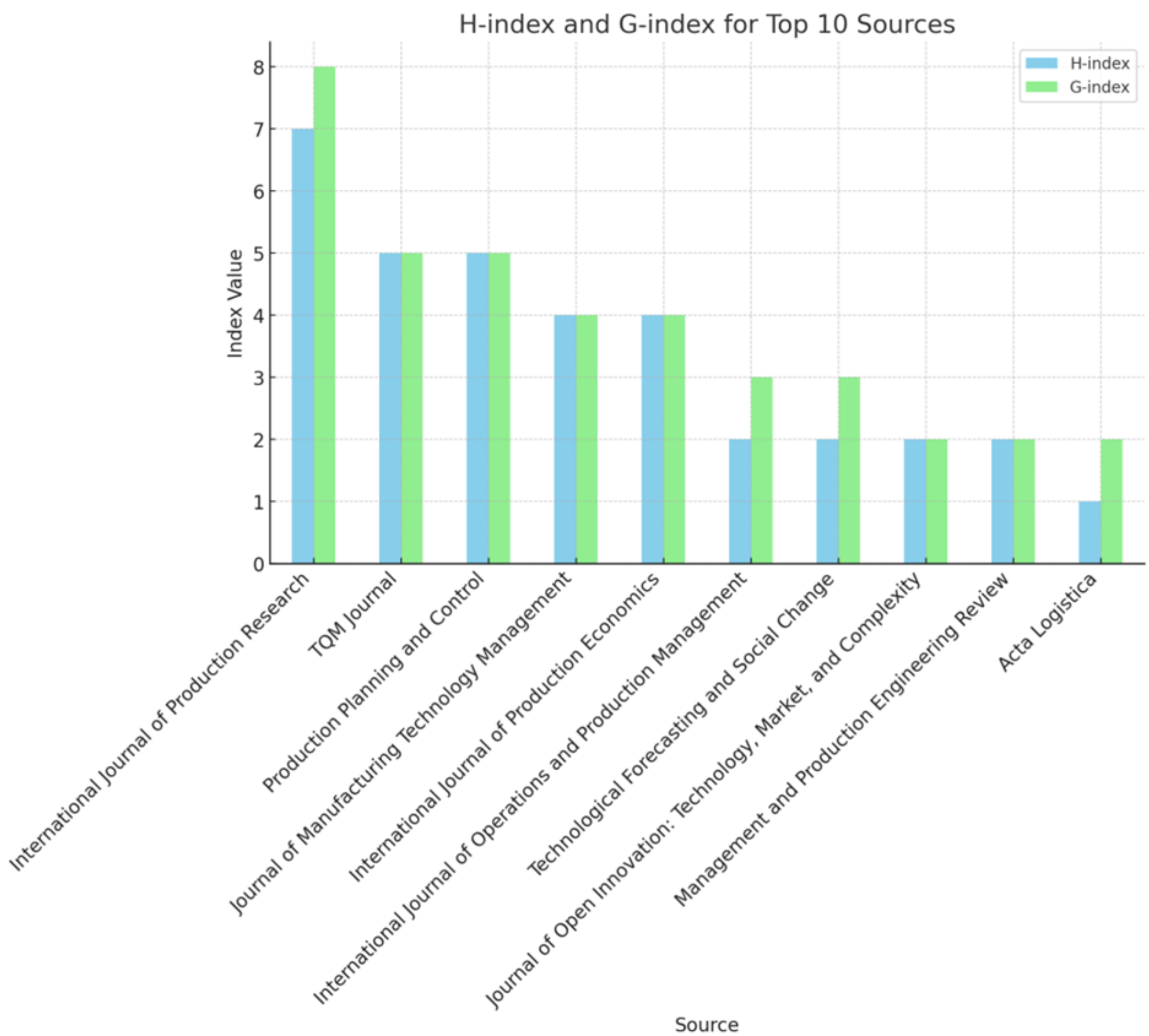

Figure 4.9: H-index and G-index for Top 10 Sources

The chart displays the H-index and G-index values for leading journals in Industry 4.0 and Lean Manufacturing. The *International Journal of Production Research* dominates these metrics, affirming its significant impact on the academic landscape. It is followed by journals like the *TQM Journal* and *Production Planning and Control*, which also demonstrate a strong balance between quality and impact.

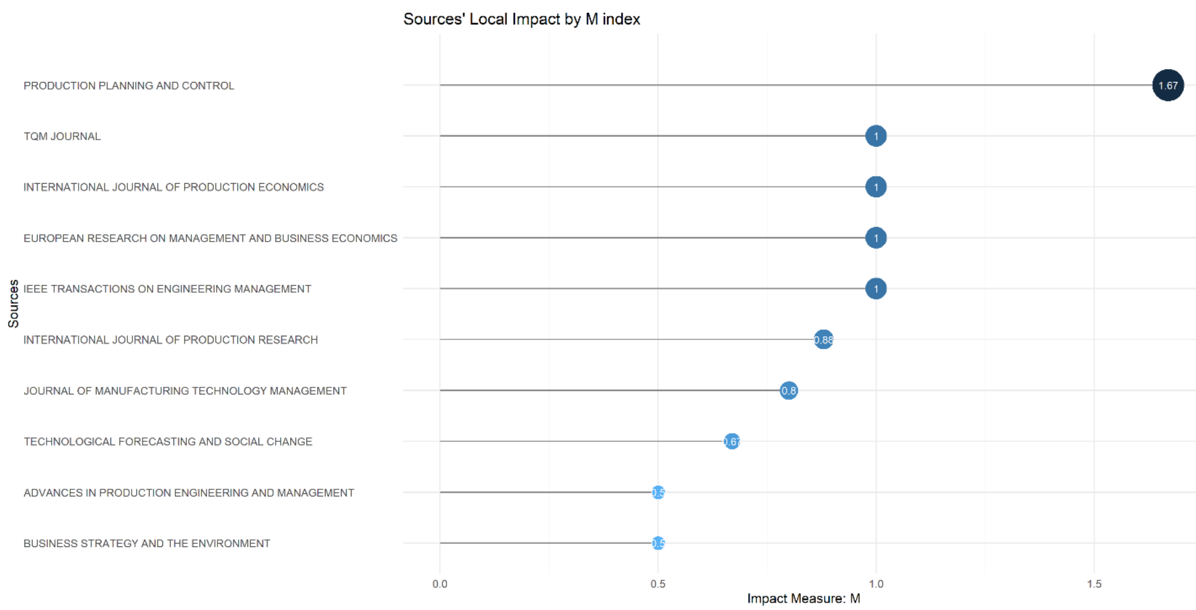

Figure 4.10: Sources' Local Impact by M index

Figure 4.10 showcases the M-index for several key journals. Notably, *Production Planning and Control* leads with an M-index of 1.67, highlighting its exceptional influence per year of activity. This journal's rapid assimilation of impactful research illustrates its pivotal role in shaping advancements within the industry.

Understanding these bibliometric indices aids researchers in making informed decisions about publication strategies. Journals with high H-index and G-index scores are established platforms for impactful research, offering visibility and recognition. Conversely, a high M-index identifies newer journals quickly gaining prominence, making them attractive venues for cutting-edge research.

For academic institutions and librarians, these metrics facilitate the development of journal collections that accurately reflect the evolving contours of scholarly communication, ensuring access to the most pertinent and influential materials.

4.1.16. Geographical Distribution of Research Contributions

4.1.16.1. Global Distribution of Publications

The geographical distribution of research contributions is important for identifying which regions are leading the discourse on Industry 4.0 and Lean Manufacturing.

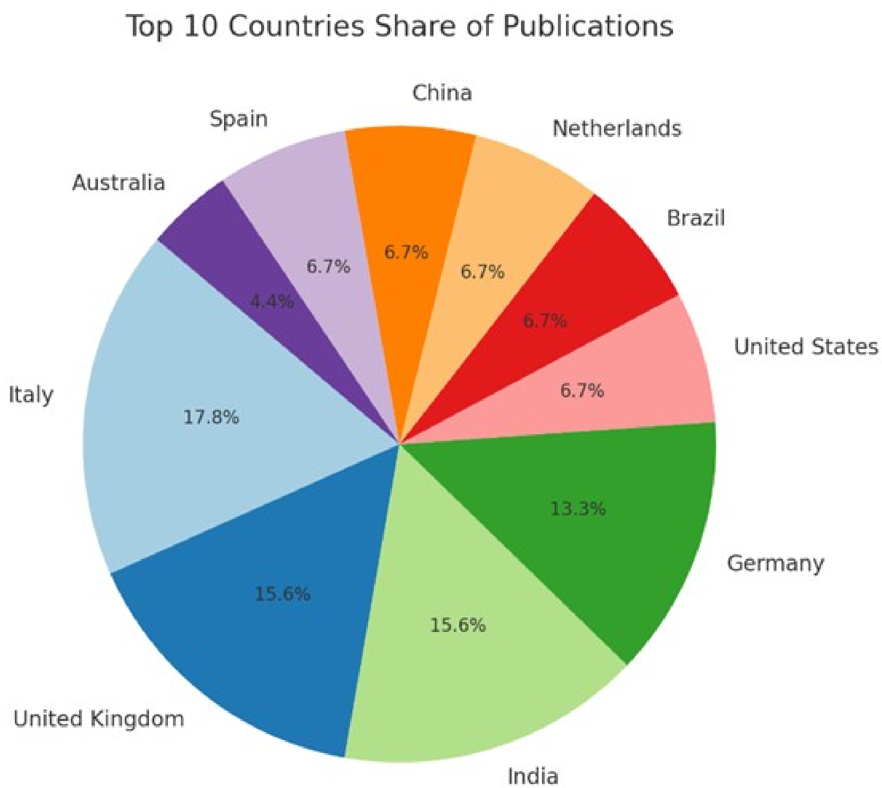

Figure 4.11: Share of Publications by Country

This analysis examines the global landscape by focusing on the countries of corresponding authors. Italy is the leading country, accounting for 17.8% of the publications, followed closely by the United Kingdom and India, each contributing around 15.6%. Other notable contributors include Germany (13.3%), Brazil (6.7%), and China (6.7%). This distribution highlights the significant contributions from European countries, particularly Italy and the UK, and strong representation from India and Germany.

4.1.16.2. International Collaboration: Single-Country Publications (SCP) vs. Multiple-Country Publications (MCP)

This analysis underscores the varying approaches to research across different countries, with some nations prioritizing domestic research while others engage more heavily in international partnerships. These collaboration patterns have significant implications for the dissemination and influence of research findings on a global scale.

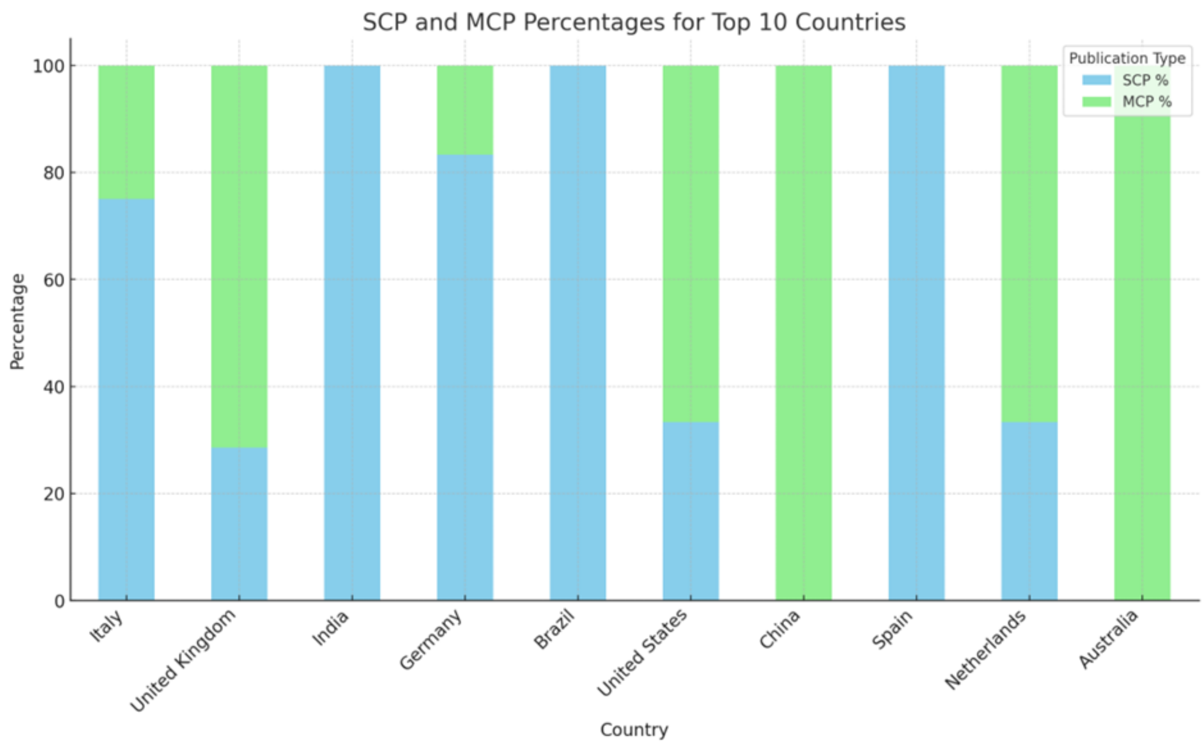

Figure 4.12: SCP vs. MCP Proportions Among Top 10 Countries

High SCP Proportions: Countries like India, Brazil, and Spain exhibit a high percentage of SCPs (100%), indicating a strong focus on domestic research efforts with minimal international collaboration.

Balanced SCP and MCP: Germany and Italy are balanced, suggesting active engagement in domestic and international research networks.

High MCP Proportions: The United Kingdom, China, and Australia demonstrate higher MCP percentages, indicating strong international collaboration and integration into global research networks.

4.1.17. Citation Impact by Country

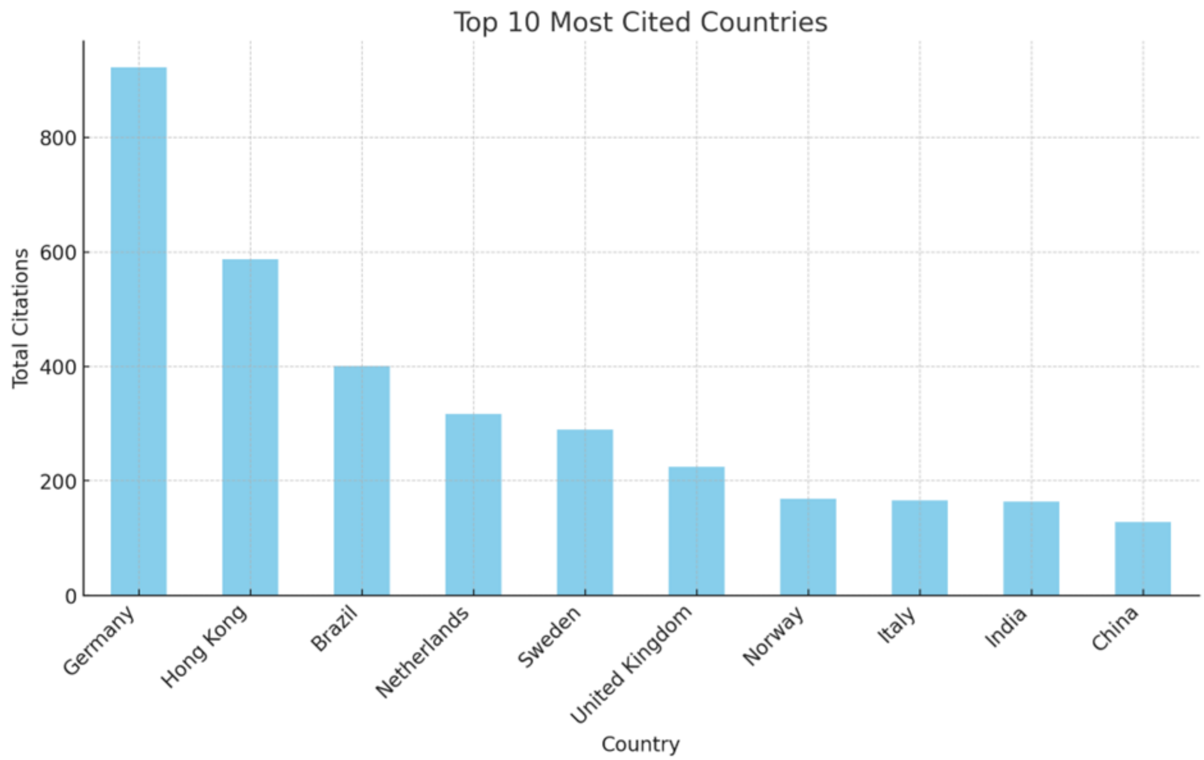

Figure 4.13: Top 10 Most Cited Countries Based on Total Citations Received

Germany ranks highest with 922 citations, followed by Hong Kong (587) and Brazil (401). High citation counts from countries like Germany and Hong Kong suggest that research outputs from these regions are prolific and highly regarded within the global academic community.

Understanding geographical trends is crucial in identifying which regions are pivotal in driving innovation and shaping the manufacturing landscape. By pinpointing these research hubs, we can gain insights into the sources of cutting-edge methodologies and technological advancements. Additionally, assessing collaboration networks is essential for understanding how ideas and practices are disseminated across borders, facilitating international cooperation and knowledge exchange. This analysis aids in strategic research planning by highlighting potential collaboration opportunities and guiding decisions regarding funding allocations. Moreover, it has significant implications for policy-making and funding strategies, as it supports the need to incentivize research activities in emerging regions, promoting a more balanced and inclusive global research environment.

4.1.18. Most Globally Cited Documents

Analyzing the most cited documents, as shown in Figure 4.14, provides insights into the seminal studies shaping Industry 4.0 and Lean Manufacturing. These articles highlight key contributions and areas receiving extensive academic focus and global recognition.

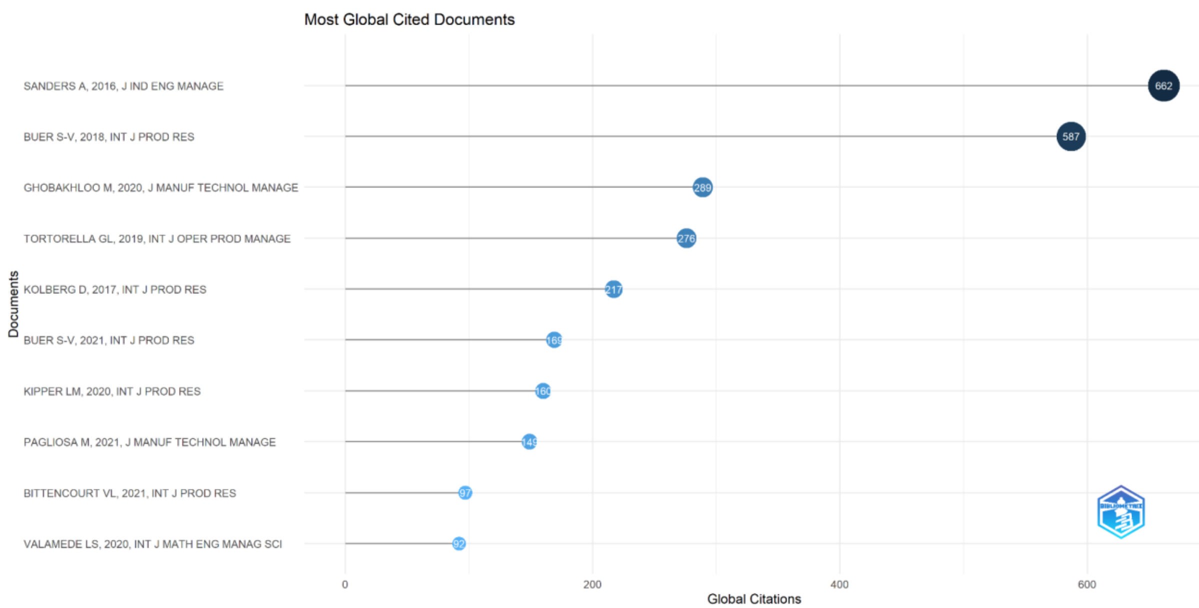

Figure 4.14: Most cited documents, Bibliometrix tool

4.1.19. Top 5 Most Globally Cited Articles

Sanders et al. (2016): "Industry 4.0 Implies Lean Manufacturing: Research Areas for Sustainable Business Models" (662 citations).

Impact: This foundational paper explores how Industry 4.0 technologies integrate with Lean Manufacturing to support sustainable business models. It has significantly influenced subsequent research on digitalization and sustainability in manufacturing processes.

Buer et al. (2018): "The Link Between Industry 4.0 and Lean Manufacturing: Exploring the Implications for Employment" (587 citations).

Impact: This study addresses the socio-economic impacts of Industry 4.0 integrations, focusing on employment shifts and labor market dynamics. Its high citation count highlights its relevance to discussions on workforce adaptation to technological advances.

Ghobakhloo & Fathi (2020): "Corporate Survival in Industry 4.0 Era: The Enabling Role of Lean-Digitized Manufacturing" (289 citations).

Impact: Discussing strategies for corporate sustainability through lean-digitized manufacturing, this paper emphasizes operational efficiency and resilience in response to rapid technological evolution.

Tortorella et al. (2019): "Industry 4.0 Adoption as a Moderator of the Impact of Lean Production Practices on Operational Performance Improvement" (276 citations).

Impact: This research explores how Industry 4.0 technologies enhance the effects of Lean Production practices on operational performance.

Kolberg et al. (2017): "Towards a Lean Automation Interface for Workstation Systems in the Industry 4.0 Era" (217 citations).

Impact: This paper focuses on optimizing lean processes through digital interfaces, which is key to understanding smart factory operations.

4.1.20. Co-occurrence Network and Thematic Analysis of Top Keywords

4.1.20.1. Co-occurrence Network Analysis

The co-occurrence network illustrates the interconnections between pivotal concepts in Industry 4.0 and Lean Manufacturing research. Central nodes such as "Industry 4.0," "lean production," and "agile manufacturing systems" highlight their fundamental role in recent scholarly discourse. Connections between "digital transformation" and "operational performance" suggest an integrative approach to enhancing manufacturing processes through advanced technologies.

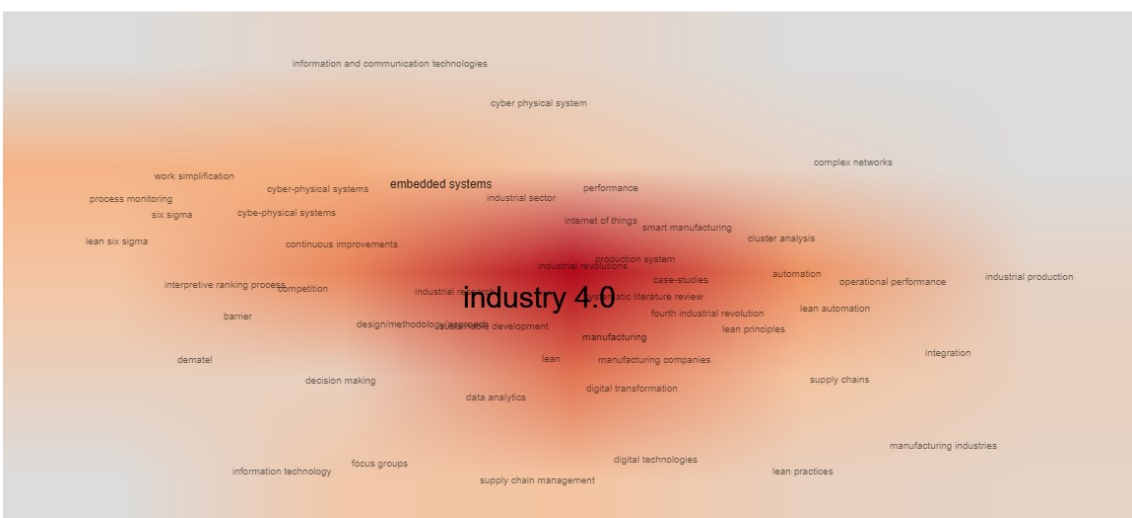

Figure 4.15: Co-occurrence Network of Top Keywords

4.1.20.2. Thematic Analysis

This preliminary thematic analysis, derived from data extracted from Scopus, organizes research topics into three distinct categories besides Basic Theme—Motor Themes, Emerging Themes, and Niche Themes—each reflecting their centrality and stage of development. This overview provides an initial framework, with a comprehensive thematic analysis to follow in the subsequent chapter.

Motor Themes include highly central and developed themes such as "Industry 4.0" and "lean production." Their foundational impact suggests they are the driving forces within the field.

Emerging Themes: Themes like "information technology" and "supply chain management" are gaining momentum, indicating potential new directions for future research.

Niche Themes represent specialized areas with focused contributions, such as "machine learning" and "mass production."

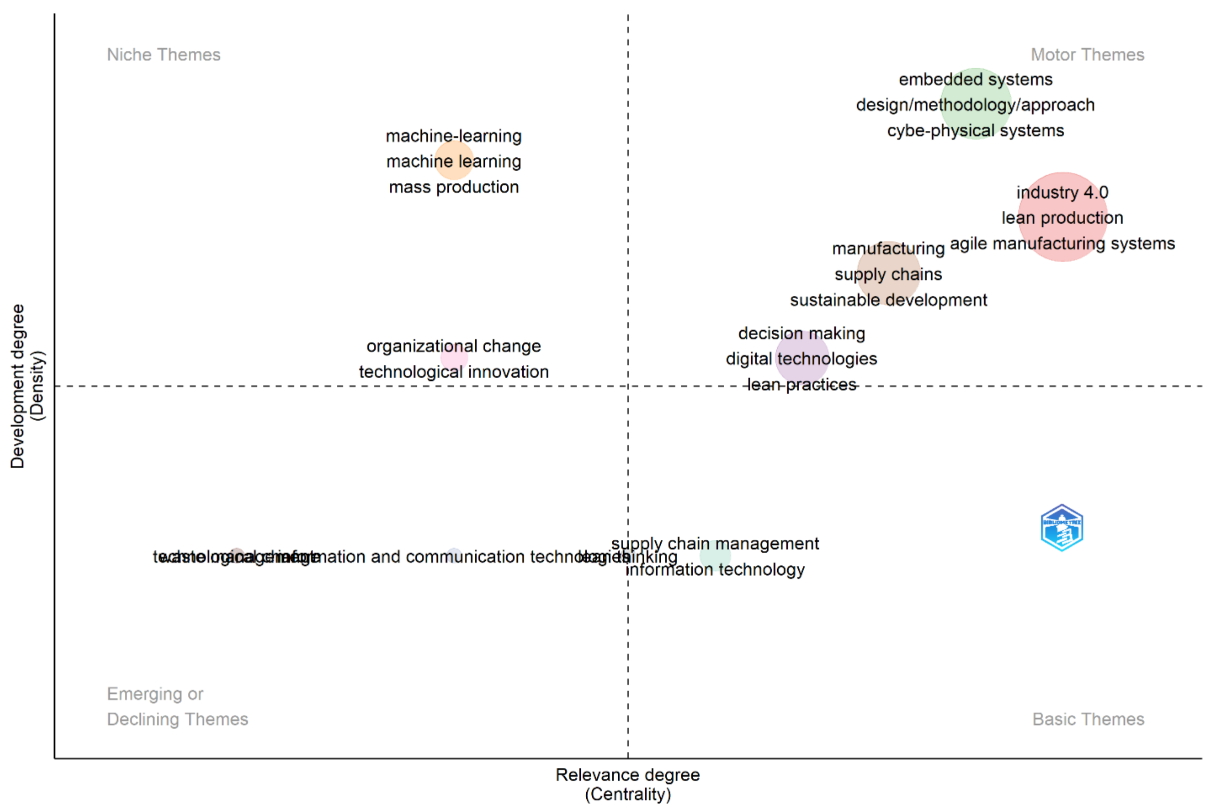

Figure 4.16: Thematic Map of Research Topics

This analysis informs stakeholders about the foundational and innovative themes likely to influence the future of manufacturing integrated with Industry 4.0 technologies. Understanding these trends helps the research community align their investigations and innovation strategies with impactful and relevant topics.

4.2. Critical Evaluation of Findings

4.2.1. Limitations of Data and Analysis Methods

Scope of Publications: While Scopus is broadly recognized and employed for research purposes, exclusive reliance on this database could potentially omit pertinent studies in other repositories, such as Web of Science or IEEE Xplore.

Geographical Bias: Concentration of studies from certain regions may overlook challenges and benefits unique to other areas.

Publication Bias: Positive outcomes are more likely to be published, which might skew the perception of benefits over challenges.

4.2.2. Potential Biases

Journal Focus: Journals specializing in industrial engineering may emphasize technological advancements, possibly underrepresenting socio-economic challenges.

Author Affiliation: Studies conducted by researchers affiliated with technology providers might exhibit bias toward promoting certain Industry 4.0 solutions.

4.2.3. Reliability of Sources

Peer-Reviewed Articles: Most filtered studies are from peer-reviewed journals, enhancing credibility.

Open Access Status: Open Access publications increase accessibility but may vary in quality.

Although the findings present valuable insights, they must be interpreted carefully, considering the study's inherent limitations and potential biases. Future research could benefit from cross-referencing additional databases and integrating grey literature to enhance the depth and reliability of these insights. In the sections that follow, the content analysis is outlined in detail. The findings are organized around seven key themes that were identified during the literature review:

- Phased Implementation of Technologies
- Impact on Operational Efficiency and Performance
- Challenges and Barriers to Integration
- Practical Decision-Guide Framework and Conceptual Framework

- Sustainability and Digital Green Lean
- Sector-Specific Variations in Implementation
- Leadership Styles and Regulatory Considerations in Integration

Each theme is explored in depth, incorporating critical analysis, case studies, empirical data, and theoretical frameworks to provide a comprehensive understanding of integrating I4.0 technologies into LM systems.

4.3. Phased Implementation of Technologies

A recurring theme in the literature is the strategic importance of adopting a phased approach when implementing I4.0 technologies within LM frameworks (Tortorella et al., 2021). This approach allows organizations to mitigate risks, manage resources effectively, and progressively build capabilities aligned with their operational maturity and specific needs.

4.3.1. Phased Implementation Framework

The phased implementation typically involves three stages: **Start-up Phase**, **In-Transition Phase**, and **Advanced Phase**.

Start-up Phase: Organizations begin by adopting foundational digital technologies such as real-time data analytics and basic Internet of Things (IoT) applications. These technologies facilitate quick wins, enhance data visibility, and establish a data-driven culture (Tortorella et al., 2021). For instance, implementing sensors and data collection tools can help monitor machine performance and identify bottlenecks in production processes. According to Frank et al. (2019), companies that started with basic IoT applications observed an average of 10% improvement in operational efficiency within the first year.

In-Transition Phase: Organizations become more comfortable with initial technologies and adopt more complex systems like advanced IoT devices, Radio-Frequency Identification (RFID) systems, and cloud computing. These technologies enhance real-time data collection and improve process control, significantly improving operational efficiency (Buer et al., 2021). For example, using RFID systems in inventory management has resulted in a 25% reduction in inventory levels and a 30% decrease in stockouts (Tabanli & Ertay, 2013).

Advanced Phase: Organizations fully integrate sophisticated technologies such as Artificial Intelligence (AI), Cyber-Physical Systems (CPS), and advanced analytics. These enable predictive analytics and autonomous decision-making, dramatically enhancing productivity, flexibility, and responsiveness (Tortorella et al., 2021). AI algorithms can predict equipment failures before they occur, allowing for proactive maintenance and minimizing downtime. Companies adopting AI and machine learning reported a 40% reduction in machine downtime (Ma et al., 2017).

This phased approach is critical for managing the technical complexity and organizational change associated with I4.0 integration. It allows organizations to develop the necessary skills and infrastructure incrementally, reducing the risk of failure and employee resistance.

4.3.2. Challenges in Phased Implementation

Despite the potential benefits, each phase of implementing Lean 4.0 or Industry 4.0 technologies presents unique challenges. As organizations progress through the stages, the complexity increases, requiring specialized skills, greater technical expertise, and considerable financial resources. This complexity is compounded by the need to balance existing systems with newer technologies. Integrating CPS, for example, can pose significant compatibility issues with legacy systems, necessitating substantial investment in system upgrades and infrastructure (Liao et al., 2017; Tortorella et al., 2021). Firms often find that required upgrades involve reconfiguring the organization's operational architecture (Rybski & Jochem, 2020).

Financial constraints are another significant barrier, especially for small and medium-sized enterprises (SMEs). Many of these firms face difficulties in allocating the budget for advanced technologies like big data analytics, cloud computing, or smart sensors. A study by Frecassetti et al. (2024) indicated that 78% of companies view the high initial costs of integrating I4.0 technologies as a top concern. Investment required in sectors like automotive can range into millions of dollars per plant, as companies purchase robotics big data platforms and integrate these technologies with their Lean systems. Even after partial implementation, companies spend up to 5% of their annual revenue on system maintenance alone (Frecassetti et al., 2024). This leads to a cautious, phased approach but increases the risk of a drawn-out process during which costs could escalate due to evolving technological requirements (Yürekli & Schulz, 2022).

Employee resistance remains a persistent challenge. The shift from traditional lean practices to technology-intensive processes can generate significant anxiety among workers, particularly around fear of job loss due to automation. In a study by Sharma et al. (2022a), over 65% of employees expressed concerns about job security when faced with advanced automation technologies. Employees are often reluctant to alter established work routines or engage with new tools, further slowing technological adoption (Luthra & Mangla, 2018).

Finally, the cost-benefit ratio of phased implementations often remains unclear at the outset, making it harder for management to commit fully to large-scale investments. Companies frequently struggle to quantify the long-term return on investment (ROI) of I4.0 technologies, especially when benefits may take years to materialize. As Yürekli and Schulz (2022) highlight, about 71% of organizations find it challenging to accurately estimate the cost-benefit balance, leading to delays or a piecemeal approach in rolling out new technologies.

4.3.3. Implications and Practical Solutions

The implications of these challenges impact both the technological trajectory and competitive positioning of organizations. Financial constraints and technical complexities can lead to a digital divide, where larger organizations advance rapidly, disadvantaging SMEs (Moeuf et al., 2018). To address these challenges, organizations can explore collaborative approaches such as forming consortiums to share knowledge and resources, reducing individual costs (Sony & Naik, 2019). Leveraging government grants and incentives to promote digital transformation can alleviate financial burdens (Mittal et al., 2018).

Employee resistance can be mitigated through comprehensive change management strategies. This includes transparent communication about the benefits and impacts of new technologies, involving employees in planning and implementation, and providing training to upskill the workforce. Emphasizing the role of technology as an enabler rather than a replacer can help mitigate fears. Automation can take over repetitive tasks, allowing employees to focus on value-added activities enhancing job satisfaction and productivity (Kagermann et al., 2013).

Organizations can adopt an agile approach to project management to address uncertainties in cost-benefit analysis. Utilizing Minimum Viable Products (MVPs) and iterative development can help assess the effectiveness of new technologies in a controlled environment before full-scale implementation (Ries, 2011). Developing clear metrics and KPIs aligned with strategic objectives can provide better visibility into ROI and facilitate data-driven decision-making (Parida et al., 2015).

4.3.3.1. Example: Dompe eHospital Case Study

The Dompe eHospital, Sri Lanka's most appreciated and awarded digital health initiative, successfully implemented Lean and I4.0 concepts in its healthcare operations, optimizing resource allocation and reducing waiting times. By integrating cloud computing, IoT, and big data analytics, the hospital achieved a 20% improvement in resource utilization and reduced patient waiting times by 15% (Rybski & Jochem, 2020). The phased approach allowed the hospital to incrementally address initial challenges related to staff training and technology adoption.

In the Dompe eHospital case, the phased implementation strategy was instrumental in successfully integrating Lean and I4.0 concepts. The hospital began by introducing basic digital tools to streamline patient scheduling and resource allocation, addressing immediate inefficiencies without overwhelming staff (Rupasinghe et al., 2016). As staff became more comfortable, advanced technologies like IoT devices for patient monitoring and big data analytics for predictive diagnostics were introduced. This incremental approach allowed effective cost management and provided time for adequate staff training, reducing resistance to change.

Strong leadership emphasizes a patient-centric approach, aligning technological advancements with the core mission of improving patient care (Fernando et al., 2021). The leadership team engaged employees in decision-making and highlighted benefits for both patients and staff. Regular training sessions and open forums for feedback helped address concerns and foster a culture of continuous improvement.

4.3.4. Critical Analysis

While phased implementation offers a structured approach, it may delay the realization of full benefits, especially in competitive environments where rapid transformation is critical. Incremental adoption can lead to integration issues between technological stages, causing temporary inefficiencies (Tortorella et al., 2019). As shown in Table 4.1, technologies like Big Data and Additive Manufacturing have high costs and complexity, which may slow down implementation, forcing organizations to balance these challenges against potential long-term benefits.

Table 6: Cost and Complexity of Various Industry 4.0 Technologies

Technology	**Initial Cost**	**Complexity**	**Long-Term Benefits**
Big Data	High	High	Promising
Additive Manufacturing	High	Medium	Promising
AR/VR	Medium	Medium	Positive

Sensors (incl. RFID)	Low	Low	Moderate
Cyber Security	High	High	Essential
Mobile Devices	Low	Low	Positive

Companies need to evaluate cost-benefit ratios carefully. Technologies like Cyber Security and Big Data require significant investment but offer substantial long-term gains. At the same time, lower-cost solutions like Sensors and Mobile Devices deliver quicker, albeit more modest, improvements. Organizations must balance caution with urgency in digital transformation, considering their specific strategic objectives and competitive pressures.

4.4. Impact on Operational Efficiency and Performance

Integrating LM with I4.0 technologies has significantly enhanced operational efficiency and performance across various industries. By combining Lean's waste reduction focus with the real-time data, automation, and advanced analytics capabilities of I4.0, organizations create agile manufacturing systems capable of responding to complex market demands. This synergy addresses the first two research questions by identifying key I4.0 technologies applied in LM systems and highlighting the Lean practices most impacted by I4.0 integration.

4.4.1. Productivity Gains

Significant productivity improvements have been reported across various sectors. Sanders (2016), in a research study of the automotive industry, demonstrated a 25% increase in throughput after adopting real-time monitoring systems and AI-driven process optimization. The combination of Lean's Just-in-Time (JIT) methodology and I4.0's predictive maintenance resulted in smoother workflows and reduced bottlenecks.

In the electronics manufacturing sector, integrating Additive Manufacturing and Big Data Analytics led to a 40% increase in production output (Pekarcikova et al., 2020). Customization capabilities and real-time data insights allowed for faster adjustments to production processes, enhancing responsiveness to customer demands.

4.4.2. Lead-Time Reduction

Lead-time reduction is another critical benefit of integrating LM and I4.0 technologies. Companies have drastically reduced lead times using Value Stream Mapping (VSM) alongside simulation tools and IoT-enabled real-time data. Schmidtke et al. (2014) reported a reduction in lead times from 11.4 days to 1.4 days after implementing these technologies—the integration allowed for identifying and eliminating non-value-added activities, streamlining the production process.

For SMEs, IoT-based JIT systems optimized inventory and production schedules, resulting in a 33.92% reduction in work-in-progress (WIP) inventory (Erkayman, 2019). This reduction improves cash flow and minimizes storage costs and risks associated with excess inventory.

4.4.3. Cost Savings

Integrating LM and I4.0 technologies has resulted in significant cost reductions. In the automotive sector, IoT and predictive maintenance led to a 50% reduction in operational costs (Ma et al., 2017). These savings were achieved by reducing machine downtime, minimizing equipment failures, and optimizing maintenance schedules based on real-time data.

In the electronics industry, integrating Kanban and RFID technologies yielded monthly cost savings of approximately €1,039, enabling the system to recoup its initial investment of €17,882 within roughly 17 months (Tabanli & Ertay 2013). Table 4.2 illustrates the cost savings achieved by integrating specific LM practices and I4.0 technologies.

Table 7: Cost Savings from Integrating LM and I4.0 Technologies

Industry	LM Practice	I4.0 Technology	Cost Savings Achieved	Source
Automotive	Total Productive Maintenance (TPM)	IoT Sensors, AI	50% reduction in operational costs	Ma et al. (2017)
Electronics	Kanban System	RFID Technology	€1,039.8 monthly savings	Tabanli & Ertay (2013)
Manufacturing SME	5S Implementation	Digital Checklists	20% increase in productivity	Moeuf et al. (2018)

4.4.4. Improved Equipment Effectiveness

Integration has significantly improved equipment reliability and reduced downtime. Companies have enhanced equipment effectiveness by integrating TPM with I4.0 tools such as IoT sensors and Digital Twins. In the aerospace industry, IoT-enabled predictive maintenance led to an 80% improvement in equipment reliability, reducing breakdowns and unplanned maintenance (Alebrant et al., 2014).

4.4.5. Customization and Flexibility

Lean 4.0 technologies have enhanced customization capabilities, allowing companies to respond flexibly to changes in customer demand. Siemens reported a 15% improvement in productivity after integrating Additive Manufacturing and IoT into its production processes, enabling mass customization without significant additional costs (Ghadge et al., 2020).

4.4.6. Reduction in Defects and Rework

Reductions in defects and rework have been reported, contributing to quality improvements. Integrating Jidoka (automation with a human touch), 5S, and Kanban with real-time data analytics reduced defective products from 18% to 10% in electronics manufacturing. It lowered rework rates from 7% to 3% (Condé al., 2022).

4.4.7. Emerging Technologies and Trends

Recent developments up to 2024 have introduced new technologies that further enhance the integration of LM and I4.0. Advancing AI and Machine Learning (ML) has enabled more sophisticated predictive analytics and autonomous decision-making. The adoption of Edge Computing allows for real-time data processing at the source, reducing latency and improving responsiveness in manufacturing processes (Shi et al., 2016).

The implementation of 5G technology has facilitated faster and more reliable communication between devices, supporting the increased connectivity required for IoT applications in intelligent factories (Chen et al., 2020). Blockchain technology is gaining traction for enhancing transparency and security in supply chain management, contributing to Lean objectives by reducing inefficiencies and enabling traceability (Jackson et al., 2023).

Another significant trend is the focus on Cybersecurity, as increased connectivity exposes organizations to potential cyber threats. Integrating robust cybersecurity measures is essential for protecting data integrity and ensuring digitalized systems' reliability (Shamim et al., 2016).

These emerging technologies present new opportunities for organizations to optimize operations further and introduce additional complexities that require careful consideration in the integration process.

4.4.8. Critical Analysis

While the benefits are significant, the extent of improvement varies across industries and depends on organizational readiness, employee skills, and technology adoption levels. Substantial investments in technology and training are required, which may not be feasible for all organizations, particularly SMEs with limited resources. There is also a risk of over-reliance on technology, potentially neglecting the human-centric aspects of Lean principles. A balanced approach that leverages technology while focusing on people and processes is essential for sustainable success.

4.5. Challenges and Barriers to Integration

Despite the significant benefits, integrating I4.0 technologies into LM systems presents several challenges and barriers. Understanding these challenges is crucial for organizations to develop effective strategies for successful integration.

4.5.1. Technical and Knowledge Barriers

A primary challenge is SMEs' lack of technical expertise in deploying I4.0 technologies and aligning them with operational excellence (Joshi et al., 2024). The complexity of integrating new technologies into existing systems can be daunting. Approximately 43% of reviewed studies identified the complexity of integration with legacy systems as a significant challenge (Tortorella et al., 2019). Compatibility issues and the need for system interoperability can hinder progress, requiring significant investment in upgrading or replacing existing infrastructure.

4.5.2. Financial Constraints and Initial Costs

The financial burden of adopting I4.0 technologies is significant, particularly for SMEs (Ericson et al., 2020). These systems require substantial capital investments for infrastructure, software, and training, which can be prohibitive. Justifying the long-term benefits of specific technologies remains challenging, with 71% of participants in a study struggling with cost-benefit analyses of digital adoption (Rybski & Jochem, 2020).

4.5.3. Lack of Standardization and Skilled Workforce

The lack of standardization in deploying operational excellence strategies and I4.0 technologies makes interoperability between systems difficult (Luthra & Mangla, 2018). SMEs often face a shortage of skilled workers with the technical acumen required for I4.0 and the management skills to implement Lean methodologies effectively (Sharma et al., 2021). Rapid technological advancements further exacerbate this skills gap.

4.5.4. Organizational Resistance

Resistance to change is prevalent within SMEs, especially regarding Lean and I4.0 integrations. Issues like fear of job losses due to automation, reluctance to abandon traditional practices, and inadequate involvement of top management limit the scope of successful integration (Sharma et al., 2022a). In a study by Joshi et al. (2024), 60% of organizations reported employee resistance as a significant barrier.

4.5.5. Strategies for Overcoming Challenges

Several strategies have been proposed to address these challenges:

Phased Implementation: Allows companies to adopt new technologies incrementally, enabling gradual workforce training and adjustment to cultural shifts (Joshi et al., 2024).

Pilot Projects: Using pilot projects as a testing ground reduces risks and provides proof of concept for more significant investments (Wagner et al., 2017).

Employee Training Programs: Investment in training and development builds the skills required for digital transformation (Moeuf et al., 2018).

Government and Institutional Support: SMEs could benefit from government incentives, such as grants and subsidies, to offset the high costs of I4.0 technology adoption (Luthra & Mangla, 2018).

Table 8: Challenges and Strategies for Integrating LM and I4.0

Challenge	**Description**	**Proposed Strategies**	**Source**

Technical and Knowledge Barriers	Complexity in integrating new technologies with existing systems	Employee Training Programs; Phased Implementation	Joshi et al. (2024); Moeuf et al. (2018)
Financial Constraints	High initial costs for technology adoption	Government Support; Pilot Projects	Ericson et al. (2020); Luthra & Mangla (2018)
Lack of Skilled Workforce	Shortage of employees with the necessary skills	Employee Training Programs; Recruitment of Skilled Personnel	Sharma et al. (2021)
Organizational Resistance	Resistance to change among employees and management	Change Management Strategies; Leadership Engagement	Sharma et al. (2022a); Joshi et al. (2024)

4.6. Practical Decision-Guide Framework and Conceptual Framework

Building upon the thematic analysis and addressing the three research questions, this study proposes a novel Practical Decision-Guide Framework for integrating Lean Manufacturing (LM) and Industry 4.0 (I4.0) technologies. This framework represents an original contribution by offering a comprehensive, adaptable approach considering organizational maturity, resources, and sector-specific factors. It is designed to guide organizations through a tailored integration process, emphasizing dynamic capabilities, continuous improvement, and strategic alignment.

4.6.1. Overview of the Framework

The proposed framework guides organizations through five interconnected stages:

- Assess Current State
- Categorize Company Type
- Select Appropriate Integration Path
- Implement and Monitor
- Evaluate and Improve

These stages are interconnected through feedback loops, enabling organizations to adapt and refine their strategies based on new insights and changing environments.

Table 9: Practical Decision-Guide Framework for Integrating LM and I4.0

Stage	**Key Actions**	**Tools/References**
Stage 1: Assess Current State	- Lean Maturity Assessment - Digital Readiness Assessment - Resource Availability Check - Dynamic Capabilities Evaluation	Lean Maturity Matrix (Tortorella et al., 2021); I4.0 Maturity Models (Frank et al., 2019); Resource et al. (Upadhyay et al., 2023); Dynamic Capabilities Framework (Teece, 1997)
Stage 2: Categorize Company Type	- Classify the organization into one of four types: Type A: High Lean, Low Digital Type B: Low Lean, High Digital Type C: Balanced Lean and Digital Type D: Low Lean, Low Digital	Company Categorization Model (Adapted from Tortorella et al., 2021)

Stage 3: Select Appropriate Integration Path	- Choose the integration path that aligns with the company type: Type A: Enhance Digital Capabilities Type B: Strengthen Lean Practices Type C: Implement Lean Smart Manufacturing Type D: Build Foundational Capabilities	Proposed Integration Paths - This Study - Adopted from Frameworks Li (2019); Tortorella et al. (2021); Upadhyay et al. (2023)
Stage 4: Implement and Monitor	- Pilot Projects - Feedback Loops - Iterative Scaling	Pilot Implementation Guidelines (Frank et al., 2019); Continuous Improvement Practices (Li, 2019)
Stage 5: Evaluate and Improve	- Performance Metrics - Continuous Adaptation	KPI Dashboards (Rossini et al., 2021); Continuous Improvement Cycles (Upadhyay et al., 2023)

4.6.2. Detailed Explanation of the Framework

Stage 1: Assess Current State

- Organizations begin by thoroughly assessing their current LM practices and digital readiness. This includes:
- Lean Maturity Assessment: Evaluating the implementation and effectiveness of Lean tools and methodologies such as 5S, Kaizen, Just-in-Time (JIT), and Value Stream Mapping (VSM).
- Digital Readiness Assessment: Examining the adoption and utilization of digital technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and data analytics.

- Resource Availability Check: Assessing financial capabilities, technological infrastructure, and human resources to support integration efforts.
- Dynamic Capabilities Evaluation: This involves determining the organization's ability to sense opportunities, seize them through strategic action, and transform processes to sustain competitiveness (Teece, 2007).

In this stage, the organization exercises its sensing capabilities by identifying internal strengths and weaknesses, as well as external opportunities and threats.

Stage 2: Categorize Company Type

Based on the assessments, organizations categorize themselves into one of four types:

- Type A: High Lean maturity, Low Digital readiness
- Type B: Low Lean maturity, High Digital readiness
- Type C: Balanced Lean and Digital Maturity
- Type D: Low Lean maturity, Low Digital readiness

The organization utilizes its seizing capabilities to select strategic options that align with its current state. This categorization is essential for tailoring the integration strategy to the organization's specific context.

Stage 3: Select Appropriate Integration Path

Each company type follows a specific integration path:

- Type A: Enhance Digital Capabilities
  - Focus: Integrate advanced digital technologies into existing Lean practices.
  - Strategies:
    - Adopt Digital Twin technologies for process simulation and optimization.
    - Implement IoT sensors to collect real-time data for continuous improvement.
- Type B: Strengthen Lean Practices
  - Focus: Improve Lean methodologies while leveraging existing digital capabilities.
  - Strategies:
    - Introduce Lean tools like 5S and Kaizen events to eliminate waste.
    - Use data analytics to identify bottlenecks and enhance process flow.
- Type C: Implement Lean Smart Manufacturing

    - Focus: Leverage advanced digital technologies alongside mature Lean practices for synergistic benefits.
    - Strategies:
        - Integrate cyber-physical systems for real-time decision-making.
        - Co-create value with customers and suppliers through collaborative platforms.
- Type D: Build Foundational Capabilities
    - Focus: Develop foundational competencies in both Lean practices and digital technologies.
    - Strategies:
        - Start with basic Lean tools and simple digital solutions.
        - Emphasize training and development to build organizational capabilities.

The organization further exercises its seizing capabilities by selecting and committing to the appropriate integration path.

Stage 4: Implement and Monitor

Organizations implement the selected integration path through:

- Pilot Projects: Testing new processes and technologies in controlled environments to minimize risks.
- Feedback Loops: Establishing mechanisms to gather data, monitor performance, and capture insights.
- Iterative Scaling: Gradually expanding successful pilots, adjusting strategies based on feedback.

At this stage, the organization employs its transforming capabilities to reconfigure resources and processes, adapting to new technologies and practices.

Stage 5: Evaluate and Improve

Organizations continuously evaluate performance and seek improvements by:

- Performance Metrics: Using Key Performance Indicators (KPIs) to measure operational efficiency, flexibility, and sustainability.
- Continuous Adaptation: Refining strategies and processes based on performance data and changes in the external environment.

The organization reinforces its transforming capabilities, ensuring long-term competitiveness through continuous learning and adaptation.

4.6.3. Conceptual Framework

The conceptual framework is depicted as a cyclical model, emphasizing the interconnectedness of the stages and the continuous improvement cycle. Feedback loops between stages allow organizations to revisit previous steps based on new insights or changing conditions.

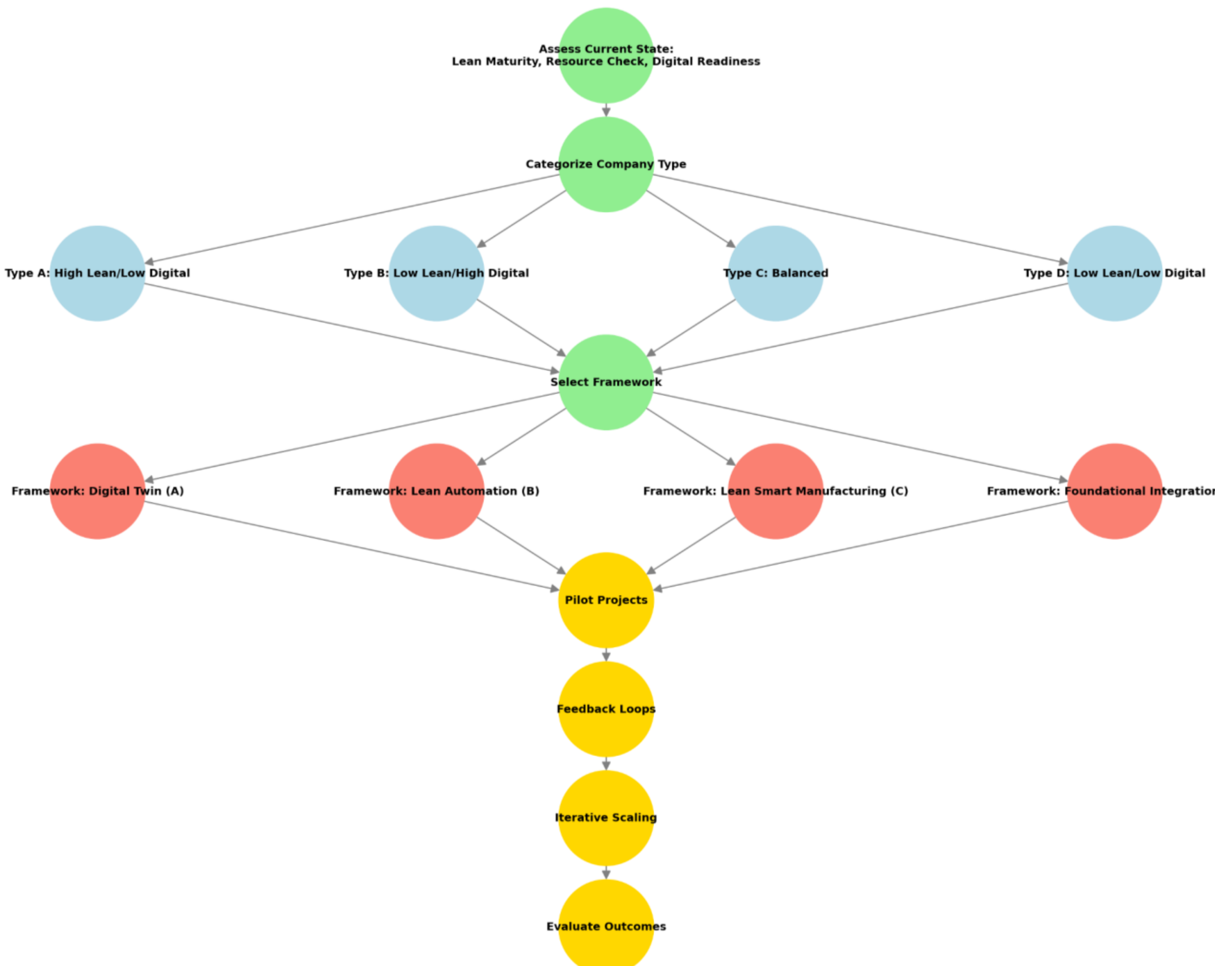

Figure 4.17: Conceptual Framework for Integrating LM and I4.0

The figure illustrates a circular flow connecting all five stages, with feedback loops enabling movement back to earlier stages. Dynamic capabilities are central, represented by a core that influences all stages. Continuous improvement encircles the framework, highlighting the ongoing nature of the integration process.

4.6.3.1. Key Components and Interactions within the Framework:

- Dynamic Capabilities: Central to the framework, enabling organizations to sense opportunities, seize them, and transform resources for sustained competitiveness (Teece, 2007).
- Feedback Loops: Facilitate adjustments and refinements between stages, promoting agility and responsiveness.
- Phased Implementation: Supports gradual integration, managing risks, and building capabilities incrementally.
- Continuous Improvement: Aligns with the Lean principle of Kaizen, emphasizing ongoing enhancements based on performance data and feedback.
- Sector-Specific Adaptation: Allows customization of strategies to align with sector-specific needs and constraints.

4.6.3.2. Practical Application:

To illustrate the application of the framework, consider the following detailed case examples:

Case Example 1: Type A Company

A manufacturing SME with strong Lean practices but limited digital adoption:

- **Stage 1**: Conducts assessments confirming high Lean maturity and low digital readiness.
- **Stage 2**: Categorizes as Type A.
- **Stage 3**: Selects the Enhance Digital Capabilities integration path.
- **Strategies**:
    - Implement Digital Twin technologies to simulate and optimize production processes.
    - Invest in IoT sensors for real-time data collection and monitoring.
- **Stage 4**: Launches pilot projects on select production lines and establishes feedback loops to monitor performance.
- **Stage 5**: Evaluate KPIs such as cycle time reduction and defect rates, leading to iterative improvements and scaling across the organization."

Case Example 2: Type D Company

A small enterprise with low Lean maturity and low digital readiness:

- **Stage 1**: Assesses both Lean practices and digital technologies as minimal.
- **Stage 2**: Categorizes as Type D.
- **Stage 3**: Selects the Build Foundational Capabilities integration path.
- Strategies:
    - Begin with basic Lean training for staff to instill Lean culture.
    - Adopt simple digital tools like spreadsheet-based inventory tracking.
- **Stage 4**: Implements small-scale Lean initiatives and monitors progress through simple feedback mechanisms.
- **Stage 5**: Measures waste reduction and process consistency improvements and adjusts strategies as capabilities grow.

The framework allows organizations to revisit previous stages. For instance, as a Type D company develops its foundational capabilities, it may reassess and recategorize itself, selecting a new integration path that aligns with its evolved state.

4.6.3.3 Critical Analysis

While the framework offers a comprehensive and adaptable approach, its effectiveness depends on:

- Accurate Self-Assessment: Organizations must honestly evaluate their Lean maturity and digital readiness. Inaccurate assessments can lead to misalignment of strategies.
- Commitment Across Organizational Levels: Successful implementation requires commitment from leadership and engagement of employees at all levels.
- Resource Availability: Adequate resources must be allocated for integration efforts.

Mitigation Strategies

- Use of Standardized Assessment Tools: Employ third-party audits or standardized maturity models to enhance accuracy.

- **Leadership Development**: Invest in training leaders to champion change and foster a culture that embraces innovation.
- **Resource Planning**: Conduct thorough resource planning and secure necessary investments before proceeding.

4.6.3.4. Novel Contributions and Distinctions from Existing Frameworks

The proposed framework distinguishes itself from existing ones through its comprehensive, adaptable approach. The following matrix compares the key dimensions of existing frameworks with the proposed framework.

Table 10: Comparison of Integration Frameworks

Dimension	Li et al. (2019)	Tortorella et al. (2021)	Frank et al. (2019)	Upadhyay et al. (2023)	Proposed Framework
Focus	Strategic Co-creation	Operational Phased Implementation	Technology-Centric Adoption	Holistic Integration	Comprehensive Decision Guide
Scope	Integration of Physical and Cyber-Systems	Gradual Integration of Automation and I4.0	Systematic Adoption of I4.0 Technologies	Organizational Readiness and External Factors	Organizational Maturity, Resources, Sector-Specific Factors
Applicability	Mature Lean Organizations	Organizations at Various Lean Stages	Large Enterprises	Small and Medium Enterprises (SMEs)	Adaptable to All Organizations
Novel Contributions	Emphasis on Continuous Co-creation	Phased Approach to Automation	Layered Technology Adoption	Balanced Approach for SMEs	Tailored Integration Paths Based on Company Type
Integration Pathways	Continuous Improvement	Stage-Based Implementation	Technology Prioritization	Holistic Assessment	Customizable Paths with Feedback Loops

The proposed framework distinguishes itself through several novel features that address gaps in existing models. Firstly, it offers a tailored approach by providing customizable integration paths based on company type, considering both Lean maturity and digital readiness. This customization allows organizations to select strategies that align closely with their specific circumstances, enhancing the relevance and effectiveness of the integration process.

Secondly, the framework integrates Dynamic Capabilities Theory, effectively linking theoretical constructs to practical steps. Grounding the framework in this theory emphasizes the importance of seizing opportunities through strategic action and transforming processes to sustain competitiveness. This linkage provides a robust theoretical foundation and offers practical guidance on how organizations can develop and leverage their dynamic capabilities while integrating LM and I4.0 technologies.

Thirdly, incorporating feedback loops throughout all stages introduces continuous feedback and adaptation mechanisms. This ensures that organizations can adjust their strategies based on real-time insights and evolving conditions, promoting agility and fostering a culture of continuous improvement. The feedback loops enhance the framework's responsiveness and help organizations navigate the complexities of digital transformation more effectively.

Lastly, due to its customizable nature, the framework's universal applicability makes it adaptable to organizations of various sizes and sectors. Unlike existing models that may be tailored to specific industries or company sizes, this framework provides a versatile tool that can be adjusted to meet different organizations' unique needs and constraints. This broad applicability enhances its practical utility and potential impact across diverse organizational contexts.

4.6.4 Recommendations for Future Research

Given that the proposed framework is a suggested model derived from the synthesis of available literature and this study's findings, future research should focus on several key areas to validate and enhance its effectiveness.

Firstly, empirical validation is essential. Testing the framework in various organizational settings through case studies and longitudinal research will provide insights into its practical applicability, identify potential challenges in implementation, and offer evidence of its impact on organizational performance.

Secondly, assessment tools need to be refined. Developing standardized instruments for evaluating Lean maturity and digital readiness will improve the accuracy of organizational selfassessments. Enhanced assessment tools will help organizations more precisely determine their starting point, leading to better alignment of integration strategies and potentially increasing the success rate of implementation efforts.

Thirdly, exploring sector-specific applications is an important avenue for future research. Investigating how the framework can be adapted to specific industries with unique challenges and requirements will extend its relevance and utility. Sector-specific studies can uncover tailored strategies and best practices that address industry-specific barriers and leverage unique opportunities.

Finally, measuring the impact on performance is crucial for demonstrating the framework's value. Quantifying the benefits of integrating LM and I4.0 using the framework—such as efficiency, flexibility, and competitiveness improvements—will provide tangible evidence of its effectiveness. This data can inform further refinements of the framework and encourage its adoption by showcasing the potential return on investment.

4.6.5 Contribution to Practice and Theory

Contribution to Practice

The proposed framework significantly contributes to organizational practice by providing a clear, actionable tool for integrating Lean Manufacturing and Industry 4.0 technologies tailored to each organization's context. By leveraging dynamic capabilities, organizations can enhance their adaptability and responsiveness to market changes, thereby improving their competitiveness in an increasingly digital economy. The framework's phased implementation and incorporation of feedback loops assist organizations in managing the risks associated with digital transformation. This structured approach allows for gradual adoption and continuous refinement, reducing the likelihood of costly missteps and fostering sustainable change.

Contribution to Theory

Theoretically, the framework advances Dynamic Capabilities Theory by extending its application to integrating LM and I4.0. It operationalizes the concepts of sensing, seizing, and transforming capabilities within the context of digital and Lean integration, providing a practical illustration of how these theoretical constructs can be enacted in organizational settings. Additionally, the framework contributes to the literature by integrating multiple dimensions—combining strategic alignment, operational execution, and technological adoption into a single, cohesive model. This holistic approach offers a comprehensive perspective on organizational transformation, bridging gaps between theory and practice and enriching the understanding of how organizations can navigate the complexities of Industry 4.0.

4.7. Sustainability and Digital Green Lean

The integration of Lean Manufacturing (LM) and Industry 4.0 (I4.0) technologies provides substantial benefits across environmental, social, and economic dimensions, contributing significantly to the Sustainable Development Goals (United Nations, 2015). This integration addresses the pressing demands for environmental responsibility and sustainable practices within the manufacturing sector.

4.7.1. Resource Optimization and Energy Efficiency

The deployment of real-time data analytics, the Internet of Things (IoT), and predictive maintenance systems in manufacturing processes enhances resource usage and energy consumption monitoring and optimization. For instance, in the electronics sector, integrating IoT sensors with Lean practices has resulted in a 10% reduction in energy consumption. This achievement supports SDG 7: Affordable and Clean Energy, emphasizing the role of industry innovation in promoting energy efficiency (Alvandi et al., 2016).

4.7.2. Minimization of Defects and Waste

Lean 4.0 practices significantly reduce production defects and minimize waste, thereby enhancing material efficiency and lowering environmental impact. In the automotive sector, implementing Artificial Poka-Yoke systems has decreased defective products by 8%, reducing material waste and energy usage, aligning with SDG 12: Responsible Consumption and Production (Abed et al., 2020).

4.7.3. Reduction in Carbon Emissions

Efficient energy management and waste reduction enabled by I4.0 technologies assist manufacturers in reducing their carbon emissions. Notably, IoT-based predictive maintenance in the automotive industry has led to a 4.8% reduction in carbon emissions, directly contributing to SDG 13: Climate Action (Tortorella et al., 2020).

4.7.4. Digital Green Lean (DGL) and Sustainable Production

The Digital Green Lean (DGL) framework integrates sustainability goals into Lean 4.0 practices, achieving significant environmental improvements such as reduced material waste, decreased energy consumption, and lower emissions. This proactive approach supports SDG 9: Industry, Innovation, and Infrastructure, highlighting the benefits of sustainable industrialization (Benkhati et al., 2022)

4.7.5. Circular Economy Practices

Lean 4.0 technologies enable manufacturers to transition from linear production models to more sustainable, circular economies. Companies can reduce waste and promote resource efficiency by promoting closed-loop production systems. In the electronics industry, firms reduced raw material consumption by 15% using advanced data analytics tools that optimized material usage and waste recycling processes (Buer et al., 2018). This shift reduces waste and enhances resource efficiency, further supporting SDG 12: Responsible Consumption and Production.

4.7.6. Social and Economic Dimensions of Sustainability

Beyond environmental impacts, the integration of LM and I4.0 technologies significantly contributes to the social and economic pillars of sustainability:

- Social Sustainability: By enhancing job satisfaction and improving workplace safety, Digital Green Lean practices foster a culture of continuous learning and inclusivity (Buer et al., 2021; Morrar et al., 2017).
- Economic Sustainability: Operational efficiencies and waste reduction lead to cost savings, allowing firms to gain competitive advantages and potentially access new markets (Galeazzo et al., 2021).

4.7.7. Contribution to the Triple Bottom Line

Digital Green Lean practices align with the triple bottom line by advancing environmental stewardship, social well-being, and economic prosperity simultaneously. By reducing environmental impact, improving employee welfare, and enhancing financial performance, organizations can achieve sustainable growth and contribute positively to society (Elkington, 1997).

4.8. Sector-Specific Variations in Implementation

The impact of integrating LM and I4.0 technologies varies significantly across sectors due to socio-economic, technological, and organizational differences. Understanding these variations is essential for tailoring integration strategies effectively.

4.8.1. Manufacturing Sector

Early adopters like Toyota integrated Lean Production with I4.0 technologies in the automotive industry, achieving significant operational improvements, such as a 25% reduction in lead times and a 30% decrease in waste (Sanders et al., 2016). German SMEs implementing I4.0 tools alongside Lean saw an average 15% increase in output and a 12% reduction in machine downtime (Sanders et al., 2016).

Adopting Additive Manufacturing and Big Data Analytics in the electronics sector led to a 40% increase in production output (Pekarcikova et al., 2020). These improvements were attributed to enhanced customization capabilities and efficient production processes.

4.8.2. Healthcare Sector

The healthcare sector has begun integrating Lean practices with I4.0 technologies. A case study in Turkey highlighted the implementation of Lean practices in hospitals, where patient wait times were reduced by 18% after implementing Lean scheduling techniques and real-time data monitoring systems (Yilmaz et al., 2022). The integration enhanced patient flow and resource utilization, improving patient satisfaction and operational efficiency.

4.8.3. Emerging vs. Developed Economies

Tortorella et al. (2021) compared the adoption of Lean Automation between Brazilian and Italian firms. In Brazil, 63% of firms reported partial adoption of I4.0 technologies, compared to 83% in Italy. The level of Lean Automation implementation in developed economies like Italy was 20% higher than in Brazil, primarily due to differences in resource availability, technological readiness, and governmental support.

4.8.4. Impact Measurement Techniques

Real-time data analytics enabled firms to accurately measure the effectiveness of I4.0 and Lean implementation. Companies compared key performance indicators (KPIs) such as cycle time, firstpass yield, and customer response times to industry benchmarks. Firms adopting I4.0 alongside Lean outperformed their peers by 10-15% in key areas like production speed and defect rates (Sanders et al., 2016). Effective measurement allows organizations to quantify benefits and make informed decisions.

4.8.5. Critical Analysis

Sector-specific variations highlight the importance of customizing integration strategies. Industries with high levels of standardization and automation may find it easier to integrate LM and I4.0 technologies. In contrast, sectors requiring high flexibility or facing resource constraints may encounter more challenges. Organizations in emerging economies may need more support to overcome barriers related to infrastructure and skills shortages. Policymakers and industry associations can play a role in facilitating access to resources and knowledge sharing.

4.9. Leadership Styles and Regulatory Considerations in Integration

Leadership and regulatory compliance are critical factors influencing the successful integration of LM and I4.0 technologies. This section explores the impact of different leadership styles and the regulatory considerations that organizations must address.

4.9.1. Impact of Leadership Styles in Integrating LM and I4.0

Leadership style significantly affects the integration process, influencing employee engagement, innovation, and adaptability to change.

4.9.1.1. Transformational Leadership

Transformational leadership is identified as the most effective style for integrating I4.0 with LM. This leadership approach focuses on vision, innovation, and motivating employees to embrace technological changes aligning with LM principles and I4.0 advancements.

Vision and Change: Transformational leaders create a compelling vision and guide organizations through the complexities of digital transformation. They provide direction and inspiration to align teams with emerging trends of I4.0, particularly in lean environments that prioritize continuous improvement and waste reduction (Bittencourt et al., 2019; Ciano et al., 2020).

Empowerment and Innovation: Transformational leaders emphasize empowerment and foster a culture of experimentation and innovation, which is critical for incorporating I4.0 tools like IoT and automation into LM systems (Rosin et al., 2020). They encourage employees to take initiative and contribute to problem-solving.

Evidence: A study by Tortorella and Fogliatto (2019) on Brazilian plants implementing I4.0 found that transformational leaders positively impacted team innovation and process optimization by encouraging employee engagement in the change process. These leaders fostered higher receptiveness to technological changes and supported an environment of continuous learning, facilitating smoother integration with LM principles.

4.9.1.2. Servant Leadership

Servant leadership, characterized by a focus on the development and well-being of employees, is also effective in integrating LM and I4.0.

Employee-Centric Approach: Servant leaders prioritize the needs and growth of their team, complementing Lean's emphasis on respect for people. They promote a supportive culture where employees are empowered to experiment and grow (Dombrowski & Mielke, 2013).

Enhancing Employee Competence: In Lean organizations, servant leaders build employees' capabilities to handle new I4.0 technologies such as robotics, big data analytics, and IoT devices (Sanders et al., 2016). They ensure employees are not overwhelmed by introducing advanced tools by offering proper training and ongoing support.

Evidence: A study of Toyota's production system demonstrated that servant leadership was highly effective in managing transitions to automated processes, maintaining employee morale, and driving operational excellence through a strong focus on teamwork and learning (Maroukian & Gulliver, 2020).

4.9.1.3. Transactional Leadership

Transactional leadership, characterized by a focus on performance, supervision, and rewards, is less effective in integrating LM with I4.0 than transformational or servant leadership.

Supervision and Control: The rigid structures of transactional leadership can hinder innovation and adaptability. LM and I4.0 require flexibility and creative problem-solving that transactional leadership does not typically foster (Seidel et al., 2017).

Limitation in Fostering Innovation: Transactional leaders focus on maintaining existing processes and rewarding performance based on established metrics. In the context of I4.0 and LM integration, leaders need to promote experimentation and be comfortable with uncertainty, which is not aligned with the transactional approach (Saabye et al., 2020).

Evidence: Research indicates that companies led by transactional leaders were slower to adopt automation and data-driven processes than those led by transformational leaders. A study by Van Assen (2018) showed that transactional leadership limited the organization's ability to adapt to the dynamic nature of I4.0 technologies.

Table 11: Impact of Leadership Styles on LM and I4.0 Integration

Leadership Style	**Impact on LM-I4.0 Integration**	**Supporting Evidence**
Transformational	- Encourages innovation, vision, and continuous improvement - Empowers employees to use I4.0 tools effectively	Tortorella & Fogliatto (2019); Rosin et al. (2020); Ciano et al. (2020)
Servant	- Focuses on employee development and well-being - Builds competence in managing I4.0 technologies	Maroukian & Gulliver (2020); Dombrowski & Mielke (2013)
Transactional	- Less flexible, emphasizes control and rewards - Hinders innovation and adaptability in dynamic environments	Van Assen (2018); Saabye et al. (2020)

4.9.2. Regulatory Considerations in Implementing Technologies

When implementing technologies for LM and I4.0 initiatives, organizations must address several critical regulations and compliance issues.

4.9.2.1 Data Privacy and Security Regulations

Data Privacy and Security Regulations Compliance with data protection laws, such as the General Data Protection Regulation (GDPR), which is enforced by the European Union and is concerned with **protecting individual privacy rights and ensuring data security**, is essential when implementing technologies that collect, process, and store sensitive information. I4.0 often involves massive data generation from connected devices (IoT), real-time analytics, and cloud services. Non-compliance can lead to significant penalties and risks of data breaches (Yürekli & Schulz, 2022).

4.9.2.2. Health and Safety Regulations

Introducing advanced technologies, such as robotics or automation, requires adherence to occupational health and safety regulations. These technologies may alter the work environment, introducing potential risks to employees. Regulatory frameworks, like the Occupational Safety and Health Act (OSHA), must be followed to ensure the safety and well-being of workers (Yilmaz et al., 2022).

4.9.2.3. Quality Standards and Certifications

Meeting industry-specific quality standards and certifications, such as ISO 9001 (International Organization for Standardization, 2015), ensures that new technologies maintain desired quality levels in production processes. ISO 9001 is a **global standard** for quality management systems (QMS) that provides a framework for companies to ensure controlled processes and continuous improvement, enhancing customer satisfaction. Compliance with these standards aligns technology implementation with regulatory expectations and ensures that Lean objectives like waste reduction and process optimization are achieved without compromising product quality (Yürekli & Schulz, 2022).

4.9.2.4. Environmental Regulations

Compliance with environmental regulations becomes crucial when implementing technologies that may influence resource consumption, waste generation, or emissions. Standards such as ISO 14001 (International Organization for Standardization, 2015), which specify requirements for an effective environmental management system, provide a framework for organizations to enhance their environmental performance. Alongside ISO 14001, adherence to national emissions and environmental impacts laws is essential, particularly when digital and automated systems might increase energy use or alter manufacturing processes (Yürekli & Schulz, 2022).

4.9.2.5. Ethical Guidelines

As automation and AI become integral to I4.0, following ethical guidelines ensures transparency, fairness, and accountability in decision-making processes. Implementing AI requires attention to avoiding bias, maintaining transparency in algorithmic decisions, and ensuring accountability for outcomes (Yürekli & Schulz, 2022).

4.9.2.6. Labor Laws and Regulations

Technological advancements in LM and I4.0 can impact the workforce, particularly in areas of job displacement due to automation. Compliance with labor laws is essential to protect employee rights. Regulations addressing workers' rights, fair compensation, and conditions for safe employment transitions are critical when introducing these changes (Yilmaz et al., 2022).

4.9.2.7. Industry-Specific Regulations

Different industries may have specific regulatory frameworks governing the use of technology in manufacturing or service processes. For example, the automotive industry may have stringent regulations regarding automation and AI integration in manufacturing that must be adhered to for safety and compliance (Yürekli & Schulz, 2022).

4.9.3. Critical Analysis

Leadership styles are pivotal in shaping the organizational culture and readiness for integrating LM and I4.0 technologies. Transformational and servant leadership styles are more conducive to fostering innovation, employee engagement, and adaptability, which are essential for successful integration. Conversely, transactional leadership may hinder progress due to its rigidity.

Regulatory compliance is not merely a legal obligation but also a strategic consideration that can impact the success of technology implementation. Ignoring regulatory aspects can lead to legal repercussions, financial losses, and damage to reputation. Therefore, organizations must proactively address regulatory requirements in their planning and execution of LM and I4.0 integration.

5. Conclusion

The convergence of Industry 4.0 (I4.0) technologies and Lean Manufacturing (LM) principles represents a transformative opportunity for the manufacturing sector. This study explored the integration of LM with I4.0 technologies—referred to as Lean 4.0—to enhance operational efficiency, flexibility, and sustainability in manufacturing systems. Employing a systematic literature review (SLR) and bibliometric analysis of publications up to 2024, the research addressed three primary questions: identifying the key I4.0 technologies applied in LM systems, determining which LM practices are most impacted by I4.0 integration, and exploring the benefits and challenges associated with this integration.

5.1. Summary of Key Findings

The findings reveal a synergistic relationship between LM and I4.0 technologies, offering substantial potential for revolutionizing manufacturing operations. Key technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Cyber-Physical Systems (CPS), Big Data Analytics, Additive Manufacturing, Edge Computing, and 5G technology enhance traditional LM practices by providing real-time data, predictive analytics, advanced simulations, and improved connectivity. This integration leads to more efficient, flexible, and responsive manufacturing systems.

LM practices most impacted by I4.0 integration include Just-in-Time (JIT) inventory management, Total Productive Maintenance (TPM), Value Stream Mapping (VSM), Kanban systems, and Continuous Improvement (Kaizen). Implementing digital technologies into these practices results in significant operational improvements, such as optimized inventory levels, reduced waste, minimized equipment downtime, and enhanced process mapping.

The integration of LM and I4.0 yields substantial benefits. Organizations experience notable gains in operational efficiency, with productivity increases reported across various sectors (Pekarčíková et al., 2019; Tortorella et al., 2019). Quality enhancements are evident through reduced defects and rework, achieved by leveraging real-time monitoring and advanced analytics (Guillen et al., 2018). Increased flexibility and customization capabilities enable organizations to respond swiftly to changing customer demands and market conditions (Ghadge et al., 2020). Moreover, the integration contributes to sustainability goals by optimizing resource utilization, reducing energy consumption, and minimizing waste, supporting the emergence of Digital Green Lean practices (Benkhati et al., 2023).

5.2. Critical Analysis and Theoretical Implications

The study's findings align with the Dynamic Capabilities Theory, which emphasizes an organization's ability to integrate, build, and reconfigure internal and external competencies to address rapidly changing environments (Teece, 2007). The successful integration of LM and I4.0 technologies exemplifies how organizations can sense opportunities presented by technological advancements, seize them through strategic action, and transform their operational processes to sustain competitiveness.

Furthermore, the research contributes to the academic discourse by providing updated insights into the integration of LM and I4.0, filling a gap in the literature regarding recent developments up to 2024. It underscores the importance of adopting a strategic approach to integration, supported by strong leadership and a culture of continuous improvement.

5.3. Contribution of the Conceptual Framework

A significant contribution of this study is developing a conceptual framework that guides organizations through integrating LM and I4.0 technologies. This framework is grounded in the principles of dynamic capabilities and provides a structured approach for practitioners to assess their current state, identify integration opportunities, and implement strategies effectively.

The conceptual framework comprises the following key components:

Assessment of Lean and Digital Maturity: Organizations evaluate their existing LM practices and digital capabilities to determine readiness for integration.

Identification of Integration Opportunities: Based on the assessment, organizations identify specific LM practices that can be enhanced through I4.0 technologies.

Strategic Planning and Resource Allocation: Organizations develop a phased implementation plan and allocate resources strategically to manage risks and ensure sustainable integration.

Implementation and Change Management: To facilitate successful integration, emphasis is placed on leadership, employee engagement, and continuous improvement.

Performance Measurement and Feedback: Organizations establish metrics to monitor performance improvements and use feedback mechanisms to refine processes.

This framework contributes to existing research by providing a holistic and practical model that bridges the gap between theoretical concepts and real-world applications. It extends previous models by incorporating recent technological advancements and addressing the dynamic nature of manufacturing environments.

The framework is a valuable tool for practitioners in the industry, offering actionable guidance to navigate the complexities of Lean 4.0 integration. By considering factors such as organizational culture, leadership styles, and employee involvement, the framework helps organizations implement technological solutions and foster an environment conducive to innovation and continuous improvement.

5.4. Limitations of the Study

While the study offers valuable insights, certain limitations must be acknowledged. The reliance on the Scopus database may have excluded relevant studies from other databases, potentially limiting the diversity of perspectives in the literature review. The possibility of publication bias, where studies reporting positive outcomes are more likely to be published, might skew the perception of benefits over challenges. Additionally, excluding non-English publications may have omitted valuable perspectives from research conducted in other languages.

These limitations may affect the generalizability of the findings, particularly in capturing region-specific developments or studies published in non-English languages. Future research should consider incorporating multiple databases and including studies from diverse geographic regions to enhance the comprehensiveness of the literature review.

5.5. Recommendations for Future Research

Future studies are encouraged to conduct longitudinal empirical research to examine the long-term effects of LM and I4.0 integration and to capture the evolution of technologies and practices over time. Exploring the integration in sectors beyond manufacturing, such as healthcare, agriculture, and services, could provide valuable insights into the applicability and impact of Lean 4.0 in different contexts.

Investigating employee experiences and perceptions through qualitative research can deepen understanding of organizational resistance and inform effective change management strategies. Additionally, developing standardized metrics for assessing the environmental, social, and economic impacts of integration can support organizations in aligning with sustainability goals and measuring progress effectively.

5.6. Final Reflections

The convergence of LM and I4.0 technologies presents a pivotal opportunity to revolutionize manufacturing systems fundamentally. By adeptly embracing this integration, organizations can unlock substantial enhancements in operational efficiency, elevate product quality, achieve greater flexibility, and advance sustainability initiatives. This transformative potential underscore the critical importance of organizations strategically engaging with Lean 4.0 principles to remain competitive in an increasingly dynamic global market.

Stakeholders, including practitioners, policymakers, and academics—are encouraged to consider the insights provided by this study and take proactive steps toward integrating LM and I4.0. Embracing Digital Green Lean practices drives operational excellence and contributes positively to environmental sustainability and social well-being.

In closing, integrating LM and I4.0 technologies is a technological upgrade and a strategic imperative that demands thoughtful planning, strong leadership, and a commitment to continuous learning. The conceptual framework developed in this study serves as a roadmap for organizations seeking to navigate this complex integration process. It represents a paradigm shift that promises to redefine manufacturing excellence in the 21st century. Organizations that rise to this challenge will enhance their competitiveness and contribute to shaping a more sustainable and prosperous industrial landscape.

6. Appendices

Python Codes

1. Scatter Plot & Correlation: Citations vs. Year of Publication

```
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns

# Load data
df = pd.read_csv("C:\Users\sahar\OneDrive\Desktop\python - bibolo\scopus (7).csv"")

# Scatter plot with trend line
plt.figure(figsize=(10, 6))
sns.regplot(x='Year', y='Cited by', data=df, scatter_kws={'s': 10}, line_kws={"color": "red"})
plt.title('Citations vs. Year of Publication')
plt.xlabel('Year')
plt.ylabel('Citations')
plt.grid(True)
plt.show()

# Correlation calculation
correlation = df['Year'].corr(df['Cited by'])
print(f"Correlation between Year and Citations: {correlation}")
```

2. Annual Scientific Production

```
annual_publication = df.groupby('Year').size()

# Plotting the trends
plt.figure(figsize=(10, 6))
annual_publication.plot(kind='line', marker='o')
```

```
plt.title("Annual Scientific Production from 2016 to 2024")
plt.xlabel("Year")
plt.ylabel("Number of Publications")
plt.grid(True)
plt.show()
```

3. Trends in Total Citations Over Time

```
total_citations_per_year = df.groupby('Year')['Cited by'].sum()

# Plotting
plt.figure(figsize=(10, 6))
total_citations_per_year.plot(kind='line', marker='o', color='green')
plt.title("Total Citations Over Time")
plt.xlabel("Year")
plt.ylabel("Total Citations")
plt.grid(True)
plt.show()
```

4. Most Relevant Sources

```
# Count occurrences of sources
most_relevant_sources = df['Source title'].value_counts().head(10)

# Plot
plt.figure(figsize=(10, 6))
most_relevant_sources.plot(kind='bar')
plt.title("Top 10 Most Relevant Sources")
plt.xlabel("Source")
plt.ylabel("Number of Publications")
plt.show()
```

5. Source Production Over Time

```python
# Grouping by year and source
source_output_over_time = df.groupby(['Year', 'Source title']).size().unstack(fill_value=0)

# Top 10 sources
top_sources = source_output_over_time.sum().sort_values(ascending=False).head(10).index
source_output_top = source_output_over_time[top_sources]

# Plot
source_output_top.plot(figsize=(10, 6), marker='o')
plt.title("Source Production Over Time")
plt.xlabel("Year")
plt.ylabel("Number of Publications")
plt.legend(title="Source", bbox_to_anchor=(1.05, 1), loc='upper left')
plt.tight_layout()
plt.show()
```

6. H-index and G-index for Top 10 Sources

```python
def h_index(citations):
    citations.sort(reverse=True)
    for i, c in enumerate(citations, start=1):
        if c < i:
            return i - 1
    return len(citations)

def g_index(citations):
    citations.sort(reverse=True)
    total_citations = 0
    for i, c in enumerate(citations, start=1):
        total_citations += c
        if total_citations < i ** 2:
            return i - 1
    return len(citations)
```

```
# Top 10 sources
top_10_sources = df['Source title'].value_counts().head(10).index

h_indices = {}
g_indices = {}

for source in top_10_sources:
    citations = df[df['Source title'] == source]['Cited by'].tolist()
    h_indices[source] = h_index(citations)
    g_indices[source] = g_index(citations)

# H-index and G-index output
h_indices_df = pd.DataFrame.from_dict(h_indices, orient='index', columns=['H-index'])
g_indices_df = pd.DataFrame.from_dict(g_indices, orient='index', columns=['G-index'])
print(pd.concat([h_indices_df, g_indices_df], axis=1))
```

7. Global Distribution of Publications by Country

```
# Country distribution
country_distribution = df['Affiliations'].value_counts().head(10)

# Plot
plt.figure(figsize=(10, 6))
country_distribution.plot(kind='bar', color='blue')
plt.title("Share of Publications by Country")
plt.xlabel("Country")
plt.ylabel("Number of Publications")
plt.tight_layout()
plt.show()
```

8. SCP vs MCP Proportions

```
scp_mcp = df.groupby(['Country', 'Collaboration']).size().unstack(fill_value=0)

# SCP vs MCP for top 10 countries
scp_mcp_top = scp_mcp.loc[df['Country'].value_counts().head(10).index]

# Plot
scp_mcp_top.plot(kind='bar', stacked=True, figsize=(10, 6), color=['skyblue', 'salmon'])
plt.title("SCP vs MCP Proportions Among Top 10 Countries")
plt.xlabel("Country")
plt.ylabel("Number of Publications")
plt.legend(title="Collaboration Type", loc='upper right')
plt.tight_layout()
plt.show()
```

9. Top 10 Most Cited Countries

```
citations_per_country = df.groupby('Country')['Cited by'].sum()
top_10_cited_countries = citations_per_country.sort_values(ascending=False).head(10)

# Plot
plt.figure(figsize=(10, 6))
top_10_cited_countries.plot(kind='bar', color='purple')
plt.title("Top 10 Most Cited Countries")
plt.xlabel("Country")
plt.ylabel("Total Citations")
plt.tight_layout()
plt.show()
```

7. Reference

Affydah, D., Rose, A. N. M., Ab. Rashid, M. F. F., & Mohamed, N. M. Z. (2021). Review of Lean Manufacturing with IR4.0 in Automotive Industry. *Journal of Physics: Conference Series*, *1874*, Article 012050. https://doi.org/10.1088/1742-6596/1874/1/012050

Alvandi, Samira & Li, Wen & Schönemann, Malte & Kara, Sami & Herrmann, Christoph. (2016). Economic and environmental value stream map (E 2 VSM) simulation for multi-product manufacturing systems. International Journal of Sustainable Engineering. 9. 1-9. 10.1080/19397038.2016.1161095.

Amin, A. N. M., Wan Mahmood, W. H., Kamat, S. R., & Kamalrudin, M. (2019). Continuous improvement through lean using VSM for application in machining based product company. *International Journal of Recent Technology and Engineering*, *8*(2S11), 778–784. https://doi.org/10.35940/ijrte.B1127.0982S1119

Aria, M., & Cuccurullo, C. (2017). Bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, *11*(4), 959–975. https://doi.org/10.1016/j.joi.2017.08.007

Barkokebas, Beda & Al-Hussein, Mohamed & Hamzeh, Farook. (2022). Assessment of Digital Twins to Reassign Multiskilled Workers in Offsite Construction Based on Lean Thinking. Journal of Construction Engineering and Management. 149. 10.1061/(ASCE)CO.1943-7862.0002420. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002290

Benkhati, I., Belhadi, A., Kamble, S. S., & Touriki, F. E. (2023). Linkages between smart, lean, and resilient manufacturing for sustainable development. *Business Strategy and the Environment*, *32*(6), 3689–3704. https://doi.org/10.1002/bse.3322

Bittencourt, V. L., Alves, A. C., & Leão, C. P. (2021). Industry 4.0 triggered by Lean Thinking: Insights from a systematic literature review. *International Journal of Production Research*, *59*(5), 1496–1510. https://doi.org/10.1080/00207543.2020.1832274

Bokhorst, J. A. C., Knol, W., Slomp, J., & Bortolotti, T. (2022). Assessing to what extent smart manufacturing builds on lean principles. *International Journal of Production Economics*, *253*, Article 108599. https://doi.org/10.1016/j.ijpe.2022.108599

Bornmann, L., & Daniel, H. D. (2007). What do we know about the h-index? *Journal of the American Society for Information Science and Technology*, *58*(9), 1381–1385. https://doi.org/10.1002/asi.20609

Brauner, P., & Ziefle, M. (2022). Beyond playful learning—Serious games for the human-centric digital transformation of production and a design process model. *Technology in Society*, *71*, Article 102140. https://doi.org/10.1016/j.techsoc.2022.102140

Buer, S. V., Semini, M., Strandhagen, J. O., & Sgarbossa, F. (2021). The complementary effect of lean manufacturing and digitalisation on operational performance. *International Journal of Production Research*, *59*(7), 1976–1992. https://doi.org/10.1080/00207543.2020.1790684

Buer, S. V., Strandhagen, J. O., & Chan, F. T. S. (2018). The link between Industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda. *International Journal of Production Research*, *56*(8), 2924–2940. https://doi.org/10.1080/00207543.2018.1442945

Chavez, R., Yu, W., Jacobs, M., & Wong, C. Y. (2024). Does digitalization enhance the effects of lean production on social performance? *International Journal of Operations and Production Management*, *44*(6), 1192–1216. https://doi.org/10.1108/IJOPM-05-2023-0332

Chen, B., Wan, J., Celesti, A., Li, D., Abbas, H., & Zhang, Q. (2018). Edge computing in IoT-based manufacturing. *IEEE Communications Magazine*, *56*(9), 103–109. https://doi.org/10.1109/MCOM.2018.1701231

Cirillo, V., Rinaldini, M., Staccioli, J., & Virgillito, M. E. (2021). Technology vs. workers: The case of Italy's Industry 4.0 factories. *Structural Change and Economic Dynamics*, *56*, 166–183. https://doi.org/10.1016/j.strueco.2020.09.007

Cifone, F. D., Hoberg, K., Holweg, M., & Staudacher, A. P. (2021). Lean 4.0: How can digital technologies support lean practices? *International Journal of Production Economics*, *241*, Article 108258. https://doi.org/10.1016/j.ijpe.2021.108258

Condé, Giovanni & Oprime, Pedro & Sordan, Juliano & Bueno, Carlos & Pimenta, Márcio. (2022). Defect reduction using Lean Six Sigma and DMAIC. https://www.researchgate.net/publication/362389760_Defect_reduction_using_Lean_Six_Sigma_and_DMAIC

Dombrowski, U., & Mielke, T. (2013). Lean leadership—15 rules for a sustainable lean implementation. *Procedia CIRP*, *7*, 569–574. https://doi.org/10.1016/j.procir.2013.06.034

Elkington, J. (1997). *Cannibals with forks: The triple bottom line of 21st-century business*. Capstone Publishing.

Eriksson, S., Bengtsson, L., Samen, L., & von Haartman, R. (2023). Visual management in the era of Industry 4.0: Perceived advantages and disadvantages of digital boards. *International*

Journal of Advanced Operations Management, *15*(1), 1–25. https://doi.org/10.1504/IJAOM.2023.10052710

Environmental Protection Agency (EPA). (2003). Lean manufacturing and the environment: Research on advanced manufacturing systems and the environment and recommendations for leveraging better environmental performance. U.S. EPA.

Fernando, Y., Tseng, M.-L., & Karuppiah, K. (2021). Impact of lean manufacturing and environmental sustainability on Industry 4.0 readiness. *Journal of Manufacturing Technology Management*, *32*(7), 1345–1368. https://doi.org/10.1108/JMTM-05-2019-0174

Fortuny-Santos, J., López, P. R. de A., Luján-Blanco, I., & Chen, P. K. (2020). Assessing the synergies between lean manufacturing and Industry 4.0. *Dirección y Organización*, *71*, 71–86. https://doi.org/10.37610/dyo.v0i71.579

Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics*, *210*, 15–26. https://doi.org/10.1016/j.ijpe.2019.01.004

Frecassetti, S., Kassem, B., Kundu, K., Ferrazzi, M., & Portioli-Staudacher, A. (2023). Introducing lean practices through simulation: A case study in an Italian SME. *Quality Management Journal*, *30*(2), 90–104. https://doi.org/10.1080/10686967.2023.2171326

Frecassetti, S., Rossini, M., & Portioli-Staudacher, A. (2024). Unleashing Industry 4.0: Leveraging lean practices to overcome implementation barriers. *IEEE Transactions on Engineering Management*, *71*, 10797–10814. https://doi.org/10.1109/TEM.2024.3396448

Galeazzo, A., Furlan, A., Tosetto, D., & Vinelli, A. (2024). Are lean and digital engaging better problem solvers? An empirical study on Italian manufacturing firms. *International Journal of Operations and Production Management*, *44*(6), 1217–1248. https://doi.org/10.1108/IJOPM-06-2023-0477

Gatell, I. S., & Avella, L. (2024a). A maturity model for assessing digital green lean leadership and culture implementation in manufacturing companies. *Total Quality Management & Business Excellence*, *35*(7–8), 860–897. https://doi.org/10.1080/14783363.2024.2347373

Gatell, I. S., & Avella, L. (2024b). Impact of Industry 4.0 and circular economy on lean culture and leadership: Assessing digital green lean as a new concept. *European Research on Management and Business Economics*, *30*(1), Article 100232. https://doi.org/10.1016/j.iedeen.2023.100232

Ghadge, A., Kara, M., Moradlou, H., & Goswami, M. (2020). The impact of Industry 4.0 implementation on supply chains. *Journal of Manufacturing Technology Management*, *31*(4), 669–686. https://doi.org/10.1108/JMTM-10-2019-0368

Ghobakhloo, M., & Fathi, M. (2020). Corporate survival in Industry 4.0 era: The enabling role of lean-digitized manufacturing. *Journal of Manufacturing Technology Management*, *31*(1), 1–30. https://doi.org/10.1108/JMTM-11-2018-0417

Gough, D., Oliver, S., & Thomas, J. (2017). *An introduction to systematic reviews* (2nd ed.). SAGE Publications.

Grus, J. (2019). *Data science from scratch: First principles with Python* (2nd ed.). O'Reilly Media.

Herwan, J., Misaka, T., Furukawa, Y., Ogura, I., & Komoto, H. (2023). A proposal for improving production efficiency of existing machining line through a hybrid monitoring and optimisation process. *International Journal of Production Research*, *61*(16), 5392–5410. https://doi.org/10.1080/00207543.2022.2101403

Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J., & Welch, V. A. (Eds.). (2020). *Cochrane handbook for Systematic Reviews of interventions* (2nd ed.). Wiley-Blackwell.

Imai, M. (1986) Kaizen: The Key to Japan's Competitive Success. McGraw-Hill Education, New York.

International Labour Organization. (1981). *Occupational Safety and Health Convention, 1981 (No. 155)*. https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100_ILO_CODE:C155

International Organization for Standardization. (2015a). *ISO 9001:2015 Quality management systems—Requirements*. ISO. https://www.iso.org/standard/62085.html

International Organization for Standardization. (2015b). *ISO 14001:2015 Environmental management systems—Requirements with guidance for use*. ISO. https://www.iso.org/standard/60857.html

International Labour Organization. (1981). *Occupational Safety and Health Convention, 1981 (No. 155)*. https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100_ILO_CODE:C155

Ilangakoon, T. S., Weerabahu, S. K., Samaranayake, P., & Wickramarachchi, R. (2022). Adoption of Industry 4.0 and lean concepts in hospitals for healthcare operational performance improvement. *International Journal of Productivity and Performance Management*, *71*(6), 2188–2213. https://doi.org/10.1108/IJPPM-12-2020-0654

Jackson, A., Spiegler, V. L. M., & Kotiadis, K. (2024). Exploring the potential of blockchain-enabled lean automation in supply chain management: A systematic literature review, classification taxonomy, and future research agenda. *Production Planning & Control*, *35*(9), 866–885. https://doi.org/10.1080/09537287.2022.2157746

Joshi, S., Sharma, M., Bartwal, S., Joshi, T., & Prasad, M. (2024). Critical challenges of integrating OPEX strategies with I4.0 technologies in manufacturing SMEs: A few pieces of evidence from developing economies. *The TQM Journal*, *36*(1), 108–138. https://doi.org/10.1108/TQM-08-2022-0245

Kagermann, H., Wahlster, W., & Helbig, J. (2013). *Recommendations for implementing the strategic initiative INDUSTRIE 4.0*. Final report of the Industrie 4.0 Working Group. acatech. https://en.acatech.de/publication/recommendations-for-implementing-the-strategic-initiative-industrie-4-0-final-report-of-the-industrie-4-0-working-group/

Khanzode, A. G., Sarma, P. R. S., & Goswami, M. (2023). Modelling interactions of select enablers of Lean Six Sigma considering sustainability implications: An integrated circular economy and Industry 4.0 perspective. *Production Planning & Control*, *34*(10), 1020–1036. https://doi.org/10.1080/09537287.2021.1980908

Kolberg, D., & Zühlke, D. (2015). Lean automation enabled by Industry 4.0 technologies. IFAC-PapersOnLine, 48(3), 1870–1875. https://doi.org/10.1016/j.ifacol.2015.06.359

Kolberg, D., Knobloch, J., & Zühlke, D. (2017). Towards a lean automation interface for workstations. International Journal of Production Research, 55(10), 2845–2856. https://doi.org/10.1080/00207543.2016.1223384

Kitchenham, B., & Charters, S. (2007). Guidelines for performing systematic literature reviews in software engineering. *Technical Report EBSE 2007-001*. https://www.elsevier.com/__data/promis_misc/525444systematicreviewsguide.pdf

Kumar, S., Suhaib, M., & Asjad, M. (2020). Industry 4.0: Complex, disruptive, but inevitable. *Management and Production Engineering Review*, *11*(1), 43–51. https://doi.org/10.24425/mper.2020.132942

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., & Hoffmann, M. (2014). Industry 4.0. Business & Information Systems Engineering, 6(4), 239–242. https://doi.org/10.1007/s12599-014-0334-4

Lee, J., Bagheri, B., & Kao, H.-A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters, 3, 18–23. https://doi.org/10.1016/j.mfglet.2014.12.001

Li, L. R. (2019). Lean smart manufacturing in Taiwan—Focusing on the bicycle industry. *Journal of Open Innovation: Technology, Market, and Complexity*, *5*(4), Article 79. https://doi.org/10.3390/joitmc5040079

Liao, Y., Deschamps, F., Loures, E. F. R., & Ramos, L. F. P. (2017). Past, present and future of Industry 4.0—A systematic literature review and research agenda proposal. *International Journal of Production Research*, *55*(12), 3609–3629. https://doi.org/10.1080/00207543.2017.1308576

Liker, J. K. (2004). The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer. McGraw-Hill.

Lucantoni, L., Antomarioni, S., Ciarapica, F. E., & Bevilacqua, M. (2022). Implementation of Industry 4.0 techniques in lean production technology: A literature review. *Management and Production Engineering Review*, *13*(3), 83–93. https://doi.org/10.24425/mper.2022.142385

Ly Duc, M., Hlavaty, L., Bilik, P., & Martinek, R. (2023). Enhancing manufacturing excellence with Lean Six Sigma and zero defects based on Industry 4.0. *Advances in Production Engineering & Management*, *18*(1), 32–48. https://doi.org/10.14743/apem2023.1.455

McKinney, W. (2017). *Python for data analysis: Data wrangling with pandas, NumPy, and IPython* (2nd ed.). O'Reilly Media.

Mittal, S., Khan, M. A., Romero, D., & Wuest, T. (2018). A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). *Journal of Manufacturing Systems*, *49*, 194–214. https://doi.org/10.1016/j.jmsy.2018.10.005

Moro, A., & Virgillito, M. E. (2021). Towards the factory 4.0? Convergence and divergence of lean models in Italian automotive plants (LEM Papers Series 2021/38). Laboratory of Economics and Management (LEM), Sant'Anna School of Advanced Studies. https://www.lem.sssup.it/WPLem/files/2021-44.pdf

Mordor Intelligence. (2023.). Smart factory market. Retrieved from https://www.mordorintelligence.com/industry-reports/smart-factory-market

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S., & Barbaray, R. (2018). The industrial management of SMEs in the era of Industry 4.0. International Journal of Production Research, 56(3), 1118–1136. https://doi.org/10.1080/00207543.2017.1372647

Rossini, M., Cifone, F. D., Kassem, B., Costa, F., & Portioli-Staudacher, A. (2021). Being lean: How to shape digital transformation in the manufacturing sector. Journal of Manufacturing Technology Management, 32(9), 239–259. https://doi.org/10.1108/JMTM-12-2020-0467

Rother, M., & Shook, J. (1999). Learning to See: Value Stream Mapping to Add Value and Eliminate Muda. Lean Enterprise Institute.

Parida, Vinit & Sjödin, David & Wincent, Joakim & Kohtamäki, Marko. (2014). Mastering the Transition to Product-Service Provision: Insights into Business Models, Learning Activities, and Capabilities. Research-Technology Management. 57. 10.5437/08956308X5703227.

Pekarčíková, M., Trebuňa, P., & Kliment, M. (2019). Digitalization effects on the usability of lean tools. *Acta Logistica*, *6*(1), 9–13. https://doi.org/10.22306/al.v6i1.112

Prieto, Andrés J. & Alarcon, Luis. (2023). Using Fuzzy Inference Systems for Lean Management Strategies in Construction Project Delivery. Journal of Construction Engineering and Management. 149. 10.1061/JCEMD4.COENG-12922.

Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016. General Data Protection Regulation (GDPR). *Official Journal of the European Union*, *L119*, 1–88. https://eur-lex.europa.eu/eli/reg/2016/679/oj

Rupasinghe, T., & Wijewardana, A. R. L. (2016). Lean healthcare framework for Sri Lankan healthcare supply chains: A case study of teaching hospitals. *Universal Journal of Management*, *4*(10), 517–527. https://doi.org/10.13189/ujm.2016.041001

Rybski, C., & Jochem, R. (2020). Procedure model to integrate digital elements into lean production systems. *International Journal of Quality and Service Sciences*, *13*(1), 1–15. https://doi.org/10.1108/IJQSS-03-2020-0047

Sajjad, A., Ahmad, W., Hussain, S., Chuddher, B. A., Sajid, M., Jahanzaib, M., Ali, M. K., & Jawad, M. (2024). Assessment by lean modified manufacturing maturity model for Industry 4.0: A case study of Pakistan's manufacturing sector. *IEEE Transactions on Engineering Management*, *71*, 6420–6434. https://doi.org/10.1109/TEM.2023.3259005

Sanders, A., Elangeswaran, C., & Wulfsberg, J. (2016). Industry 4.0 implies lean manufacturing: Research activities in Industry 4.0 function as enablers for lean manufacturing. *Journal of Industrial Engineering and Management*, *9*(3), 811–833. https://doi.org/10.3926/jiem.1940

Saraswat, P., Agrawal, R., & Rane, S. B. (2024). Technological integration of lean manufacturing with Industry 4.0 toward lean automation: Insights from the systematic review and further research directions. *Benchmarking: An International Journal*. Advance online publication. https://doi.org/10.1108/BIJ-05-2023-0316

Sassanelli, C., Rossi, M., & Terzi, S. (2020). Evaluating the smart maturity of manufacturing companies along the product development process to set a PLM project roadmap. *International Journal of Product Lifecycle Management*, *12*(3), 185–209. https://doi.org/10.1504/IJPLM.2020.10032146

Shamim, S., Cang, S., Yu, H., & Li, Y. (2017). Examining the feasibilities of Industry 4.0 for the hospitality sector with the lens of management practice. *Energies*, *10*(4), Article 499. https://doi.org/10.3390/en10040499

Sharma, V., Luthra, S., Joshi, S., & Kumar, A. (2022). Accelerating retail supply chain performance against pandemic disruption: Adopting resilient strategies to mitigate the long-term effects. *Journal of Enterprise Information Management*, *35*(1), 21–45. https://doi.org/10.1108/JEIM-07-2020-0286

Shi, W., Cao, J., Zhang, Q., Li, Y., & Xu, L. (2016). Edge computing: Vision and challenges. *IEEE Internet of Things Journal*, *3*(5), 637–646. https://doi.org/10.1109/JIOT.2016.2579198

Shingo, S. (1985). A Revolution in Manufacturing: The SMED System. Productivity Press.

Shingo, S. (1986). Zero Quality Control: Source Inspection and the Poka-Yoke System. Productivity Press.

Sony, Michael & Naik, Subhash. (2019). Critical factors for the successful implementation of Industry 4.0: a review and future research direction. Production Planning & Control. 31. 1-17. 10.1080/09537287.2019.1691278.

Teece, D. J. (2007). Explicating dynamic capabilities: The nature and microfoundations of (sustainable) enterprise performance. *Strategic Management Journal*, *28*(13), 1319–1350. https://doi.org/10.1002/smj.640

Tortorella, G. L., Giglio, R., & van Dun, D. H. (2019). Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement. *International*

Journal of Operations & Production Management, *39*(6/7/8), 860–886. https://doi.org/10.1108/IJOPM-01-2019-0005

Tortorella, G. L., Rossini, M., Costa, F., Portioli-Staudacher, A., & Sawhney, R. (2021). A comparison on Industry 4.0 and lean production between manufacturers from emerging and developed economies. *Total Quality Management & Business Excellence*, *32*(11–12), 1249–1270. https://doi.org/10.1080/14783363.2019.1696184

Tortorella, Guilherme & Saurin, Tarcisio & Filho, Moacir & Samson, Daniel & Kumar, Maneesh. (2021). Bundles of Lean Automation practices and principles and their impact on operational performance. International Journal of Production Economics. 235. 10.1016/j.ijpe.2021.108106.

Tortorella, G. L., Sawhney, R., Jurburg, D., de Paula, I. C., Tlapa, D., & Thurer, M. (2021). Towards the proposition of a lean automation framework: Integrating Industry 4.0 into lean production. *Journal of Manufacturing Technology Management*, *32*(3), 593–620. https://doi.org/10.1108/JMTM-01-2019-0032

Tripathi, V., Chattopadhyaya, S., Mukhopadhyay, A. K., Sharma, S., Singh, J., Pimenov, D. Y., & Giasin, K. (2021). An innovative agile model of smart lean–green approach for sustainability enhancement in Industry 4.0. *Journal of Open Innovation: Technology, Market, and Complexity*, *7*(4), Article 215. https://doi.org/10.3390/joitmc7040215

United Nations. (2015). Sustainable Development Goals (SDGs). Retrieved from https://sdgs.un.org/goals

Upadhyay, Y., Talib, F., Zaheen, S. A., & Ansari, M. S. (2023). Industry 4.0 adoption framework in MSMEs using a hybrid fuzzy AHP-TOPSIS approach. *Proceedings on Engineering Sciences*, *5*(3), 453–474. https://doi.org/10.24874/PES05.03.010

Valamede, L. S., & Akkari, A. C. S. (2020). Lean 4.0: A new holistic approach for the integration of lean manufacturing tools and digital technologies. *International Journal of Mathematical, Engineering and Management Sciences*, *5*(5), 854–868. https://doi.org/10.33889/IJMEMS.2020.5.5.066

Vinodh, S., & Shimray, S. A. (2023). Analysis of barriers for implementation of integrated Lean Six Sigma and Industry 4.0 using interpretive ranking process. *The TQM Journal*, *35*(7), 1761–1776. https://doi.org/10.1108/TQM-04-2022-0121

Wagner, T., Herrmann, C., & Thiede, S. (2017). Industry 4.0 impacts on lean production systems. Procedia CIRP, 63, 125–131. https://doi.org/10.1016/j.procir.2017.02.041

Womack, J. P., & Jones, D. T. (1996). *Lean thinking: Banish waste and create wealth in your corporation*. Simon & Schuster.

Womack, J. P., Jones, D. T., & Roos, D. (2007). *The machine that changed the world: The story of lean production*. Simon & Schuster.

Yadav, N., Shankar, R., & Singh, S. P. (2020). Impact of Industry 4.0/ICTs, Lean Six Sigma and quality management systems on organisational performance. *The TQM Journal*, *32*(4), 815–835. https://doi.org/10.1108/TQM-10-2019-0251

Yang, H., Kumara, S., Bukkapatnam, S., & Tsung, F. (2019). The Internet of Things for smart manufacturing: A review. *IISE Transactions*, *51*(11), 1190–1216. https://doi.org/10.1080/24725854.2018.1555383

Yilmaz, A., Dora, M., Hezarkhani, B., & Kumar, M. (2022). Lean and Industry 4.0: Mapping determinants and barriers from a social, environmental, and operational perspective. *Technological Forecasting and Social Change*, *175*, Article 121320. https://doi.org/10.1016/j.techfore.2021.121320

Yürekli, S., & Schulz, C. (2022). Compatibility, opportunities and challenges in the combination of Industry 4.0 and lean production. *Logistics Research*, *15*(1), Article 9. DOI_10.23773/2022_09

8. Glossary

5G: The fifth generation of mobile network technology, offering faster speeds and more reliable connections.

5S: A workplace organization method that uses five Japanese words: Seiri, Seiton, Seiso, Seiketsu, and Shitsuke (Sort, Set in order, Shine, Standardize, Sustain).

Additive Manufacturing (AM), also known as 3D printing, creates objects by adding material layer by layer.

Artificial Intelligence (AI): The simulation of human intelligence processes by machines, especially computer systems.

Big Data Analytics: The complex process of examining large and varied data sets to uncover hidden patterns and insights.

Blockchain Technology: A decentralized digital ledger that securely records transactions across many computers.

Continuous Improvement (Kaizen): A Lean principle focusing on ongoing incremental process improvements.

Cyber-Physical Systems (CPS): Integrations of computation, networking, and physical processes.

Digital Twin: A virtual replica of a physical object or system used to simulate and analyze performance.

Digital Green Lean (DGL): An approach combining digital technologies, Lean principles, and environmental sustainability.

Edge Computing: Processing data near the source of data generation to reduce latency.

Industry 4.0 (I4.0): The current trend of automation and data exchange in manufacturing technologies, including cyber-physical systems, IoT, and cloud computing.

Internet of Things (IoT): The network of physical objects embedded with sensors and software to connect and exchange data.

Just-in-Time (JIT): An inventory strategy where materials are only ordered and received as they are needed.

Key Performance Indicators (KPIs): Quantifiable measures used to evaluate the success of an organization.

Lean Manufacturing (LM): A systematic method for waste minimization within a manufacturing system without sacrificing productivity.

Machine Learning (ML): A subset of AI involving the study of algorithms that improve automatically through experience.

Predictive Maintenance: Techniques designed to help determine the condition of equipment to predict when maintenance should be performed.

Radio-Frequency Identification (RFID): Uses electromagnetic fields to identify and track tags attached to objects automatically.

Smart Factory: A highly digitalized and connected production facility that relies on smart manufacturing.

Total Productive Maintenance (TPM): A Lean approach focusing on proactive and preventative maintenance to maximize operational efficiency.

Value Stream Mapping (VSM): A Lean management method for analyzing the current state and designing a future state for processes.