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Thesis title:

Unlocking the Potential of Industry 4.0 in Italian SMEs: A Knowledge Management Perspective

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Acknowledgements

Here I am, at the end of my academic studies, at a very important moment of my life.

Over the past three years, I have grown more than ever. I lived abroad for almost one year, met a lot of new people, some of whom have become *fundamental,* and my perspective on things has radically changed.

First, I want to say thanks to my staples, who were by my side throughout this period.

Thank you, Mum, Dad, and my grandparents, for shaping me into the person that I am today, always giving me love and more than I could have ever needed, and for engaging in meaningful arguments even when we clashed.

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And lastly, but not for importance, thanks to Carlottina, to have disrupted my life, and for every second of happiness you brought me.

Ad maiora semper

Abstract

The advent of Industry 4.0, driven by disruptive technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI), has significantly transformed traditional supply chain processes, presenting both opportunities and challenges for Small and Medium Enterprises (SMEs). This thesis investigates the impact of IoT and AI, on the supply chains of Italian SMEs, with a focus on how these technologies can enhance operational efficiency, resilience, and competitiveness.

In addition to exploring technological integration, the study examines the role of knowledge management practices and the formalization of tacit and explicit knowledge within SMEs. Efficient knowledge management is critical for leveraging the insights provided by IoT and AI technologies. However, many SMEs struggle with the formalization of knowledge, which limits their ability to fully utilize the data-driven capabilities of Industry 4.0.

Through a systematic literature review and empirical data collected via a survey of Italian SMEs, this research highlights the irregular adoption of Industry 4.0 technologies. The presence of a sufficient IT infrastructure, and the awareness of the leadership about I4.0 as a support of organization’s productivity, is not adequate to counterbalance the lack of skilled personnel and the lack of investments in training and formation. Finally, the research concludes that while IoT and AI offer substantial benefits in predictive maintenance, inventory management, demand forecasting, and knowledge management, their widespread adoption is hindered by these barriers. Predictive maintenance survey results indicate that SMEs do not recognize its value, and consequently acceptance is limited.

The findings underscore the importance of knowledge formalisation as a baseline for correctly integrating the SMEs in the realm of connected industry, to increase technological readiness and to have an easier access to external collaboration and support. Finally, these factors can change the negative perception of technological impact from leadership, thus finally exploiting the potential of Industry 4.0.

This thesis contributes to the growing body of knowledge on Industry 4.0's role in transforming supply chains and knowledge management processes. It provides practical recommendations for Italian SMEs to enhance their competitiveness and resilience in an increasingly digital and interconnected market.

1. Introduction

The Fourth Industrial Revolution, commonly referred to as Industry 4.0, represents a fundamental shift in industrial operations and manufacturing processes, characterized by the integration of digital technologies into traditional supply chains and business models. Technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), and big data analytics are at the core of this transformation. These technologies enable enhanced connectivity, automation, and data-driven decision-making, which are essential for achieving higher levels of operational efficiency, predictive maintenance, and flexibility.

For Small and Medium Enterprises (SMEs), which form the backbone of many economies including Italy's, the introduction of Industry 4.0 presents both opportunities and challenges. While large corporations often have the resources to implement cutting-edge technologies, SMEs face unique barriers such as limited financial capital, lack of skilled personnel, and often outdated technological infrastructure. Nevertheless, SMEs are crucial players in the economy, and their ability to adopt and integrate Industry 4.0 technologies is key to remaining competitive in an increasingly digital and interconnected global market.

1.1 Context of the Work

The context of this thesis lies at the intersection of Industry 4.0 technologies and supply chain management, with a particular focus on IoT and AI-based algorithms. Over the past few decades, supply chain management has evolved from a series of isolated, manual processes into a highly complex, integrated system. This shift is largely driven by the demand for real-time information, faster production cycles, and more efficient logistics. However, traditional supply chains, particularly those managed by SMEs, often struggle with inefficiencies due to inadequate technological integration, which results in issues such as stock-outs, overproduction, delayed shipments, and high operational costs.

IoT, one of the core enablers of Industry 4.0, has emerged as a solution to these challenges by enabling real-time tracking and monitoring of products, assets, and processes across the supply chain. IoT devices, such as sensors and RFID tags, collect and transmit vast amounts of data, allowing companies to gain greater visibility into their operations and make informed decisions. In parallel, AI and ML technologies use this data to predict patterns, automate decision-making, and optimize performance. For example, AI-based predictive maintenance allows businesses to anticipate equipment failures and schedule repairs before breakdowns occur, thereby reducing downtime and improving overall efficiency.

Despite the clear advantages of IoT and AI technologies, their adoption remains not levered, particularly among SMEs. In Italy, SMEs form most of the industrial landscape, yet many are still in the early stages of digital transformation. These businesses often face multiple barriers, including a lack of technological expertise, insufficient financial resources, and a resistance to change from more traditional management structures. Furthermore, the integration of IoT and AI requires not only technological investments but also a shift in organizational culture, particularly in how knowledge is managed and formalized within the company.

The role of knowledge management (KM) is critical in the successful adoption of Industry 4.0 technologies. KM involves the formalization of both tacit and explicit knowledge within an organization, allowing it to be shared, stored, and used effectively. In the context of IoT and AI, efficient knowledge management enables companies to harness the data generated by these technologies, transforming it into actionable insights. However, many SMEs struggle with the formalization of knowledge, which limits their ability to fully leverage the potential of IoT and AI. Without the proper KM structures in place, the data collected may remain siloed, underutilized, or misinterpreted, thus negating the potential benefits of these technologies.

1.2 The Aim of the Thesis

The aim of this thesis is to investigate the impact of IoT and AI on supply chains of Italian SMEs. The research seeks to understand how these technologies can be effectively integrated into SME supply chains to improve operational efficiency, enhance predictive maintenance, and optimize inventory management. To do that, it will be gathered data on different levers in SMEs to get an understanding of current situation, aimed at deriving the *primary variables* that affect the successful exploitation. Furthermore, the thesis examines the role of knowledge management practices in facilitating the successful implementation of these technologies, with a focus on how SMEs can formalize and leverage the knowledge generated. Finally, there will be provided recommendations considering the results achieved.

The study is motivated by the growing importance of digital transformation in supply chain management and the recognized need for SMEs to adapt to the changing industrial landscape. By focusing on Italian SMEs, the research addresses a gap in the literature, where much of the existing research on Industry 4.0 and supply chains is focused on large multinational corporations. This thesis aims to provide a more nuanced understanding of the specific challenges and opportunities faced by SMEs in the adoption of IoT and AI technologies.

The first research question (RQ1) addressed in this thesis is:

1. *To determine the most important type of knowledge for a small and medium-sized enterprise, how it is managed, and what is the impact of Knowledge on business performance.*

The second research question (RQ2) addressed in this thesis is:

2. *To determine the current state of Industry 4.0 integration within a small and medium enterprise. What is the level of awareness of an SME regarding the impact of this technology? How willing is it to embrace change to improve "as a whole"?*

The relationship between RQ1 and RQ2 is explored through the following sub-questions:

3. *How important is the formalization of knowledge?*
4. *Is the exchange of knowledge between employees more important, or can digitisation (and the integration of Industry 4.0) improve the process of formalising knowledge and the subsequent utilisation of insights derived from it?*

By answering these questions, this thesis aims to contribute to the existing body of knowledge on Industry 4.0 and supply chain management while providing actionable insights and recommendations for SMEs looking to adopt these technologies.

1.3 Structure of the Document

This thesis is structured into several chapters, each of which addresses different aspects of the research problem, from theoretical foundations to empirical analysis and practical recommendations.

Chapter 1: Introduction

Chapter 2: Systematic Literature Review

This chapter provides the explanation of the approach used for the in-depth review of the existing literature on Industry 4.0, IoT, AI, and their impact on supply chain management. The review is structured around three main themes: the relationship between Industry 4.0 and supply chains, the core technologies involved (with a focus on IoT and AI), and the barriers to adoption faced by SMEs. A systematic approach was adopted in this review, beginning with the identification of key literature in the field. The search was conducted using academic databases such as SCOPUS, and keywords included combinations of "Supply Chain," "Industry 4.0," "IoT," "AI," and "Predictive Algorithms." A total of 49 relevant papers were selected, and the final review categorized these studies into their specific contributions, methodologies, and findings. The chapter concludes with a synthesis of the literature, identifying gaps and areas where further research is needed, particularly in the context of SMEs and knowledge management.

Chapter 3: Analysis of the State of the Art

Chapter 3 explores the current state Industry 4.0 in supply chain management. It begins by providing a historical overview of Industry 4.0, tracing its evolution from earlier industrial revolutions to the present day. The chapter then delves into the core technologies of Industry 4.0, specifically IoT and AI, analysing their benefits, limitations, and real-world applications in supply chain contexts. This chapter also addresses the economic and environmental challenges associated with the adoption of Industry 4.0 technologies. It includes discussions on the financial barriers to adoption, such as the high initial costs of implementing IoT and AI systems, as well as the need for specialized training and skilled personnel. The chapter concludes by discussing the potential role of government policies, subsidies, and training programs in overcoming these barriers.

Chapter 4: Technological Drivers and Trends

This chapter focuses specifically on the technological drivers of IoT and AI in supply chain management. It provides a detailed examination of how IoT devices enable real-time tracking, predictive maintenance, and inventory management across the supply chain. The chapter also discusses the role of AI in predictive algorithms, exploring how these technologies can be used to forecast demand, optimize logistics, and prevent equipment failures. The chapter is further supported by case studies that demonstrate the practical applications of IoT and AI in different industries. These case studies provide insights into how IoT and AI technologies have been successfully implemented in other supply chains and offer lessons that can be applied to SMEs in Italy.

Chapter 5: Small and Medium Enterprises (SMEs)

Chapter 5 shifts the focus specifically to SMEs, exploring the unique challenges and opportunities they face in adopting Industry 4.0 technologies. It begins by outlining the importance of SMEs in the Italian economy and discusses the structural and organizational barriers that hinder their ability to embrace digital transformation. The chapter also includes a case study application of I4.0 in Calabrian SMEs, a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis, highlighting their strengths, such as flexibility and close customer relationships, as well as their weaknesses, including limited financial and technical resources. The chapter concludes with recommendations on how SMEs can overcome these challenges through strategic collaborations, government support, and gradual technology adoption.

Chapter 6: Empirical Analysis and Results

This chapter presents the results of the empirical research conducted through a survey of Italian SMEs. The survey focused on knowledge management practices, the adoption of Industry 4.0 technologies, and the perceived impact of IoT and AI on supply chain performance. The chapter begins by describing the methodology used for data collection and analysis, followed by a detailed presentation of the survey findings through descriptive analysis and statistical correlation of the dimensions. The chapter also includes a factor analysis to identify the underlying drivers and barriers to the adoption of IoT and AI in SMEs. Key insights emerge regarding technological readiness, external support mechanisms, and the perception of the impact these technologies have on performance. The chapter highlights significant gaps in knowledge management practices and offers a deep dive into how formalization and better integration of knowledge-sharing systems can play a pivotal role in leveraging IoT and AI technologies more effectively.

Chapter 7: Summary of results

This chapter synthesizes the key findings of the empirical research on knowledge management practices and Industry 4.0 adoption within Italian SMEs. It answers two main research questions: the role of product and process knowledge in SMEs and the state of

Industry 4.0 integration. Moreover, it highlights the critical importance of formalizing knowledge for improving business performance and competitiveness, while also addressing the current barriers SMEs face in adopting advanced technologies such as IoT and AI. The analysis highlights that companies with strong knowledge management systems are better equipped to pursue Innovation and consequently Industry 4.0 technologies, underscoring the need for digital transformation and structured knowledge-sharing processes to drive operational improvements. Finally, it is analysed the relationship between knowledge formalisation/Industry 4.0 vs. knowledge sharing between employees, giving the author's perspective.

Chapter 8: Framework for Knowledge Management in SME

Chapter 8 presents a comprehensive approach for developing a *knowledge management framework* tailored to SMEs transitioning into Innovation and Industry 4.0. By focusing on the extraction, organization, and transformation of tacit knowledge, this chapter aims to address key challenges related to capturing unstructured, experience-based insights that reside primarily in the expertise of seasoned workers. It highlights practical methods for systematically collecting, categorizing, and storing critical knowledge, creating a foundation for informed decision-making and innovation within SMEs. Through lightweight, cost-effective techniques, this chapter sets the groundwork for sustainable knowledge sharing, promoting a culture of continuous learning that aligns with Industry 4.0's digital and technological demands.

Chapter 9: Conclusion

Chapter 9 summarises the conclusions and recommendations based on the research findings. It reports the key insights from the study, emphasizing the importance of both knowledge management and Industry 4.0 integration for enhancing business performance and competitiveness in Italian SMEs. The chapter also outlines the recommendations for overcoming barriers to adopt advanced technologies.

2. Systematic Literature review

The Literature Search entailed different phases, as it is shown in Figure 1 - Systematic literature review:

In the preliminary phase I chose the *Information Universe* that was scope of my analysis, and I worked on SCOPUS. The keywords selected were *Supply Chain AND Industry 4.0*. The information universe consisted of *2974 documents*. Subsequently, I entered the core of the Literature Search, focusing on *three (3) knowledge domains*:

i. The relationship between Industry 4.0 and supply chain (Keyword: *impact AND disruption, 83 documents*) + the reports from two of the most important strategic consulting firms (*6 documents*);
ii. The core technologies involved in (*691 documents*), narrowing the funnel focusing on two main technologies (Keywords: *AI AND IoT, 97 documents*);
iii. The external factors Impacting this relationship, economic and Environmental (*125 documents*) In a second phase I added [49] the *keyword SME* by finding just *4 documents*, a first signal that confirmed the *research questions*.

To enter in the second phase, Screening and Selection, I took into consideration the 89 documents from the relationship between Industry 4.0 and Supply Chain, the 97 documents of the main technologies, and the 4 related to external factors Industry specific of SME, giving a *Grand Total* of 190 documents.

The screening phase consisted in two subphases:

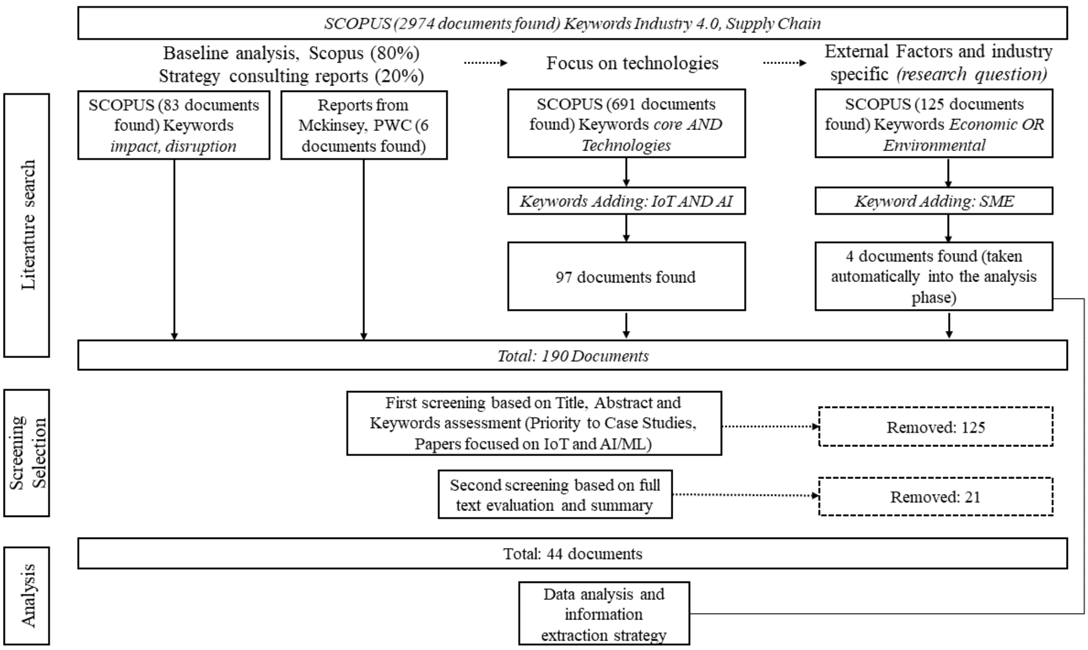

Figure 1 - Systematic literature review

- A first screening based on *Title Abstract Keywords* assessment, by prioritizing the case studies and the following technologies: AI/ML/IoT and Big Data, removing 125 documents;

- Second screening phase consisted on a full text evaluation of 65 documents, arriving to *a total of 49 documents for the scope of my analysis*.

The last phase, Analysis, entailed a full classification of the papers for (Table 1):

Table 1 - Article classification (See Table 2 for full document classification)

Title	Year	Topic	Results	Method	Keywords	Macro area	Technologies	Data type

This analysis allowed to better navigate into the pool of information and leaded to the following approach.

2.1 Systematic Literature Review – Approach and Explanation

To systematically explore the expansive and multifaceted topic of Industry 4.0 and the impact in the most organic of its applications—the Supply Chain—, I adopted a top-down approach. Initially, I conducted a baseline analysis using reports from leading strategic consulting firms like McKinsey and PWC, which helped identify the *two* critical factors (April 2022) that are reshaping global supply chains:

- Economic factors: mostly related to shrinking margins due to COGS exponential increase. This was caused by different *disrupting* factors: conflicts, the pandemic and shortage in ores of materials like silicium that are at the base of any product that is digital. The consequence is having unplanned variations in material flows that create *mismatches* between supply and demand.
- Environmental challenges: the global system of supply chains contribute currently to 80% of greenhouse gas emissions and more than 90% of the consequent impact is on air, land, water and biodiversity.

A second discovery of this baseline analysis is the evolution of the Logistics and Supply Chain, from a pure operational role into a sophisticated, standalone supply chain management function that is the transition in what we call *Industry 4.0*. This transformation includes the adoption of advanced processes like analytical demand planning and integrated S&OP. So, the question is: how did it leverage the SC on Industry 4.0 to overcome the current barriers? The natural answer emerged from the literature is through different technological drivers. The most important technological drivers and trends found through this phase are: IoT, AI, blockchain, digital twin, digital thread, Cloud Computing and Big Data.

After a detailed analysis of the research papers, the most recurring technologies proved to appear in more phases of SC, in different industries and dimensions are: the *Internet-of-Things* and the data derived (1)—that completes and updates the pool of information of the ecosystem—paired with a *brain*, the *Algorithms*(2), that can flow, in most advanced cases, into *Artificial Intelligence*. The combination is crucial to tie *the lows and spikes* of demand and the *fluxes* of supply. Through this focused analysis, it becomes evident that the data extracted from the IoT devices, the use of Cloud Computing to have different supply chains located in distant places, and the use of Algorithms specifically tied to the exigencies of that particular ecosystem leads to several advantages in production and delivery, by having *tailor-made planning*, and in support activities like maintenance, by having *predictive servicing.* These are activities that can *significantly* influence the resilience and performance of the system analysed against various types of disruptions: shortages, blocks, backlogs and external, unpredictable factors. Going further in literature review revealed that the best approach to follow to minimise the use of resources is to use them mostly in a *closed circle* for different reasons: the former is to minimize the quantity of information processed and consequently reducing the usage of resources, the latter is to reduce the possibility of external attacks.

In the final phase of my review, I examined case studies to touch-by-hand the applications, the industries that are taking advantage from it and the impacts made. The impact emerged is cross-industry, and it can be described as: IoT facilitates better coordination and operational insights, the integration of algorithms plays a crucial role in enhancing strategic decision-making and anticipating market fluctuations. However, gaps remain in the literature, particularly in the context of small and medium-sized enterprises (SMEs) that are under considered. Therefore, I decided to concentrate on how IoT and AI can bolster efficiency and resilience in SME supply chains, areas where these technologies promise considerable transformative potential yet are underexplored in existing research.

2.2 Full table classification

The following table is used to classify the papers reviewed for the Literature, classified for Title, Year of Publication, Topic, Main Keywords of the Paper, Field of Work (Macro Area), Technologies of I4.0 used, and typology of data used for the research.

Table 2 - documents classification Title	Year	Topic	Keywords	Macro area	Technologies	Data type
The role of advanced technologies and supply chain collaboration during COVID-19 on sustainable supply chain performance	2024	Impact of advanced technologies and supply chain collaboration on sustainable supply chain performance during COVID-19	COVID-19, sustainable supply chain performance, advanced technologies, supply chain collaboration, structural equation modelling	Technological Impact	Not specific	Real
IoT-enabled coordination for recommerce circular supply chain in the industry 4.0 era	2024	Examines the integration of IoT technologies in the recommerce business for enhancing circular supply chain coordination.	Circular economy, sustainability, coordination, hybrid contract, Internet of Things (IoT), Industry 4.0	Sustainability	IoT	Real
Enhancing trust in global supply chains: Conceptualizing Digital Product Passports for a low-carbon hydrogen market	2024	Conceptualization of Digital Product Passports to enhance transparency and trust in global supply chains, specifically in the low-carbon hydrogen market.	Digital Product Passports, supply chain transparency, low-carbon hydrogen, data privacy, sustainability verification, global supply chains	Case study	Blockchain	Real
Enabling Industry 4.0 Transformation in Calabria region: Framework, Machine Interconnection and ERP Synergy	2024	Investigates the implementation of Industry 4.0 technologies in Calabria, focusing on the synergies between frameworks, machine interconnection, and ERP systems to boost local SMEs.	Industry 4.0, Calabria, SMEs, machine interconnection, ERP systems, predictive maintenance, economic development	Case study	Not specific	Real
Digital economy structuring for sustainable	2024	Examines how digital technologies like blockchain and	Digital economy, blockchain, AI, sustainable development,	Sustainability	AI	Real

development: the role of blockchain and artificial intelligence in improving supply chain and reducing negative environmental impacts		AI can be structured within the digital economy to improve supply chain efficiencies and reduce environmental impacts, aiming for sustainable development.	supply chain management, environmental impacts			
Blockchain Technology in Overcoming Security Threats for Smart Manufacturing Systems - A Systematic Literature Review	2024	Explores the role of blockchain technology in enhancing the security of smart manufacturing systems against various cybersecurity threats.	Blockchain, security threats, smart manufacturing, cybersecurity, systematic literature review	Security	Blockchain	Real
Enhancing supply chain resilience: A machine learning approach for predicting product availability dates under disruption	2024	Use of machine learning to predict product availability dates in supply chains under disruption	Supply chain resilience, machine learning, product availability prediction, supply chain disruption, regression models	Resilience	AI	Simulated
The moderator effect of balance of power on the relationships between the adoption of digital technologies in supply chain management processes and innovation performance in SMEs	2024	Impact of digital technology adoption in supply chain management on innovation performance, moderated by power dynamics in SMEs	Balance of power, digital supply chain, innovation, digital technologies, SMEs	SMEs	Not specific	Real
The impact of industry 4.0 on supply chain capability and supply chain resilience: A dynamic resource-based view	2023	Impact of Industry 4.0 on supply chain capabilities and resilience	Industry 4.0, supply chain resilience, IT advancement, dynamic resource-based view, supply chain collaboration, supply chain visibility	Resilience	Not specific	Real
Digitalization of Supply Chain Management with Industry 4.0 Enabling Technologies:	2023	Digitalization of supply chain management and its sustainable impact with the integration of	Industry 4.0, sustainable supply chain, IoT, AI, blockchain, digital twin,	Sustainability	Not specific	Simulated

A Sustainable Perspective		Industry 4.0 technologies.	PRISM framework			
Industry 4.0: history of emergence, development, prospects of transformation into Industry 5.0	2023	This article provides a historical review and future outlook of Industry 4.0, detailing its evolution, defining characteristics, and the potential transformation into Industry 5.0.	Industry 4.0, Industry 5.0, digital economy, cyber-physical systems, human-machine collaboration, environmental sustainability, product customization	Baseline	Not specific	Real
Digitalization and industry 4.0 within the supply chain: a review of contributions and barriers	2023	A systematic review of the contributions and barriers of digitalization and Industry 4.0 within supply chains.	Digitization, Industry 4.0, Supply chain, Barriers, Contributions	Baseline	Not specific	Real
Revealing the hidden potentials of Internet of Things (IoT) - An integrated approach using agent-based modelling and system dynamics to assess sustainable supply chain performance	2023	Use of IoT to enhance sustainable supply chain performance	Sustainable supply chain (SSC), System dynamics (SD), Agent-based modelling (AB), Internet of Things (IoT), Life cycle assessment (LCA), Life cycle costing (LCC)	Technological Impact	IoT	Real
IoT-based supply chain management: A systematic literature review	2023	Examination of IoT applications in supply chain management	IoT, Supply Chain Management, Real-time data, Sensors, Smart analytics, Automation	Technological Impact	IoT	Real
Unfolding the link between big data analytics and supply chain planning	2023	Big data analytics in supply chain planning	Big data analytics, supply chain planning, Delphi, supply chain processes, data-driven optimization	Technological Impact	Big Data	Real
Disruption-resilient supply chain entities with decentralized robust-stochastic capacity planning	2023	Decentralized robust-stochastic capacity planning for supply chain resilience	Supply chain resilience, robust-stochastic optimization, decentralized capacity planning, discrete-time Markov chain, bi-objective optimization, disruption modelling	Analytics	AI	Simulated
Information sharing and	2023	Information sharing and	Industry 4.0, information	SMEs	Not specific	Real

multi-tier supply chain management of SMEs in the context of Industry 4.0		supply chain management in SMEs under Industry 4.0	sharing, multi-tier supply chain management, SMEs, digital networks			
Big data-driven innovation for sustaining SME supply chain operation in post COVID-19 scenario: Moderating role of SME technology leadership	2022	Big data-driven innovation in SME supply chain management post-COVID-19	Big Data, IoT, SME Performance, COVID, Supply chain, Innovation, Sustainability, SME Leadership Support	SMEs	Big Data	Real
What does Industry 4.0 mean to Supply Chain?	2017	Examines the implications of Industry 4.0 on the supply chain, focusing on the transformation of traditional supply chain management through advanced technologies.	Industry 4.0, supply chain management, Internet of Things (IoT), operational efficiency, collaboration, transparency	Baseline	IoT	Real
How digitization makes the supply chain more efficient, agile, and customer-focused	2016	Discusses how the digitization of supply chains leads to enhanced efficiency, agility, and customer focus, driven by Industry 4.0 technologies.	Industry 4.0, digitization, supply chain efficiency, integrated supply chain ecosystem, logistics visibility, autonomous logistics, smart procurement, advanced analytics	Baseline	Not specific	Real
Challenges and implications of Industry 4.0 in supply chains	2022	Industry 4.0 in supply chains	Industry 4.0, Supply Chains, Challenges	Baseline	Not specific	Real
Barriers to Industry 4.0 adoption in small and medium enterprises	2023	Industry 4.0 adoption in SMEs	Industry 4.0, SMEs, Adoption Barriers	SMEs	Not specific	Real
The need for skilled workforce in Industry 4.0	2022	Workforce in Industry 4.0	Industry 4.0, Skilled Workforce	Baseline	Not specific	Real
Training programs for Industry 4.0 workforce	2022	Training for Industry 4.0 workforce	Industry 4.0, Training Programs	Baseline	Not specific	Real
Cybersecurity challenges in Industry 4.0	2023	Cybersecurity in Industry 4.0	Industry 4.0, Cybersecurity	Security	Blockchain	Real
Economic impact of	2023	Cyber threats on supply chains	Cyber threats, Supply Chains,	Security	Blockchain	Real

cyber threats on supply chains			Economic Impact			
Financial implications of maintaining Industry 4.0 systems	2022	Financial implications of Industry 4.0	Industry 4.0, Financial Implications	Baseline	Not specific	Real
Managing transition disruptions in Industry 4.0	2022	Transition disruptions in Industry 4.0	Industry 4.0, Transition Disruptions	Case Study	Not specific	Real
Workforce displacement and Industry 4.0	2023	Workforce displacement in Industry 4.0	Industry 4.0, Workforce Displacement	Baseline	Not specific	Real
Collaborative partnerships in the era of Industry 4.0	2023	Collaborative partnerships in Industry 4.0	Industry 4.0, Collaborative Partnerships	Baseline	Not specific	Real
Government incentives for Industry 4.0 adoption	2022	Government incentives for Industry 4.0	Industry 4.0, Government Incentives	Baseline	Not specific	Real
Public-private partnerships in Industry 4.0	2022	Public-private partnerships in Industry 4.0	Industry 4.0, Public-Private Partnerships	Baseline	Not specific	Real
Scalable technologies for Industry 4.0	2022	Scalable technologies in Industry 4.0	Industry 4.0, Scalable Technologies	Technological Impact	IoT	Real
Cybersecurity frameworks for Industry 4.0	2023	Cybersecurity frameworks in Industry 4.0	Industry 4.0, Cybersecurity Frameworks	Security	Blockchain	Real
Predictive analytics in supply chain resilience	2023	Predictive analytics in supply chain	Predictive Analytics, Supply Chain Resilience	Technological Impact	AI	Real
The role of digital twins in supply chain management	2023	Digital twins in supply chain management	Digital Twins, Supply Chain Management	Technological Impact	Digital Twin	Real
Real-time visibility with IoT in supply chains	2022	IoT in supply chains	IoT, Real-time Visibility, Supply Chains	Technological Impact	IoT	Real
Collaborative networks in supply chain resilience	2023	Collaborative networks in supply chain	Collaborative Networks, Supply Chain Resilience	Technological Impact	AI	Real
Blockchain energy consumption and environmental impact	2023	Blockchain in Industry 4.0	Blockchain, Energy Consumption, Environmental Impact	Technological Impact	Blockchain	Real
Data-driven supply chain optimization	2023	Data-driven supply chain	Data-driven, Supply Chain Optimization	Technological Impact	Big Data	Real
IoT in asset management and tracking	2023	IoT in asset management	IoT, Asset Management, Tracking	Technological Impact	IoT	Real
Licensing advanced algorithms for	2023	Advanced algorithms in Industry 4.0	Advanced Algorithms,	Technological Impact	AI	Real

competitive advantage			Competitive Advantage			
AI and machine learning in data analytics	2023	AI and machine learning in Industry 4.0	AI, Machine Learning, Data Analytics	Technological Impact	AI	Real
Real-time data for quality control in supply chains	2023	Real-time data in supply chains	Real-time Data, Quality Control, Supply Chains	Technological Impact	Big Data	Real

3. Analysis of the State of Art

In the following chapter it is analysed the State of Art of industry 4.0 in the Supply Chain industry, by analysing its definition, the main technologies and the current challenges associated.

3.1 Industry 4.0 definition and Supply Chain *Management shift*

The advent of Industry 4.0 marks a transformative era in manufacturing and supply chain management, redefining the paradigms under which industrial operations and logistics functions. Originating as a strategic initiative from the high-tech strategy project by the German government, the term Industry 4.0 encompasses a broad array of technologies and concepts that aim to revolutionize the interface between physical operations and digital technologies. This fourth industrial revolution builds upon the digital innovations of the third revolution, such as the Internet of Things (IoT), cyber-physical systems (CPS), artificial intelligence (AI), and big data analytics, aiming to create smarter, more efficient, and highly integrated supply chain ecosystems.

3.1.1 Strategic Framework and Theoretical Underpinnings

The theoretical foundation of Industry 4.0 is rooted in the digital transformation of manufacturing systems, leveraging technologies that enhance connectivity, automation, machine learning, and real-time data processing. These technologies are not merely evolutionary but represent a disruptive force that shifts manufacturing from centralized, top-down control schemes to decentralized, autonomous operations (Son & Breka, 2023). This shift is not only technological but also involves significant socio-economic implications, particularly in terms of labour markets, economic structures, and international trade dynamics (Geissbauer et al., 2016). Furthermore, the integration of these advanced technologies aims to enhance operational efficiency and agility, reducing waste and increasing speed to market, which are crucial in today's highly competitive business environment (Tjahjono et al., 2017).

Economically, the implementation of Industry 4.0 technologies has been both a response to and a catalyst for addressing the inefficiencies in traditional manufacturing and supply chain frameworks. Issues such as demand-supply mismatches, production bottlenecks, and inventory excesses are targets for Industry 4.0 solutions. Technologies such as IoT and AI enable more accurate demand forecasting and adaptive production systems, potentially reducing the costs associated with overproduction and storage (Son & Breka, 2023). However, these advances also come with high initial capital investments and significant maintenance costs, posing substantial economic challenges, particularly for small and medium enterprises (SMEs) that may lack the financial resources to adopt such technologies without significant external support (Geissbauer et al., 2016).

Environmentally, the shift towards Industry 4.0 could offer significant benefits in terms of resource efficiency and waste reduction. The potential for "smart factories" to minimize carbon footprints through optimized energy use and reduced material waste is substantial

(Son & Breka, 2023). Nevertheless, the environmental impact of producing and disposing of high-tech equipment used in these factories—such as sensors, servers, and other connected devices—remains a critical concern. The lifecycle impacts of these technologies, including their contribution to electronic waste, are significant and must be considered in the broader context of environmental sustainability (Tjahjono et al., 2017).

3.1.2 Core Technologies: Benefits and Limitations

To have a better understanding of the underlying tools that hide behind the macro-argument of Industry 4.0, in the Table 3 will be presented the core technologies, with a deeper analysis lately in the literature review.

Table 3 - core technologies

Technology	Type	Description	Impact on Efficiency	Financial Cost	Sustainability
IoT	Connectivity	By connecting devices across the supply chain, IoT facilitates real-time data capture and sharing, enhancing visibility and traceability throughout the supply chain. However, it raises issues regarding data security and privacy.	High	High	Medium - While it improves efficiency and reduces waste, the production and disposal of sensors contribute to e-waste.
Big Data and Analytics	Data Processing and Analysis	The ability to analyse large sets of data to derive actionable insights allows firms to predict market trends, optimize production processes, and personalize customer offerings.	High	Medium	Medium - Efficient use of resources, but significant energy use for data storage and processing.
AI and Machine Learning	Automation and Intelligence	AI automates complex decision-making processes by identifying patterns and making predictions based on vast datasets. In supply chain management, it streamlines logistics, enhances inventory management, and manages supplier relationships.	High	High	Medium - Reduces waste and improves efficiency, but the high computational power needed has a significant energy footprint.
Blockchain	Ledger Technology	Blockchain provides a secure, immutable record of transactions,	Medium	High	Low - Offers transparency and traceability

		enhancing transparency and trust across the supply chain, particularly useful in scenarios requiring certification of authenticity.			but has high energy consumption issues, especially with proof-of-work mechanisms.

Here it was presented briefly the most important components behind the ecosystem of Industry 4.0, but the success, as we are going to explore, will depend on a collaborative approach that includes stakeholders from industry, government, academia, and civil society. Together, these groups must strive to ensure that the benefits of Industry 4.0 are realized broadly and equitably, leading to sustainable industrial practices that benefit not only the bigger players but all the businesses, by having a *total societal impact*. As this literature review progresses, it will continue to explore these themes, providing a comprehensive examination of how Industry 4.0 is reshaping the landscape of manufacturing and supply chain management.

3.2 Baseline Analysis of Industry 4.0

The objective of this subchapter is to trace the historical context of the industry 4.0, its definition, and the enabling technologies associated.

3.2.1 Historical Context and Definitions

The genesis of Industry 4.0 is deeply rooted in the historical evolution of industrial revolutions, each distinctly marked by technological breakthroughs that transformed production processes and societal structures. The term "Industry 4.0" originates from a strategic initiative dubbed "Industrie 4.0" by the German government, aimed at promoting the computerization of manufacturing industries. It was officially introduced at the Hannover Fair in 2011, conceptualized as the fourth industrial revolution that integrates cyber-physical systems into manufacturing technologies (Nikishina, 2023).

The past

The first industrial revolution began in the late 18th century, characterized by the shift from hand production methods to machines through the use of steam-powered engines and the mechanization of textile manufacturing. This period saw the rise of factory systems and significant socioeconomic shifts. The second revolution, starting in the late 19th century, introduced mass production with the help of electrical power, leading to the creation of production lines and significant advancements in the chemical, electrical, and steel industries. The third industrial revolution, emerging in the late 20th century, is often referred to as the digital revolution. It was marked by the advent of electronics, telecommunications, and computers, which facilitated automation in production processes (Nikishina, 2023).

The present and the future

Industry 4.0 represents a fundamental change in the paradigm of industrial operations. Unlike its predecessors, it is not marked by the emergence of a new energy source but by the integration of digital technology into all areas of business and production. This revolution enhances the connectivity and interaction between systems and entities in the manufacturing process through the Internet of Things (IoT), making smart factories possible. In smart factories, machinery and equipment are able to improve processes through automation and self-optimization. The benefits extend beyond simple production efficiency and include significant improvements in the speed of operation and the personalization of products to meet customer needs more effectively. The transformation into Industry 5.0 is already on the horizon, with a focus shifting towards more personalized production, increased sustainability, and a stronger integration between humans and machines. The core of Industry 5.0 emphasizes the return of human hands and minds into the industrial structure, working alongside robots and smart machines to enhance creativity and flexibility in production processes. This upcoming phase aims to combine the capabilities of both human and machine to create a more holistic approach to industrial production, potentially overcoming the limitations of fully automated systems by including human ingenuity and complex decision-making processes (Nikishina, 2023).

3.2.2 Industry 4.0 enabling technologies

The technological backbone of Industry 4.0 comprises several key components that work synergistically to create highly efficient, automated, and flexible production environments. These technologies not only revolutionize manufacturing processes but also significantly impact supply chain management, leading to what is often termed as the digital supply chain (Chauhan et al., 2023). Here, it will be presented the integration of the different parts of the information system:

- *Cyber-Physical Systems (CPS):* Integrations of computation, networking, and physical processes. Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa. The deployment of CPS in manufacturing leads to the creation of smart factories that are capable of self-monitoring, analysis, and diagnostics.

- *Internet of Things (IoT):* This involves the connection of all relevant devices, machines, and systems to a dynamic network, enabling them to communicate without human intervention. The IoT enhances manufacturing and production capabilities by seamlessly integrating different phases of the production line, from initial design to final product delivery, optimizing operations through data collection and analysis.

- *Big Data and Analytics:* The vast amounts of data generated by digital operations require effective tools for collection, analysis, and utilization. Big data analytics in Industry 4.0 allows for predictive maintenance, enhanced supply chain management, and ultimately, more informed decision-making processes that streamline operations and reduce costs.

- *Cloud Computing:* Cloud technologies provide scalable and flexible computing resources, offering enhanced data storage, processing, and analytics capabilities. They facilitate the remote operation and monitoring of manufacturing processes, enabling the decentralization of production operations and enhancing collaboration across geographical boundaries.

- *Artificial Intelligence (AI) and Machine Learning:* AI provides systems the ability to automatically learn and improve from experience without being explicitly programmed. In the context of Industry 4.0, AI facilitates the analysis of big data to optimize operations, predict system failures, and adaptively manage supply chains in real-time.

- *Additive Manufacturing (3D Printing):* This technology builds parts layer-by-layer, which allows for the creation of complex geometries that are not possible with traditional subtractive manufacturing methods. Additive manufacturing is particularly useful for prototyping, small batch production, and on-demand manufacturing.

- *Augmented Reality (AR) and Virtual Reality (VR):* AR and VR offer tremendous potential in the context of industrial maintenance, training, and product development. They provide workers with real-time, immersive, and interactive environments, improving the understanding of complex operations and enhancing the speed and quality of decision-making.

These core technologies of Industry 4.0 integrate to form a robust digital ecosystem capable of self-regulation, adaptation, and enhanced resource efficiency, fundamentally altering the landscape of industrial production and paving the way for unprecedented levels of operational efficiency and agility in the manufacturing sector (Nikishina, 2023).

3.3 Thematic Exploration

The objective of the subchapter is to navigate the challenges associated with Industry 4.0, and the perspectives accompanying its enabling perspectives.

3.3.1 Economic Challenges

The advent of Industry 4.0 has brought significant advancements in technology, promising substantial improvements in efficiency, productivity, and overall supply chain performance as we have said in the previous paragraphs. However, alongside these benefits, the implementation of Industry 4.0 also presents several economic challenges that businesses must navigate to fully leverage its potential. This subchapter delves into the economic challenges posed by Industry 4.0 on supply chain capabilities and resilience, examining the barriers to adoption, the financial implications, and the strategies aimed to overcome these limits.

Barriers to Adoption – external factors

One of the primary economic challenges in the implementation of Industry 4.0 is the substantial initial investment required. Advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), robotics, and big data analytics necessitate significant capital expenditure. For many companies, particularly small and medium-sized enterprises (SMEs), these costs can be prohibitive, limiting their ability to adopt these innovations. This financial barrier creates a disparity between large corporations and SMEs, potentially widening the competitive gap within industries (Huang et al., 2023). Furthermore, the integration of Industry 4.0 technologies demands a highly skilled workforce proficient in new and complex systems. Training existing employees and hiring new talent with the requisite skills entails additional costs (Gupta & George, 2022; Raman & Ganapathy, 2022). This need for specialized knowledge also underscores the broader issue of workforce readiness, as the current workforce may not be adequately equipped to handle the demands of these advanced technologies (Davis, 2023). Another significant barrier is the high cost of cybersecurity. With the increased connectivity and data exchange inherent in Industry 4.0, the risk of cyber threats escalates. Companies must invest heavily in robust cybersecurity measures to protect sensitive data and ensure the integrity of their supply chains. This includes not only financial investments but also the development of policies and protocols to mitigate risks. The potential costs associated with cyber breaches, both financial and reputational, further exacerbate the economic challenges (Nguyen, 2023).

The financial implications of adopting Industry 4.0 technologies extend beyond initial investments. Maintenance and upgrade costs for these sophisticated systems can be substantial. Continuous updates are necessary to keep up with technological advancements and to address any emerging security vulnerabilities. These ongoing expenses can strain financial resources, particularly for smaller companies with limited budgets (Kumar, 2022). Moreover, the transition to Industry 4.0 can disrupt existing business processes, leading to temporary inefficiencies and productivity losses. During the implementation phase, companies may experience downtime as they integrate new technologies and train staff. These disruptions can result in short-term financial setbacks, impacting profitability and operational efficiency (Smith, 2022). Companies must therefore carefully manage the transition process to minimize these adverse effects, by leveraging a step-by-step digitalisation, starting from the inbound logistics (Butala et al., 2022). The shift towards automation and digitization also raises concerns about job displacement. While Industry 4.0 can create new job opportunities in tech-driven roles, opening new dimensions in the supply chain ecosystem, it can also render certain manual jobs obsolete. This potential displacement can lead to economic challenges for workers, necessitating measures such as retraining programs and social safety nets (Davis, 2023).

To navigate the economic challenges associated with Industry 4.0, companies must adopt different strategic approaches. One effective strategy is to seek collaborative partnerships. By partnering with technology vendors and IT consultancy businesses, companies can share the financial burden of adopting new technologies, by taking advantage of the expertise and the flexibility of industry experts (Lewis, 2023). Collaborative efforts can also facilitate knowledge exchange and innovation, enhancing overall supply chain capabilities (Wang, 2023). Government support plays a crucial role in mitigating economic challenges. Policymakers can provide financial incentives, such as grants, subsidies, and tax breaks, to encourage the adoption of Industry 4.0 technologies, fast-tracking the broad adoption of an innovation (Patel, 2022). Additionally, government-funded training programs can help build a skilled workforce, reducing the financial burden on individual companies (Walker, 2022). Public-private partnerships can further accelerate the implementation of Industry 4.0 by combining resources and expertise (Martinez, 2022). Investing in scalable and flexible technology solutions is vital, specifically for small business that have less financial availability. Technologies that can be scaled up or down based on the needs offer flexibility to adapt to changing market conditions. Furthermore, this can help manage costs and minimize financial risks associated with technology investments (Garcia, 2023). Focusing on modular technologies allows for incremental implementation, spreading costs over time and diluting the financial impact (Jones et al., 2023).

Another fundamental practice to reduce the risks of inefficiency and failures is by integrating Risk Management. Implementing robust Risk Management practices is essential for addressing the cybersecurity challenges of having a system with a connection to the external digital world. Proactive measures to identify and mitigate cyber threats can prevent costly breaches and protect financial resources (Carter, 2023). Building a culture of cybersecurity awareness within the organization is equally important to have a human-proof system, that avoids unnecessary errors (Thompson, 2023). Another interesting point that deserves to be analysed is the diversification and redundancy. As we saw in the last years, we live in a VUCA world, in which natural disasters, geopolitical tensions, and other unforeseen events can have far-reaching effects on supply chains that could lead to heavy delays (we can think of the car sector due to the crisis of the rare materials needed to produce the infotainment parts) in the product production (Smith, 2022). Diversifying supply sources and building redundancy into the supply chain can reduce dependency on single suppliers and enhance resilience (Martinez, 2022). Additionally, leveraging predictive analytics and AI can help anticipate disruptions and enable a more informed decision-making (Chen, 2023). Digital twins, for example, create virtual models of physical supply chains, allowing companies to simulate different scenarios and assess the potential impact of disruptions (Zhang, 2023). This capability enables more effective planning and response strategies, without impacting heavily on costs (Smith, 2022). Moreover, IoT devices can provide real-time visibility into supply chain operations, enabling rapid detection and problem resolution (Kim, 2022; Lee, 2023).

How *intrinsically* the digital supply chain can help to scale-up the value delivered

While the economic challenges of I4.0 are significant, there are also considerable opportunities that businesses can capitalize on to enhance their supply chain capabilities and resilience. By strategically leveraging these opportunities, companies can not only offset the costs associated with Industry 4.0 but also gain a competitive edge in the market. One such opportunity lies in the optimization of operational efficiencies. Industry 4.0 technologies, such as IoT-derived data collection and Machine Learning, enable predictive maintenance and real-time monitoring of equipment, reducing downtime and maintenance costs (Lee, 2023). These technologies can predict equipment failures before they occur, allowing for timely interventions that minimize disruptions and extend the lifespan of machinery (Smith, 2022). Additionally, automation through robotics and AI can streamline repetitive tasks, reducing labour costs and increasing productivity (Raman & Ganapathy, 2022). For instance, automated guided vehicles (AGVs) and robotic arms can handle material handling and assembly processes with greater precision and speed than human workers (Martinez, 2022). This not only reduces the risk of human error but also enhances the speed and consistency of production processes. The resultant improvements in productivity can lead to higher output and better utilization of resources (Carter, 2023). The use of big data analytics and IoT devices allows for enhanced demand forecasting and inventory management. By analysing large volumes of data from various sources, companies can gain deeper insights into market trends and customer preferences (Jones et al., 2023). This enables more accurate demand forecasting, reducing the risk of overproduction or stockouts (Kim, 2022). Improved inventory management can lead to lower holding costs and more efficient use of warehouse space, further contributing to cost savings (Smith, 2022).

The supply chain as a new revenue opportunity

Another economic opportunity is the potential for new revenue streams through data monetization. The vast amounts of data generated by Industry 4.0 technologies can be valuable assets. Companies can analyse and monetize this data by offering insights and analytics services to other businesses. For example, a manufacturing firm could provide data-driven consultancy services to optimize the supply chains of other companies. This creates a new business model and an additional source of revenue. The ability to monetize data levers on the advanced analytics capabilities enabled by AI, machine learning, and big data analytics. These technologies allow companies to process and analyse large datasets quickly and accurately, uncovering patterns and insights that can drive strategic decision-making (Smith, 2023). For instance, predictive analytics can help businesses forecast demand, manage inventory more efficiently, and optimize production schedules. These insights can be offered as a service to other companies, creating a lucrative market for data-driven consultancy. By providing tailored analytics solutions, firms can help their clients enhance operational efficiency, reduce costs, and improve overall supply chain performance (Jones et al., 2023).

Furthermore, the implementation of IoT devices across supply chains generates real-time data that can be harnessed for various applications. For example, IoT sensors can monitor the condition of goods during transit, providing data that ensures product quality and compliance with regulations. This real-time monitoring capability can be marketed to companies that require stringent quality control, such as those in the pharmaceutical or food industries (Wang, 2023). Additionally, IoT data can be used to improve asset management by tracking the location and status of equipment and inventory. Companies can offer asset tracking services that enhance transparency and reduce losses due to theft or misplacement, adding another revenue stream (Lee, 2023).

Blockchain technology also plays a crucial role in data monetization by providing secure and transparent data sharing mechanisms. Blockchain's decentralized ledger ensures the integrity and immutability of data, which is essential for building trust in data-driven services. Companies can use blockchain to create platforms where data is securely shared and monetized among stakeholders. For example, a logistics firm could develop a blockchain-based platform where real-time shipping data is shared with customers, enabling better tracking and delivery predictions (Garcia, 2023). This not only improves customer satisfaction but also opens new revenue opportunities through subscription-based access to premium data services (Patel, 2023).

Moreover, the integration of AI and machine learning in data analytics can lead to the development of sophisticated algorithms that provide deeper insights and more accurate predictions. Companies can license these algorithms to other businesses, generating revenue from intellectual property. For example, a company that develops an advanced demand forecasting algorithm could license it to retailers to optimize their stock levels and reduce waste (Martinez, 2023). This approach allows companies to monetize their technological innovations and establish themselves as leaders in the data analytics market (Smith, 2023).

The value of data monetization extends beyond immediate revenue generation. By leveraging data to create new services and business models, companies can achieve a competitive advantage. Data-driven insights enable businesses to innovate and differentiate their offerings, attracting more customers and increasing market share. For example, a manufacturing firm that uses data analytics to optimize production processes can offer these capabilities as a service to other manufacturers, positioning itself as an industry leader in efficiency and innovation (Jones et al., 2023). Additionally, the ability to provide real-time insights and predictive analytics can enhance customer relationships by offering greater value and support, fostering long-term loyalty (Wang, 2023).

Furthermore, the use of data monetization strategies can lead to the development of partnerships and collaborations that drive further growth. Companies that offer data analytics services can collaborate with technology providers, academic institutions, and other industry players to expand their capabilities and market reach. These partnerships can lead to the co-development of new solutions and services, creating additional revenue streams and enhancing the overall value proposition (Lee, 2023). For instance, a partnership between a manufacturing firm and a tech company could result in the creation of a joint analytics platform that serves multiple industries, broadening the customer base and increasing revenue potential (Patel, 2023).

The ethical and regulatory considerations surrounding data monetization must also be addressed to ensure sustainable growth. Companies need to implement robust data governance frameworks to protect customer privacy and comply with regulations such as the General Data Protection Regulation (GDPR) (Garcia, 2023). By demonstrating a commitment to data security and ethical practices, companies can build trust with their customers and stakeholders, which is crucial for the long-term success of data monetization initiatives (Smith, 2023).

In conclusion, data monetization represents a significant economic opportunity for companies in the era of Industry 4.0. By leveraging advanced analytics, IoT, blockchain, and AI technologies, businesses can create new revenue streams through data-driven services and solutions. This not only enhances their market position but also drives innovation and operational efficiency. However, to fully realize the potential of data monetization, companies must address ethical and regulatory challenges and build robust partnerships that foster sustainable growth. As the digital economy continues to evolve, data monetization will play a pivotal role in shaping the future of business and industry.

3.3.2 Environmental Challenges

The digital economy, driven by Industry 4.0 technologies, promises significant advancements in efficiency and productivity. However, the integration of these technologies also presents substantial environmental challenges. This subchapter explores the environmental challenges posed by Industry 4.0 on supply chain sustainability, examining resource consumption, waste generation, and strategies to mitigate these impacts.

Energy and waste management

The deployment of Industry 4.0 technologies involves considerable resource consumption and energy use. Advanced manufacturing processes, IoT devices, and data centres require substantial amounts of electricity. Data centres are notorious for their high energy consumption due to the need for continuous operation and cooling systems. This energy demand contributes to increased greenhouse gas emissions, exacerbating climate change (Nikishina, 2023). The reliance on fossil fuels for energy in many regions further compounds the environmental impact of these technologies (Tjahjono et al., 2017). In addition to energy consumption, the production and disposal of electronic devices contribute to environmental degradation. The manufacturing of IoT devices, sensors, and other Industry 4.0 components requires significant amounts of raw materials, including rare earth elements. The extraction and processing of these materials often result in habitat destruction, soil and water pollution, and high carbon emissions (Chauhan et al., 2023). Moreover, electronic waste (e-waste) generated from outdated or obsolete devices poses a significant environmental challenge. E-waste contains hazardous substances that can leach into the soil and water, causing long-term environmental harm (Nikishina, 2023).

The use of blockchain technology, while offering transparency and traceability in supply chains, also raises environmental concerns. Blockchain networks, particularly those using proof-of-work consensus mechanisms, require substantial computational power. The energy-intensive nature of these networks can lead to a significant carbon footprint. For instance, Bitcoin mining alone consumes more energy than some entire countries, highlighting the environmental cost of blockchain applications (Tjahjono et al., 2017).

Resource Consumption in Supply Chains

The increased connectivity and data exchange in Industry 4.0 supply chains require robust IT infrastructure. Building and maintaining this infrastructure involves considerable resource consumption, including metals, plastics, and energy. The lifecycle of IT equipment, from production to disposal, has a substantial environmental impact. Companies must consider the environmental cost of upgrading and expanding their IT infrastructure to support Industry 4.0 technologies (Tjahjono et al., 2017). Transportation and logistics, integral components of supply chains, also face environmental challenges. Industry 4.0 technologies aim to optimize logistics through real-time data and predictive analytics. While these advancements can reduce inefficiencies, the overall environmental impact of transportation remains significant. The use of fossil fuels for transportation contributes to air pollution and carbon emissions. Additionally, the increased demand for fast delivery in e-commerce results in more frequent and smaller shipments, which can increase the carbon footprint of logistics operations (Chauhan et al., 2023).

Strategies for implementing a *Sustainable Industry 4.0*

To address the environmental challenges, we can look at different strategies that can be implemented. One effective strategy is the use of renewable energy sources to power data centres and manufacturing facilities. By transitioning to solar, wind, or hydropower, companies can significantly reduce their carbon footprint (Nikishina, 2023). For example, Big Techs like Google and Amazon have invested heavily in renewable energy to power their data centres, setting a precedent for sustainable practices in the digital economy. Another strategy is the development of energy-efficient technologies. Advances in AI and machine learning can optimize energy use in manufacturing processes and IT operations. For instance, AI algorithms can dynamically adjust power usage based on real-time demand, reducing unnecessary energy consumption (Tjahjono et al., 2017). Implementing energy-efficient cooling systems in data centres can also mitigate the environmental impact of these facilities. These innovations not only reduce energy use but also lower operational costs, offering a dual benefit of environmental and economic sustainability (Chauhan et al., 2023).

Another strategy is to shift from a linear, *cradle-to-gate* product lifecycle to the *circular economy*. The adoption of these principles can also enhance the sustainability of Industry 4.0. A circular economy emphasizes the reuse, refurbishment, and recycling of materials and products, minimizing waste and resource consumption. Companies can design IoT devices and other electronic components for easier disassembly and recycling. By recovering valuable materials from e-waste, companies can reduce the need for new raw materials and lower their environmental impact (Nikishina, 2023). Moreover, implementing take-back programs and promoting the refurbishment of products can extend their lifecycle and reduce e-waste generation (Chauhan et al., 2023).

Companies can also leverage digital twins and simulation technologies to improve sustainability. By modelling different scenarios, companies can identify the most energy-efficient and sustainable practices. For example, a digital twin of a manufacturing plant can simulate the impact of different energy sources, production schedules, and maintenance practices on energy consumption and emissions (Tjahjono et al., 2017).

Policy Considerations

Government regulations play a crucial role in promoting the sustainable implementation of Industry 4.0. Policymakers can provide incentives for companies to adopt renewable energy, energy-efficient technologies, and circular economy practices (Nikishina, 2023). For instance, tax credits, grants, and subsidies can reduce the financial burden of investing in sustainable technologies. Regulatory frameworks that mandate energy efficiency standards and waste management practices can also drive companies towards more sustainable operations (Tjahjono et al., 2017). International cooperation is essential to address the global nature of supply chains and the environmental challenges they pose. Cross-border collaboration on environmental standards, carbon pricing, and sustainability reporting can harmonize efforts and ensure that companies adhere to consistent and robust environmental practices (Chauhan et al., 2023). Additionally, international organizations can facilitate the exchange of best practices and technologies, accelerating the global transition to sustainable digital supply chains (Nikishina, 2023).

In conclusion, addressing the environmental challenges of Industry 4.0 requires a holistic approach that considers the entire lifecycle of technologies and products. By prioritizing sustainability, companies can not only reduce their environmental impact but also gain a competitive advantage in an increasingly eco-conscious market (Son & Breka, 2023). The transition to a sustainable digital economy is essential for ensuring long-term environmental health and economic prosperity (Chauhan et al., 2023).

4. Technological Drivers and Trends

The following chapter has the purpose to examine the two most used technologies of Industry 4.0 in supply chains, IoT (Internet of Things) and AI (Artificial Intelligence), investigating benefits and limitations. There will be presented different case studies, to give to the reader perspectives in real world applications.

4.1 Internet of Things (IoT)

4.1.1 Definition and Introduction

The Internet of Things (IoT) is a transformative technology that has significantly impacted various sectors, including supply chain management (SCM). IoT refers to a network of physical objects embedded with sensors, software, and other technologies to connect and exchange data with other devices and systems over the internet. The primary goal of IoT is to collect and exchange data to facilitate automation and improve efficiency in various processes (Kumar et al., 2024). *Kevin Ashton, a British technology pioneer*, coined the term "*Internet of Things*" in 1999. He envisioned a system where the internet is connected to the physical world via ubiquitous sensors, enabling the collection of data from the environment to drive *intelligent decision-making*. IoT is built on a layered architecture comprising three main layers: the Perception layer, the Network layer, and the Application layer. The Perception layer involves the physical components, such as sensors and actuators, which collect data. The Network layer transmits this data to different devices and servers for processing. The Application layer provides specific services to end-users based on the processed data, facilitating an intelligent IoT-based environment (Ding et al., 2023).

In the context of Industry 4.0, IoT plays a crucial role by integrating advanced technologies such as artificial intelligence (AI), machine learning (ML), and cloud computing. This integration allows IoT to enhance various industrial processes, making them more efficient and responsive. For supply chains, IoT offers numerous advantages, including real-time tracking, predictive maintenance, and improved inventory management. By leveraging IoT, businesses can gain better visibility and control over their supply chain operations, leading to reduced costs and increased efficiency (Ding et al., 2023; Kumar et al., 2024).

Drivers and the Integration with other Technologies

Several trends are shaping the future of IoT, particularly in supply chain management. The adoption of *edge computing* is one such trend. Edge computing involves processing data closer to the source (i.e., IoT devices) rather than relying solely on centralized data centres. This reduces latency and bandwidth usage, enabling real-time decision-making and improving the efficiency of IoT applications. This trend is driven by the increasing volume of data generated by IoT devices, which necessitates faster and more efficient data processing methods to ensure timely and actionable insights (Cucurachi et al., 2023). In supply chain management, edge computing facilitates various improvements. By processing data locally, edge computing reduces the time it takes for information to travel from IoT devices to central servers and back, significantly decreasing latency. This is crucial for applications that require immediate responses, such as monitoring perishable goods in transit, where any delay could result in spoilage (Ding et al., 2023). Furthermore, edge computing can enhance the reliability of IoT systems by mitigating the risks associated with network disruptions. Since data processing occurs locally, the system can continue to operate even if the connection to the central server is temporarily lost, and this can introduce a better energy management (Ward et al., 2024).

Another emerging trend in IoT for supply chain management is the integration of artificial intelligence (AI) and machine learning (ML). These technologies leverage the vast amounts of data generated by IoT devices to provide predictive analytics and advanced decision-making capabilities. For instance, AI and ML algorithms can analyse historical and real-time data to forecast demand more accurately, optimize inventory levels, and predict potential supply chain disruptions. This predictive capability is especially valuable in the context of just-in-time (JIT) inventory management, where precise timing is essential to minimize storage costs and avoid stockouts (Kim, 2022). AI and ML also enable more sophisticated automation within supply chains. Automated systems can manage routine tasks such as order processing, inventory tracking, and shipment scheduling, reducing the need for manual intervention and minimizing human error. Additionally, AI-driven systems can identify patterns and anomalies in data that may indicate issues such as equipment malfunctions or security breaches, allowing for proactive maintenance and enhanced cybersecurity measures (Kim, 2022).

The integration of blockchain technology with IoT is another significant trend. Blockchain provides a secure and transparent method for recording transactions and tracking assets throughout the supply chain. When combined with IoT, blockchain can enhance traceability, accountability, and trust among supply chain participants. For example, IoT sensors can record the conditions under which goods are transported and stored, while blockchain ensures that this data is immutable and verifiable. This combination is particularly beneficial for industries that require strict compliance with regulatory standards, such as pharmaceuticals and food and beverage (Lee, 2023). Moreover, blockchain can streamline and automate contractual processes through smart contracts. These are self-executing contracts with the terms of the agreement directly written into code. Smart contracts can automatically trigger actions such as payments or shipments when predefined conditions are met, reducing the need for intermediaries and expediting transactions (Cucurachi et al., 2023).

The growing emphasis on sustainability is also influencing the adoption of IoT in supply chain management. IoT-enabled systems can monitor and optimize energy usage, reduce waste, and track the environmental impact of supply chain activities. For instance, IoT devices can provide real-time data on energy consumption, allowing companies to identify inefficiencies and implement measures to reduce their carbon footprint. Additionally, IoT can support the circular economy by facilitating the tracking and management of products throughout their lifecycle, from production to recycling or disposal (Ding et al., 2023).

In summary, the future of IoT in supply chain management is being shaped by several key trends: the adoption of edge computing for faster and more reliable data processing (Ding et al., 2023; Cucurachi et al., 2023), the integration of AI and ML for predictive analytics and automation (Ding et al., 2023), the combination of blockchain for enhanced traceability and security (Ward et al., 2024), and the focus on sustainability to reduce environmental impact

(Ding et al., 2023). These advancements are poised to revolutionize supply chain operations, making them more efficient, resilient, and sustainable. As these technologies continue to evolve and mature, their adoption will likely become increasingly widespread, driving further innovation and transformation in supply chain management (Cucurachi et al., 2023).

Macro-improvements inside the Supply Chain

As we referred before in this paper, the integration among the technological trends and IoT enhances various industrial processes, making them more efficient and responsive. For supply chains, IoT offers numerous advantages, including real-time tracking, predictive maintenance, and improved inventory management. By leveraging IoT, businesses gain better visibility and control over their supply chain operations, leading to reduced costs and increased efficiency.

One of the primary advantages of IoT in supply chain management is *real-time tracking*. IoT devices, such as sensors and RFID tags, provide continuous data on the location and status of goods. This real-time visibility helps businesses monitor their inventory, track shipments, and manage assets more effectively. For example, the integration of IoT in supply chains can reduce the average product storage and shipment fluctuations, as demonstrated in a study on Li-ion battery delivery chains. The study showed that IoT-enabled supply chains could minimize storage levels and increase transportation efficiency, leading to a 30% increase in overall profitability and a significant reduction in carbon emissions (Ward et al., 2024). *Inventory management* is another area where IoT can make a substantial impact. By providing real-time data on inventory levels, IoT helps businesses optimize their stock levels and reduce the risk of overstocking or stockouts. This capability is crucial for maintaining a lean inventory and reducing carrying costs. IoT-enabled inventory management systems can automate the reordering process based on predefined thresholds, ensuring that inventory is always at optimal levels. This automation not only reduces manual labour but also improves the accuracy and reliability of inventory data (Ding et al., 2023).

The combination of these enhancements in the chain enables an improved coordination by having better communication and collaboration among different stakeholders. IoT devices share real-time data across the network, leading to more synchronized production schedules, optimized logistics, and faster response times to market changes. For instance, a study on the recommerce circular supply chain highlighted the role of IoT in enhancing coordination and operational insights, leading to more efficient and sustainable supply chain practices (Kumar et al., 2024).

The implementation of IoT in supply chains also contributes to environmental sustainability and resilience against disruption. IoT technologies can help reduce carbon emissions by optimizing transportation routes, minimizing energy consumption, and improving waste management. For example, IoT-enabled smart logistics and inventory management systems can significantly curb carbon emissions and have a sustained positive impact on the environment. In the study of the Li-ion battery supply chain, IoT implementation resulted in a reduction of 60-70% in heating and lighting emissions during the storage process and a decrease of at least 50% in transportation emissions under high-demand scenarios (Ding et al., 2023). IoT can enhance risk management and resilience in supply chains by providing real-time data on potential disruptions and enabling quicker response times. IoT devices can monitor environmental conditions, track the movement of goods, and detect anomalies that may indicate supply chain disruptions. By having access to this real-time data, businesses can develop contingency plans and take proactive measures to mitigate risks. The ability to quickly adapt to changing conditions and recover from disruptions is crucial for maintaining supply chain continuity and resilience (Ding et al., 2023).

4.1.2 Challenges

The adoption and integration of the Internet of Things (IoT) in supply chain management has introduced numerous opportunities for improving efficiency, sustainability, and profitability. However, these advancements come with significant challenges that need to be addressed to realize the full potential of IoT, in different contexts. This section explores the primary challenges associated with the implementation of IoT in supply chains, including security concerns, data management issues, integration complexities, and the financial implications.

Security Concerns

Security remains one of the most critical challenges in IoT adoption within supply chains. IoT devices are often vulnerable to cyber-attacks due to their interconnected nature and the vast amount of data they handle. These security issues can range from unauthorized access and data breaches to more sophisticated attacks like distributed denial of service (DDoS). IoT devices collect and transmit sensitive information, such as inventory levels, shipment tracking, and production schedules. If this data is intercepted or manipulated, it can lead to significant disruptions in the supply chain. According to a study by Ding et al. (2023), IoT-enabled supply chains have significant advantages in efficiency and cost reduction but face increased risks of cyber threats due to the higher connectivity and data flow between devices and systems. Ensuring robust cybersecurity measures is essential to protect the integrity and confidentiality of data. Implementing security protocols such as encryption, secure booting, and regular firmware updates can mitigate these risks. Additionally, adopting a comprehensive cybersecurity framework tailored for IoT can help organizations manage these threats more effectively. However, these measures often require substantial investment and expertise, which can be particularly challenging for SMEs with limited resources.

Data concerns

The sheer volume of data generated by IoT devices presents another significant challenge. Effective data management involves the collection, storage, analysis, and utilization of data to drive decision-making processes. However, many organizations struggle with the integration and interpretation of this data due to its complexity and the need for real-time processing. IoT devices generate continuous streams of data that must be processed and analysed promptly to be useful. This real-time data flow requires advanced data analytics tools and a robust IT infrastructure. According to Guan et al. (2021), the use of system dynamics (SD) models can help in managing these data flows and improving decision-making in supply chain operations. However, implementing such sophisticated data management systems can be daunting for small enterprises. Moreover, ensuring data accuracy and consistency across different IoT devices and platforms is crucial. Discrepancies in data can lead to flawed analyses and poor decision-making, ultimately affecting supply chain performance. Establishing standardized protocols for data management and employing advanced analytics can help address these issues, but these solutions again require significant investment and expertise.

Integration Complexities

Integrating IoT technologies into existing supply chain systems is another major challenge. Many supply chains consist of legacy systems that are not designed to handle the interconnected nature of IoT devices. The integration process can be complex, requiring significant modifications to existing infrastructure and processes.

IoT integration involves not only the physical installation of devices but also the integration of data systems and software platforms. This process can be disruptive and requires careful planning and execution. According to a review by Rajeev et al. (2017), the lack of standardization in IoT technologies and protocols exacerbates these integration challenges. Different IoT devices and platforms often use incompatible communication protocols, making seamless integration difficult. The financial aspect of IoT adoption is a significant barrier, especially for enterprises short on funds. While IoT technologies can lead to substantial long-term savings and efficiency gains, the initial investment required for IoT devices, infrastructure, and integration can be prohibitive. The cost of IoT implementation includes the purchase of devices, installation, maintenance, and ongoing management of the system. Additionally, there are costs associated with training employees to use and manage the new technologies. A study by Awan et al. (2022) highlights that the high adoption cost is a major deterrent for SMEs, despite the potential benefits of IoT-enabled supply chain management.

Project Concerns

Project planning and management is another area where IoT adoption poses challenges. Implementing IoT in supply chains requires careful project management to ensure that all aspects of the integration are considered and addressed. Effective project management for IoT implementations involves coordinating various stakeholders, managing timelines, and ensuring that all technical and operational requirements are met. The complexity of IoT projects can lead to scope creep, delays, and cost overruns if not managed properly. According to a systematic review by Whalen (2019), many IoT projects fail to meet their objectives due to poor project management practices and unrealistic expectations. To overcome these challenges, organizations need to adopt a structured project management approach, such as Agile or Lean methodologies, which can provide flexibility and adaptability throughout the implementation process. Additionally, involving all relevant stakeholders from the outset and maintaining clear communication channels can help mitigate risks and ensure successful project outcomes (Soonh, 2023).

4.1.3 Case Study 1 - A comprehensive survey on digital twin for future networks and emerging Internet of Things industry (*Hakiri et Al., 2024*)

This study provides a detailed analysis of how IoT can enhance operational efficiency within the supply chain through various examples and technological implementations. The integration of IoT in supply chains has shown significant improvements in real-time operations, predictive maintenance, and resource optimization. This critical analysis will focus on key findings from the study, emphasizing the application of IoT in improving operational efficiency in supply chains.

5GROWTH initiative

The 5GROWTH initiative, which focuses on leveraging 5G technology to enhance manufacturing processes, aims to optimize production lines by integrating IoT and digital twins, leading to improved service delivery and *Service Level Agreements* (SLA) in 5G virtualized edge networks. By offloading edge computation resources and supporting efficient data exchange between physical devices and their virtual counterparts, 5GROWTH has successfully reduced the costs of physical connected objects. This has improved real-time operations, enabling faster responses to environmental changes, critical for diverse applications such as visualization and remote control that require ultra-low latency and high reliability.

IoT-NGIN initiative

Another notable project, IoT-NGIN, has implemented Meta-Level Digital Twins to enhance efficiency and reduce traffic congestion in smart cities. This project employs a microservices-oriented architecture and a distributed ledger to ensure security and trust within the federated digital twin network. By mimicking the behaviour of connected *IoT devices*, IoT-NGIN facilitates interaction between physical and virtual twins, increasing service reliability and boosting the performance of data service provisioning. This has significant implications for supply chain management, particularly in improving the trackability and traceability of goods throughout the supply chain.

Bosch IoT-Suite

The Bosch IoT Suite is another significant example of how IoT can enhance supply chain efficiency. This advanced digital twin platform provides manufacturing companies with the tools and technologies needed to build and scale IoT solutions. By offering an open data model and unified device APIs, the Bosch IoT Suite facilitates the integration of IoT into supply chain operations. This integration allows for real-time monitoring and control, improving the overall efficiency and responsiveness of supply chain processes. The suite's ability to connect to various communication protocols further enhances its applicability across different sectors.

Industry-Specific Synergies

In agriculture, digital twins and IoT are employed to manage farm operations more effectively. By integrating remote sensing and control capabilities, IoT devices can monitor and manage farm activities, leading to precision farming practices. This results in optimized resource usage, better crop yields, and reduced environmental impact. The application of digital twins in smart farming demonstrates how IoT can transform traditional agricultural practices into highly efficient and sustainable operations.

The healthcare sector also benefits from IoT and digital twins, particularly in managing the healthcare supply chain. By monitoring health data and predicting medical resource allocation needs, IoT devices help ensure that medical supplies are available where and when they are needed. This capability is particularly important in managing responses to health crises, such as the COVID-19 pandemic, where timely and efficient distribution of medical supplies can save lives.

In transportation, digital twins enable better planning and monitoring of travel schedules and transportation networks. By integrating IoT devices with digital twin models, transportation systems can achieve higher levels of efficiency and reliability. This integration helps in managing traffic flows, reducing congestion, and improving the overall experience for commuters. Additionally, the ability to predict and manage transportation-related issues in real-time enhances the operational efficiency of logistics and supply chains dependent on transportation networks.

In the next pages there will be presented other two case studies: in the former is measured the tangible impact of IoT inside the Healthcare supply-chain and the latter about the improvement in last mile distribution of a Logistics Supply Chain.

4.1.4 Case Study 2 - The benefits of integrating AI, IoT, and Blockchain in healthcare supply chain management: A multidimensional analysis with case study (*Tagne et Al., 2024*)

The following Case Study investigates how the integration of advanced technologies can transform healthcare supply chain management (HCSM). The authors focus on the potential of Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain to overcome traditional supply chain challenges, enhancing visibility, efficiency, data-driven decision-making, security, and trust. Healthcare supply chains face several challenges, including a lack of transparency and visibility, fragmented systems, limited interoperability, inefficient inventory management, and inadequate data management. These issues can lead to delays, errors, and increased costs, ultimately impacting patient care. The study highlights the importance of innovative solutions to address these problems and improve overall supply chain performance.

IoT's Role in Enhancing Supply Chain Visibility

IoT plays a crucial role in improving visibility and transparency within the healthcare supply chain. IoT devices, such as sensors and RFID tags, enable real-time tracking of medical supplies, allowing stakeholders to monitor the condition and location of products throughout the supply chain. This real-time data collection is vital for maintaining the quality and integrity of medical products, especially those that are temperature sensitive. For instance, IoT sensors can track the ambient temperature during the transportation of pharmaceuticals, ensuring they are stored under appropriate conditions to prevent spoilage and maintain efficacy. One of the case studies presented in the paper focuses on the use of IoT in pharmaceutical distribution. IoT devices attached to drug shipments provide continuous monitoring, transmitting data about the location, temperature, and condition of the products to a central server. This real-time visibility allows pharmaceutical distributors to identify and address potential issues promptly, reducing the risk of product spoilage and ensuring timely deliveries. By leveraging IoT, distributors can optimize their operations, reduce waste, and improve overall supply chain efficiency, ultimately benefiting patients by ensuring the availability of high-quality medications.

Improving Inventory Management

IoT also enhances inventory management within healthcare facilities. Traditional inventory systems often struggle with accurate demand forecasting and stock management, leading to either overstocking or stockouts. IoT-enabled inventory systems can track stock levels in real-time and provide accurate data for better demand forecasting. For example, IoT sensors in hospital inventory systems can automatically alert staff when stock levels are low, triggering timely reorders and preventing stockouts. This real-time inventory management helps healthcare providers maintain optimal stock levels, reduce waste due to expired products, and ensure that necessary supplies are always available for patient care.

Another case study in the paper illustrates how IoT contributes to inventory optimization in hospitals. The study describes how IoT sensors can be attached to medical supplies, capturing real-time data on stock levels and transmitting this information to a centralized system. This integration allows hospital staff to monitor inventory in real-time, ensuring that supplies are reordered promptly and preventing stockouts. The IoT-enabled system also helps reduce waste by tracking expiration dates and ensuring that supplies are used before they expire. This approach not only improves inventory management but also reduces costs and enhances the overall efficiency of the supply chain.

Enhancing Data-Driven Decision Making

IoT devices generate vast amounts of real-time data, which can be analysed using AI algorithms to optimize supply chain operations. This data-driven approach enables healthcare organizations to make informed decisions about procurement, logistics, and distribution. For instance, AI can analyse data from IoT devices to predict demand patterns, enabling healthcare providers to adjust their inventory levels accordingly. This predictive capability ensures that the right products are available at the right time, enhancing the overall efficiency and responsiveness of the supply chain. The study includes a case on data-driven decision-making in healthcare networks. By leveraging data analytics tools and techniques, healthcare organizations can gain insights into their supply chain operations and make informed decisions. AI can analyse large amounts of data to identify patterns and trends, optimizing supply chain processes and predicting future demand. IoT devices provide real-time monitoring of inventory, enabling proactive measures to ensure the availability of necessary supplies. This integrated approach allows healthcare organizations to optimize their supply chain operations, reduce costs, and improve patient outcomes.

Ensuring Security and Trust

The integration of blockchain, IoT, and AI improves trust and security in the healthcare supply chain. By identifying irregularities and questionable activity, AI systems lower the possibility of fraud and theft. Real-time monitoring is made possible by IoT devices, which also guard against unwanted access to medical supplies. A trustworthy and impenetrable record of supply chain transactions is provided by blockchain's immutable ledger, which guarantees that data cannot be changed. Maintaining the integrity of the healthcare supply chain and guaranteeing patient safety depend heavily on this increased security and trust.

The use of blockchain technology in pharmaceutical distribution is the subject of one of the case studies in the publication. Blockchain ensures the validity and integrity of data along the supply chain by offering a transparent and safe ledger for tracking medicinal supplies.

Every product movement or transaction is documented on the blockchain, resulting in an enduring and authentic record. This openness is also helpful in the fight against fake medications, which is a major problem for the pharmaceutical sector. Blockchain technology enables stakeholders to track the provenance and path of every product, guaranteeing that patients receive only authentic and secure drugs.

Overall Impact of IoT Integration

There are several advantages of integrating IoT into healthcare supply chain management, such as higher security and trust, better visibility, increased efficiency, and data-driven decision-making. IoT devices ensure the integrity and quality of medical items by offering real-time tracking and monitoring. Blockchain provides a transparent and safe ledger that makes data sharing and traceability easier. AI uses blockchain and Internet of Things data to give advanced insights and streamline supply chain operations. When combined, these technologies produce a healthcare supply chain that is incredibly quick, secure, and efficient—improving patient outcomes while cutting costs.

4.1.5 Case Study 3 - Improving last mile distribution systems through the Internet of Things: A South African case (*Kafile and Mbhele, 2023*)

The following case study critically explores the integration of IoT technologies in last-mile logistics of South Africa. It has been decided to present the following case study due to the specificity of the economic tissue, which is mainly formed *by small-medium enterprises with limited capital.* There are over 2 million micro, small, and medium enterprises, representing more than 98% of formal businesses in the country (UNCTAD, 2024). Kafile and Mbhele's analysis addresses how IoT adoption can enhance cost efficiency and service quality in last-mile delivery, a crucial yet challenging phase of the supply chain, particularly heightened by the rapid growth of e-commerce and the pressures of the Covid-19 pandemic.

Enhanced Vehicle Tracking and Route Optimization

The study emphasizes that vehicle tracking is the most important use of IoT in last-mile logistics. 98.9% of the participants in the survey said that their companies track cars using IoT. Better route optimization is made possible by this real-time monitoring, which also shortens delivery times and uses less gasoline. These benefits directly improve service quality and cost effectiveness. For example, GPS technology, which is used by 97.2% of respondents, makes it easier to track precisely and plan routes effectively, which guarantees on-time delivery and increases customer satisfaction.

Expanded Delivery Routes

Expanded delivery routes were made possible by IoT adoption, according to about 89.4% of the participants. Through IoT route optimization, businesses can cover more ground without sacrificing productivity. In a country with as diverse as South Africa, this growth is essential for reaching geographically distant clients, cutting overall operating costs, and boosting delivery reliability.

Improved Order Fulfilment and Inventory Management

In 76.5% of the situations, the IoT was integrated with order fulfilment. Because they give real-time visibility into stock levels and movement, IoT technologies like RFID and sensors enhance inventory management. This increased visibility minimizes order processing errors, guarantees on-time delivery, and maximizes inventory turnover, resulting in substantial cost savings and better service quality.

Advanced Delivery Improvements

IoT's impact on delivery improvements was significant, with 70.4% of respondents acknowledging enhancements. These improvements include better coordination of delivery schedules, real-time tracking of parcels, and predictive analytics to foresee and mitigate potential delays. Such advancements not only reduce operational costs but also elevate the customer experience by providing more reliable and timely delivery services.

Adoption of IoT Technologies

The study reveals that IoT technologies like end-to-end tracking (99.4%) and GPS (97.2%) are most commonly used, reflecting their critical role in enhancing visibility and control over the logistics processes. Sensors and RFID also contribute, albeit to a lesser extent, by providing granular data on the condition and location of goods, further improving decision-making and operational efficiency.

Recommendations emerged

In order to attain cost-efficiency and service quality, logistics organizations had to give precedence to the incorporation of IoT technology into their operations. Purchasing sensors, RFID, GPS, and IoT-enabled cars can greatly increase output, effectiveness, and customer happiness. Strong cybersecurity defences are essential to preventing any threats to IoT systems and sensitive data. IoT application integrity may be preserved, and dangers can be reduced by putting encryption mechanisms into place and conducting frequent security audits.

Improving the capacities of data gathering and processing is essential for precise and timely analysis, which facilitates improved decision-making and resource efficiency. This enhancement will lower waste and raise efficiency in terms of cost and quality. Establishing thorough norms and standards for IoT implementation in logistics through collaboration with industry stakeholders and regulatory agencies will guarantee responsibility and compliance. This standardization will assist in resolving regulatory issues and creating an atmosphere that is favourable to the deployment of IoT. In order to provide effective data transfer and real-time operational control, connectivity concerns can be mitigated by implementing alternate connectivity solutions like edge computing and 5G networks. In Table 4 is resumed the main impact of IoT in different aspects of Last Mile Distribution.

Table 4 - Improvements and Outcomes

Aspect	Description
Efficiency in Fleet Management	IoT facilitates comprehensive fleet management, which was noted in 98.9% of the cases. Real-time tracking and monitoring of vehicles enable more efficient fleet utilization, reducing idle

	times and maintenance costs. This efficiency translates into lower operational costs and higher delivery reliability, crucial for maintaining competitiveness in the logistics sector.
Enhanced Reporting and Decision-Making	IoT's contribution to reporting and decision-making was highlighted by 99.4% of the respondents. The data collected through IoT devices provide valuable insights into operational performance, enabling managers to make informed decisions. This data-driven approach enhances strategic planning, resource allocation, and overall operational efficiency.
Cost and Quality Efficiency	It has found a strong correlation between IoT adoption and improvements in cost and quality efficiency. Accurate and timely data collection through IoT sensors equips businesses to optimize resource allocation, minimize waste, and enhance service quality. These improvements align with the goals of Logistics 4.0 initiatives, which aim to reduce logistical expenses, increase productivity, and improve customer satisfaction.
Challenges	Despite the benefits, challenges such as cybersecurity (97.8%), data collection and processing (94.4%), and connectivity issues (18.4%) were identified. Investments in robust cybersecurity measures, efficient data management infrastructure, and reliable connectivity solutions are essential to safeguard sensitive data, ensure real-time functionality, and maintain high-quality service delivery.

4.2 Artificial Intelligence (AI)

4.2.1 Definition of AI

Artificial Intelligence (AI) is a broad field of computer science focused on creating systems capable of performing tasks that typically require human intelligence. John McCarthy, one of the pioneers of AI, defined it as "the science and engineering of making intelligent machines, especially intelligent computer programs" (Cioffi et al., 2020). AI encompasses a range of computational techniques that enable machines to mimic cognitive functions such as learning, problem-solving, and pattern recognition. AI is not a single technology but an amalgamation of various subfields, including machine learning (ML), neural networks, natural language processing (NLP), robotics, and computer vision. Each of these subfields contributes to the overarching goal of creating systems that can adapt, learn from experience, and perform tasks autonomously.

Main components

Machine Learning (ML)

Machine learning, a subset of AI, focuses on developing algorithms that allow computers to learn from and make decisions based on data. ML algorithms build models from sample data, known as training data, to make predictions or decisions without being explicitly programmed to perform the task. This ability to learn and improve over time makes ML a powerful tool for handling complex tasks in dynamic environments (Cioffi et al., 2020).

ML techniques can be broadly categorized into supervised learning, unsupervised learning, and reinforcement learning. Supervised learning involves training a model on a labelled dataset, where the algorithm learns to map inputs to outputs based on examples. Unsupervised learning, on the other hand, deals with unlabelled data and aims to find hidden patterns or intrinsic structures within the data. Reinforcement learning involves training models to make sequences of decisions by rewarding them for desirable outcomes and penalizing them for undesirable ones (Hong & Xiao, 2024).

In the context of supply chains, ML has shown significant potential in enhancing *efficiency and resilience*. For instance, ML algorithms can predict demand patterns, optimize inventory levels, and improve logistics by analysing large volumes of data from various sources (Hong & Xiao, 2024). The ability to adapt to changing conditions and learn from new data makes ML an indispensable tool for modern supply chains.

Neural Networks

Neural networks, inspired by the human brain's structure, are a key component of AI, particularly in the realm of *deep learning*. These networks consist of interconnected nodes or neurons that process data in layers. The power of neural networks lies in their ability to learn complex patterns and representations from large datasets (Cioffi et al., 2020).

Deep learning, a subset of ML, uses neural networks with many layers (*hence "deep"*) to model intricate patterns in data. These deep neural networks have revolutionized fields such as image and speech recognition, natural language processing, and autonomous driving. By learning hierarchical representations of data, neural networks can achieve remarkable accuracy in tasks that were previously thought to be the domain of human intelligence (Hong & Xiao, 2024).

In supply chain management, neural networks can be used for predictive maintenance, quality control, and demand forecasting. For example, predictive maintenance models can analyse sensor data from machinery to predict failures before they occur, reducing downtime and maintenance costs (Hong & Xiao, 2024).

Natural Language Processing (NLP)

NLP is another critical area of AI, dealing with the interaction between computers and human languages. It involves the development of algorithms that enable computers to understand, interpret, and generate human language. NLP applications include language translation, sentiment analysis, and chatbots (Cioffi et al., 2020).

In supply chains, NLP can enhance communication and collaboration by enabling automated processing of documents, emails, and other text-based data. For instance, NLP algorithms can extract relevant information from invoices and contracts, reducing manual processing time and improving accuracy (Hong & Xiao, 2024).

Robotics

Robotics integrates AI to create machines that can perform tasks autonomously or with minimal human intervention. These tasks range from simple repetitive actions to complex operations in unpredictable environments. Robotics relies heavily on AI techniques for perception, decision-making, and control (Cioffi et al., 2020).

In supply chain operations, robots equipped with AI can automate warehouse operations, handle materials, and perform quality inspections. AI-powered robots enhance productivity and accuracy, reduce labour costs, and improve safety by taking over hazardous tasks (Hong & Xiao, 2024).

Computer Vision

Computer vision, a subfield of AI, enables machines to interpret and understand the visual world. By processing images and videos, computer vision algorithms can identify objects, track movements, and detect anomalies. This capability is crucial for applications such as automated inspection, surveillance, and autonomous vehicles (Cioffi et al., 2020).

In the supply chain sector, computer vision can be used for inventory management, where it helps in tracking stock levels and detecting damaged goods. Automated inspection systems use computer vision to ensure product quality by identifying defects on production lines (Hong & Xiao, 2024).

Food for thought

AI, with its diverse subfields including machine learning, neural networks, NLP, robotics, and computer vision, is transforming industries by enabling machines to perform tasks that require human-like intelligence. In the realm of supply chain management, these technologies enhance efficiency, resilience, and sustainability by automating processes, optimizing resource use, and providing deep insights from data. As AI continues to evolve, its integration into supply chains promises even greater advancements in operational efficiency and strategic decision-making. By harnessing the power of AI, industries can not only achieve operational excellence but also drive innovation and sustainability, ensuring their competitiveness in an increasingly digital and interconnected world (Hong & Xiao, 2024; Cioffi et al., 2020).

4.2.2 AI-Driven Supply Chain Optimization

Predictive Analytics

Predictive analytics, leveraging artificial intelligence (AI) and machine learning (ML), revolutionizes supply chain optimization by transforming data into actionable insights, enhancing efficiency, and bolstering resilience. This technology enables businesses to forecast future events, facilitating proactive decision-making to optimize supply chain operations.

There are different on-field applications of predictive analytics.

One significant application is in *demand forecasting*. By analysing historical sales data, market trends, and external factors, predictive models can accurately forecast future demand. This enables companies to adjust their production schedules and manage inventory levels effectively, reducing the risk of stockouts or overstocking (Cioffi et al., 2020). For example, AI-driven predictive analytics in the pharmaceutical supply chain has improved demand forecasting accuracy by incorporating time series data and pattern recognition algorithms (Camur et al., 2024). *Inventory management* also benefits significantly from predictive analytics. Traditional inventory systems often rely on static rules and historical data, leading to inefficiencies. AI-driven models continuously learn from new data, allowing for dynamic inventory adjustments. This real-time adaptability ensures optimized inventory levels, reducing holding costs (Hong & Xiao, 2024). Advanced models like Long Short-Term Memory (LSTM) networks and random forests have been used to predict inventory needs in multi-channel retail, showing superior performance compared to traditional methods (Punia et al., 2020). Predictive analytics plays a crucial role in *risk mitigation* by identifying potential supply chain disruptions. AI models analyse patterns and trends to detect early signs of supplier instability or geopolitical risks, enabling companies to develop contingency plans proactively (Hong & Xiao, 2024). This proactive approach was particularly beneficial during the COVID-19 pandemic, where predictive analytics helped companies manage supply and demand disruptions, ensuring continuity of operations (Naz et al., 2021).

The efficiency at operations level is further enhanced through *predictive maintenance*. AI analyses data from sensors embedded in machinery to predict failures before they occur, allowing for timely maintenance and reducing downtime (Cioffi et al., 2020). This approach not only ensures continuous production but also lowers maintenance costs and extends equipment lifespan (Xu et al., 2023). *Logistics and transportation optimization* are also key areas where predictive analytics excels. By analysing factors like traffic patterns, weather conditions, and fuel prices, AI models can suggest the most efficient routes and schedules. This reduces transit times, lowers fuel consumption, and minimizes the carbon footprint of logistics operations (Hong & Xiao, 2024). Blockchain technology further enhances this by providing secure and transparent data flows, enabling efficient freight management and predictive analytics for proactive decision-making (Liu et al., 2022).

Resilience is another critical application of predictive analytics. The integration of AI in supply chain management supports the identification of potential risks and enables swift responses. During the pandemic, companies leveraging predictive analytics were better equipped to handle disruptions, highlighting the importance of these technologies in maintaining operational continuity (Naz et al., 2021). Collaborative networks benefit significantly from predictive analytics by fostering better coordination among supply chain partners. Sharing predictive insights helps synchronize operations, improving the alignment of supply and demand across the supply chain. This not only enhances efficiency but also builds trust among partners, leading to more resilient supply networks (Hong & Xiao, 2024).

Sustainability is helped by predictive analytics. By having the right-amount at the right-time of inventory companies using predictive analytics lower their environmental impact. Efficient logistics and transportation planning reduce fuel consumption and emissions, contributing to greener supply chain operations (Ghahremani-Nahr et al., 2022).

The implementation of predictive analytics, however, is not without challenges. It requires significant investment in technology and skilled personnel. Ensuring data quality and security is paramount, as inaccurate, or compromised data can lead to erroneous predictions and decisions (Cioffi et al., 2020). Despite these challenges, the benefits of predictive analytics in supply chain management are undeniable. Advanced models, such as deep reinforcement learning and graph neural networks, continue to improve predictive capabilities and enhance supply chain visibility (Alves & Mateus, 2022).

Predictive analytics, driven by AI and ML, offers transformative potential for supply chain optimization. From demand forecasting and inventory management to risk mitigation and operational efficiency, predictive analytics enables companies to make data-driven decisions that enhance their competitiveness and resilience. By leveraging big data and pushing collaboration among supply chain partners, companies can build more robust and sustainable supply chains. As technology evolves, the adoption of predictive analytics will likely become even more integral to successful supply chain management strategies (Hong & Xiao, 2024; Cioffi et al., 2020).

The “Enormous” Big Data

Big data analytics (BDA) plays a pivotal role in supply chain planning by providing the vast amounts of information necessary for effective predictive models. By integrating data from various sources such as customer transactions, social media, and IoT devices, companies gain a comprehensive view of their supply chain operations, leading to enhanced decision-making capabilities. The use of BDA in supply chain management allows for the collection and analysis of large datasets, which are essential for identifying patterns and trends that traditional data processing methods might overlook (Xu et al., 2023). Some of this vast amount of data can come from platforms that seem far in the chain from the operations, but in a fully integrated system the insights are not anymore organized in a *waterfall process.* Platforms like social media data provides insights into consumer sentiment and emerging trends, which can significantly influence supply chain decisions. By monitoring social media platforms, companies can detect early signs of changing consumer preferences or potential disruptions. This real-time feedback enables businesses to respond quickly to market changes, enhancing their agility and responsiveness. For example, a sudden surge in social media mentions of a particular product can prompt a company to increase production or expedite shipping to capitalize on the increased demand (Hong & Xiao, 2024).

The holistic view provided by BDA enables more accurate predictions and better decision-making. Advanced analytics techniques, such as machine learning algorithms, can process and analyse vast datasets to identify patterns and correlations that human analysts might miss. These insights help companies optimize their supply chain processes, from procurement and production to distribution and logistics. For example, predictive analytics can identify the most efficient transportation routes, reducing fuel consumption and delivery times (Xu et al., 2023). BDA is a cornerstone of modern supply chain planning, offering a comprehensive and real-time view of operations. By integrating diverse data sources, companies can enhance their predictive capabilities, optimize decision-making, and improve overall supply chain efficiency. The ability to analyse large volumes of data from customer transactions, social media, and IoT devices provides a strategic advantage, enabling businesses to stay ahead of market trends and potential disruptions (Cioffi et al., 2020; Naz et al., 2021).

4.2.3 Case Study 1 - Enhancing Food Integrity through Artificial Intelligence and Machine Learning: A Comprehensive Review (*Gbashi & Njobeh ,2024*)

The impact of machine learning (ML) on enhancing transparency in the food supply chain is multifaceted and profound. It offers a range of capabilities that address critical issues like food fraud, safety, quality control, and overall supply chain integrity. This analysis critically examines these aspects, focusing on the efficacy and challenges of ML in ensuring a transparent and secure food supply chain.

The 2 T's: Traceability & Transparency

The potential of machine learning to improve traceability and transparency in the food supply chain is one of its most important contributions. The human record-keeping and inspection processes used in traditional food product tracking methods are very vulnerable to fraud and inaccuracies. On the other hand, massive volumes of data from different points in the supply chain, from production to retail, can be analysed by ML algorithms, guaranteeing that every stage is verified and recorded.

The AIoT (Agricultural Internet of Things) integration in China, specifically designed for the agricultural sector, employs a combination of IoT devices, ML algorithms, and blockchain technology to ensure that data collected at every stage of the supply chain is accurate and tamper-proof. Sensors deployed in farms, storage facilities, and transport vehicles collect data on temperature, humidity, and other environmental conditions that could affect food quality. This data is then analyzed in real-time using ML algorithms to detect any anomalies that could indicate potential issues such as spoilage, contamination, or unauthorized tampering. Finally, this system allows stakeholders to access real-time data about the condition and location of food products, significantly improving transparency and reducing the risk of fraud and contamination. This notable pilot project in China highlighted the system's efficacy. Researchers demonstrated the system's efficacy. AIoT ecosystem could trace food products from farms to consumers, providing detailed information on each product's journey. This transparency helps in building consumer trust, as they can verify the origin and quality of the food they purchase. Additionally, it enables swift action in case of a food safety incident, as authorities can quickly identify and isolate the source of contamination, preventing widespread outbreaks.

ML models are particularly effective in detecting and preventing food fraud, which includes the adulteration, mislabeling, and substitution of food products for economic gain. These models can scrutinize ingredient information, supply chain records, and consumer feedback to identify patterns and anomalies indicative of fraud. For example, Bayesian networks and deep neural networks have been employed to predict and classify food fraud incidents with high accuracy, allowing for proactive measures to prevent such activities. The implementation of these technologies not only helps in detecting fraud but also in identifying the vulnerable points in the supply chain where fraud is most likely to occur. This predictive capability enables companies and regulators to implement targeted interventions, thereby enhancing the overall integrity of the food supply chain.

Barriers and Strategies

Different challenges and limits of the technology will be explained. One of the primary issues is the quality and consistency of data. ML models require large amounts of high-quality data to function effectively, but in many parts of the food supply chain, data collection can be inconsistent or incomplete. This can lead to inaccuracies in the models' predictions and limit their effectiveness. Another challenge is the integration of ML technologies with existing systems and practices. Many food companies, especially small and medium-sized enterprises (SMEs), may lack the technical expertise or financial resources to implement advanced ML solutions. This creates a gap between large corporations that can afford these technologies and smaller players that cannot, potentially leading to disparities in food safety and quality standards across the industry. The use of ML in the food supply chain also raises ethical and regulatory considerations. Ensuring that these technologies are used responsibly and ethically is critical. This includes addressing concerns about data privacy, as the extensive use of sensors and data collection devices can lead to significant amounts of personal and proprietary information being collected. It is essential to implement robust data governance frameworks to protect this information and ensure compliance with relevant regulations. Furthermore, as ML technologies evolve, there will be a need for ongoing updates to regulatory frameworks to address new challenges and ensure that these technologies are used to enhance rather than undermine food safety and integrity. Collaborative efforts between food companies, governments, regulatory agencies, and other stakeholders will be crucial in achieving this goal.

The comprehensive adoption of ML technologies, coupled with strategic regulatory and ethical frameworks, will be pivotal in driving the food industry towards a future where transparency and integrity are the norms rather than the exceptions. The collaboration among various stakeholders and continuous innovation will be key to fully realizing the benefits of ML in the food supply chain.

5. Small Medium Enterprises

The adoption of Industry 4.0 technologies presents a multifaceted array of challenges and benefits for small and medium-sized enterprises (SMEs). Industry 4.0, characterized by the integration of cyber-physical systems, Internet of Things (IoT), and artificial intelligence, promises to revolutionize manufacturing and supply chain processes by enhancing efficiency, productivity, and innovation as we saw in the previous chapters. However, the implementation of these technologies is not without significant hurdles, particularly for SMEs which often lack the necessary resources and expertise to fully leverage these advancements. In the following chapter, it is presented the current state of art of SMEs regarding I4.0, presenting also an (exceptional) application in the field of production in the South of Italy.

5.1 Challenges

One of the primary challenges SMEs faces in adopting Industry 4.0 is the high initial investment required for technology and infrastructure upgrades. This financial burden is exacerbated by the ongoing costs associated with maintenance, training, and integration of new systems with existing operations. SMEs typically operate with limited budgets and financial constraints, making it difficult to allocate sufficient funds for such transformative projects. Additionally, the return on investment for Industry 4.0 technologies may not be immediately apparent, further deterring SMEs from making these substantial financial commitments. The complexity of Industry 4.0 technologies requires a significant upgrade in the technical skills and knowledge of the workforce. SMEs often struggle with a lack of in-house expertise in areas such as data analytics, cybersecurity, and advanced manufacturing techniques. This skills gap necessitates *actions* that are translated into significant investments in training and development programs to equip employees with the necessary competencies. However, SMEs frequently face challenges in providing such training due to limited resources and the need to balance day-to-day operational demands with strategic developmental initiatives.

The integration of Industry 4.0 technologies also presents significant operational challenges. SMEs must ensure seamless interoperability between new and existing systems, which often involves overcoming compatibility issues and managing data integration from disparate sources. This requires robust IT infrastructure and advanced software solutions, which may not be readily available to smaller enterprises. Additionally, the transition to more automated and digitized processes necessitates a comprehensive change management strategy to address potential resistance from employees and to ensure smooth adaptation to new workflows and processes.

5.2 Scaling-up with the benefits

Despite these challenges, the benefits of adopting Industry 4.0 for SMEs are substantial. Enhanced operational efficiency is one of the most significant advantages. Automation and real-time data analytics enable SMEs to optimize production processes, reduce waste, and improve overall productivity. For instance, predictive maintenance facilitated by IoT sensors can minimize downtime and extend the lifespan of equipment, leading to cost savings and improved operational reliability. Industry 4.0 also enables SMEs to develop new products and services that meet the evolving needs of the market. The ability to quickly adapt to changes in demand and customize products to individual specifications gives SMEs an important boost. For instance, an SME in the retail sector might use Big Data analytics to analyze customer purchase patterns and preferences. This analysis can reveal trends such as a growing demand for sustainable products or a preference for online shopping. Armed with this information, the SME can introduce new product lines or enhance its e-commerce platform to better serve its customers. The ability to quickly adapt to changing market conditions and customer preferences gives SMEs a competitive edge in a dynamic business environment (Chatterjee et al., 2022). Additionally, the integration of advanced manufacturing technologies can enhance product quality and consistency, further strengthening market positioning. Finally, the adoption of Industry 4.0 can improve supply chain visibility and collaboration (Chatterjee et al., 2022). For example, an SME in the manufacturing sector might use IoT sensors to monitor the health of its production line. Data from these sensors can indicate when a machine is likely to fail, allowing maintenance to be scheduled during planned downtime rather than causing an unexpected halt in production. This not only ensures continuous operations but also optimizes resource allocation, as maintenance activities can be better planned and executed (Chatterjee et al., 2022).

5.3 Reaching and exploiting competitivity

To successfully navigate the adoption of Industry 4.0, SMEs need to adopt a strategic approach. This involves conducting a thorough assessment of current capabilities and identifying specific areas where Industry 4.0 technologies can add the most value. Developing a clear roadmap for implementation, including timelines, budgets, and key performance indicators, is essential. Additionally, SMEs should seek to build partnerships with technology providers, industry associations, and academic institutions to access the necessary resources and expertise. Government support and incentives can also play a crucial role in facilitating the adoption of Industry 4.0 among SMEs. Policies that provide financial assistance, tax breaks, and grants can help alleviate the financial burden associated with technology investments. Moreover, initiatives that promote collaboration and knowledge sharing within industry clusters can enhance the overall readiness of SMEs to embrace digital transformation.

By strategically addressing the financial, technical, and operational barriers, and leveraging support from various stakeholders, SMEs can effectively navigate the transition to Industry 4.0 and secure a sustainable competitive advantage in the digital age.

5.4 Practical example 1 - Enabling Industry 4.0 Transformation in Calabria region: Framework, Machine Interconnection and ERP Synergy (*Borda et al., 2024*)

In the following pages an in-depth analysis is presented of the value creation of Industry 4.0 technologies in SMEs tissue of the Calabria region, in Italy.

The case studies of 10 Calabrian SMEs presented in the paper offer practical examples of how Industry 4.0 technologies have created value for these companies. The case studies cover a diverse range of manufacturing sectors, including rod and piston production, aluminum production for the building sector, metal carpentry, waste processing, mattress production, window frame production, consumer products processing, juice and citrus concentrate production, and automated teller machine (ATM) production. These case studies illustrate the tangible benefits that Industry 4.0 technologies have brought to these companies, including increased revenue, higher production value, and the activation of more research and development (R&D) projects.

5.4.1 Structured networks that create value.

The study emphasizes the adoption of the Industry 4.0 framework, machine interconnection, and Enterprise Resource Planning (ERP) systems, and how these elements have collectively enhanced manufacturing processes and economic development in the region. One of the central aspects discussed is the Industry 4.0 framework, which is designed to integrate various industrial components in a *structured manner*. This framework has been instrumental in optimizing production lines and supply chains for the SMEs in Calabria. By incorporating *intelligent networks* that facilitate real-time data analysis and autonomous decision-making, the framework has enabled these companies to streamline their operations and reduce inefficiencies. This optimization has directly translated into increased productivity and cost savings, thereby adding significant value to the companies' operations. The machine interconnection aspect of Industry 4.0, facilitated by the *integration of Internet of Things (IoT)* sensors and data analytics, has been a critical factor in creating value for the analyzed companies. The interconnection allows for continuous monitoring of machine performance, enabling predictive maintenance and reducing downtime. This real-time data collection and analysis have allowed companies to anticipate and address potential issues before they result in costly disruptions. For instance, it is highlighted how Calabrian industries have achieved enhanced productivity and operational efficiency by utilizing IoT sensors to monitor machinery and equipment, thereby ensuring optimal performance and reducing maintenance costs.

5.4.2 ERP scaled in the Industry 4.0 framework

Another significant technological advancement discussed in the paper is the integration of ERP systems within the Industry 4.0 framework. ERP systems have played a crucial role in the integration, optimization, and management of business processes for the SMEs in Calabria. These systems facilitate comprehensive data management and support better resource planning and coordination across different departments within a company. By providing end-to-end visibility and enabling better planning and informed decision-making, ERP systems have helped these companies achieve improved collaboration and operational efficiency.

Financial Benefits

The analysis of financial data from these companies shows significant growth in both revenue and production value since the implementation of Industry 4.0 technologies (Table 5). For example, the cumulative revenue of the analyzed companies increased from €65 million in 2017 to €145.4 million in 2022, with corresponding growth rates that highlight the substantial impact of these technologies on the companies' financial performance. Similarly, the cumulative production value rose from €67.9 million in 2017 to €154.2 million in 2022, indicating improved efficiency and output. The number of R&D projects also increased, reflecting the companies' enhanced capacity for innovation and development of new products and processes, overcoming one of the biggest hurdles of small realities, the resistance to change.

Table 5 - Aggregated data for I4.0 Investments (Borda et al., 2024)

Year	Cumulative I4.0 investments [€]	Impact on revenue [%]
2017	2,400,000.00	3,69
2018	8,300,000.00	10,13
2019	5,500,000.00	6,34
2020	1,800,000.00	1,83
2021	3,100,000.00	2,47
2022	7,000,000.00	4,81

5.4.3 SWOT Analysis

Through the case study a strategic assessment is made, focusing on internal and external factors influencing the success of Industry 4.0 adoption in Calabria.

Strengths identified include good regional positioning in ICT and university research, which provide a strong foundation for technological innovation. The presence of leading companies and qualified personnel in the region also contributes to the successful implementation of Industry 4.0 technologies. However, the analysis also highlights several weaknesses, such as difficulties in software integration and a weak supply chain approach, which can hinder the full realization of the benefits of Industry 4.0. Opportunities identified in the analysis include the potential for creating synergies with leading companies in the area, the availability of qualified graduates in mechanical and management engineering, and the demand for process and product innovations within the regional entrepreneurial system. These opportunities provide a favorable environment for the continued growth and development of Industry 4.0 technologies in Calabria. On the other hand, threats such as increased competition and complex bureaucratic processes pose challenges that need to be addressed to ensure the sustained success of Industry 4.0 initiatives.

5.4.4 Food for thought: the stakeholders' role: government and workforce

The Italian government's incentives for the modernization of industries and production processes, as well as specific tax credits for I4.0 investments, have played a crucial role in encouraging companies to adopt these technologies. The analysis shows that the facilitation measures have enabled significant growth even during the challenging period of the COVID-19 pandemic, highlighting the resilience and adaptability of companies that have embraced Industry 4.0. Technological innovation must be accompanied by organizational innovation, which requires a workforce capable of understanding and adapting to new technologies. The need for upskilling and reskilling the workforce is critical to ensure that employees can effectively operate and maintain advanced technological systems. Investing in human capital and fostering a culture of continuous learning and innovation are essential for maximizing the benefits of Industry 4.0.

6. Analysis

6.1 Introduction

As we presented in the Literature Review, Industry 4.0 has revolutionized the industrial landscape. The integration of Internet of Things, Artificial Intelligence, and Machine Learning has redefined the operational paradigms of supply chains, offering new paths for efficiency, transparency, and responsiveness. The scope of the research of this work is to *measure, understand and exploit* the impact of Industry 4.0 in small and medium-sized enterprises (SMEs), with a particular focus on the role of IoT and AI/ML technologies.

The Fourth Industrial Revolution represents a shift from traditional manufacturing and industrial practices to more connected and automated systems. This transformation facilitates real-time data collection, analysis, and decision-making. IoT, with its ability to link physical objects to the digital world, and AI/ML, which can process vast amounts of data to make predictions and optimize operations, are at the forefront of this shift. For SMEs, these technologies present both opportunities and challenges, as it was presented in the previous chapter. This paradigm offers the potential for enhanced productivity, cost savings, and improved customer satisfaction, but they also require significant investment, technical expertise, and a *willingness to embrace change*.

To better understand and exploit the critical relationship between SMEs and I4.0 paradigm, the analysis will focus on two parts, that will be explained in detail in the next chapter: examine the critical relationship between *knowledge formalization* (1) and the successful adoption of Industry 4.0 technologies (2) within small and medium enterprises in Italy.

6.1.1 Preface to Analysis

Knowledge Formalisation aims to gather insights about the *knowledge* management and formalisation (if any) of the Small-medium enterprises in *Italy*.

What does it mean *knowledge?*

With knowledge it is intended all the information and intangible assets that make a company unique in its culture and value proposition. Usually, in small-medium enterprises the knowledge is highly specific to the area of expertise of the company, and in most cases implicit: it derives from the founder/s purpose of the company.

Why *Italy*?

This work aims to understand and (if possible) give guidance to SMEs to reduce the competitive distance with big companies, and I decided to undertake this work in Italy for two reasons:

1. In Italy the average number of employees per company is 3.9 (Istat, 2023), meaning that 76.5% of workforce in Italy is occupied in a SME.
2. The territoriality of Italy is deeply diverse, different regionalities have their own sector of expertise (F&B, textile, heavy industry etc..). The interesting point is the high level of craftmanship maintained, giving a quite interesting statistical sample.

The latter part of the work is focused on IoT and AI/ML, aiming to provide a nuanced understanding of how these technologies can be leveraged to improve supply chain performance in SMEs. The questionnaire used was designed to assess the level of knowledge, adoption, and integration of Industry 4.0 technologies in these enterprises, as well as the perceived barriers and drivers of this adoption.

In conclusion, the scope of the analysis is to investigate how the formalization of knowledge within SMEs impacts the integration and effectiveness of Industry 4.0 technologies, particularly IoT (Internet of Things) and AI/ML (Artificial Intelligence/Machine Learning) predictive algorithms, and vice versa.

The questionnaire is designed to gather data from SMEs on various aspects, including their current practices in knowledge management (1), the level of digital transformation they have achieved, and the specific Industry 4.0 practices they have adopted or plan to adopt (2).

6.2 Scope of work

6.2.1 Introduction to the questionnaire

Survey on Knowledge Management Methods and the Integration of Industry 4.0 Principles, focusing on Data Collection Technologies (IoT and Big Data) and their Intelligent Use (Machine Learning) in Italian SMEs

The questionnaire is developed to explore the intersection of Knowledge Management Methods and Industry 4.0 principles, specifically within the context of Small and Medium Enterprises (SMEs) in Italy. The focus on these areas stems from the recognition that both knowledge management and the integration of Industry 4.0 technologies play a pivotal role in driving business performance, innovation, and competitiveness in today's dynamic market environment.

The questionnaire was carefully designed to address two key levels of inquiry. Firstly, it seeks to understand how knowledge—both tacit and explicit—is managed within SMEs, and how its effective management can impact business performance. Knowledge management is a fundamental component of organizational success, as it contributes to improved decision-making, enhanced productivity, and sustainable growth. Through the questions in this section, the aim is to gather insights into how Italian SMEs handle knowledge, what types of knowledge are most critical to their operations, and how knowledge management practices are implemented and perceived within their organizations.

Secondly, the questionnaire focuses on the current state of Industry 4.0 integration within SMEs. Industry 4.0, characterized using data-driven technologies such as the Internet of Things (IoT) and Machine Learning (ML), is essential for enhancing productivity and maintaining competitiveness. This section of the questionnaire aims to assess the level of awareness among SMEs regarding Industry 4.0 technologies, their willingness to embrace change, and the challenges they face in implementing these innovations. Understanding the barriers and opportunities for Industry 4.0 adoption will provide valuable insights into how SMEs can leverage these technologies to gain a competitive edge in an increasingly uncertain and competitive market.

The development of this questionnaire followed a structured approach, ensuring that the questions were aligned with the research goals of the thesis. It was created using digital tools such as Microsoft Forms, allowing for efficient data collection from respondents. This method was chosen to ensure a broad reach and to facilitate the participation of SMEs across various sectors and regions in Italy. The questions are a mix of open and closed formats, enabling both quantitative and qualitative data collection. Open-ended questions were included to capture detailed insights into the specific challenges and opportunities related to knowledge management and Industry 4.0 integration, while closed questions were designed to allow for easier data analysis and comparison across different organizations.

6.2.2 Questionnaire (translated in English)

The questionnaire is intended to support a Master's Thesis in Management Engineering at the Politecnico di Torino, in the field of Small and Medium Enterprises (SMEs), aimed at analysing the impact (if any) of Industry 4.0 in their processes.

The following analysis will propose a two-level approach:

1. *To determine the most important type of knowledge for a small and medium-sized enterprise, how it is managed, and what is the impact of Knowledge on business performance.*

2. *To determine the current state of Industry 4.0 integration within a small and medium enterprise. What is the level of awareness of an SME regarding the impact of this technology? How willing is it to embrace change to improve "as a whole"?*

From here, two sub-questions arise concerning the relationship between these two levels:

- How important is the formalization of knowledge?

- Is the exchange of knowledge between employees more important, or can digitisation (and the integration of Industry 4.0) improve the process of formalising knowledge, and the subsequent utilisation of insights derived from it?

Section 0 – General Questions

- **Sector**
- **Number of employees**
- **Turnover (range according to EU definition for SME division)**
- **Role of the respondent within the organization.**
- **(Optional) Number of production processes and type**

Section 1 – Knowledge Management

Every company develops different forms of knowledge, for example, related to its products, processes, customers, supply chain, etc..

Each of these forms is typically part of the experience of the workers involved (tacit knowledge), but it can also be shared and stored (explicit knowledge) in documents such as market reports, technical documentation, customer requirements documentation, quality reports/8D, lessons learned, best practices.

Whether tacit or explicit, its correct management contributes in improving the quality of business decisions, productivity, innovation rate, and efficiency. Furthermore, knowledge is one of the necessary elements for the sustainable growth of the organization, thanks to preservation, standardisation, transference and replication of acquired skills.

The purpose of the questions in this section is to better understand how Italian companies manage knowledge and how these practices influence their performance. The information collected will allow us to identify best practices and provide useful recommendations for improving knowledge management in Italian SMEs.

Open question:

1. What type of knowledge is most important for your company (product, process, customers, etc., tacit/explicit) and what are the main critical issues due to its management (e.g. written formalisation of knowledge, difficulties in retrieval and/or re-use)?

Closed questions:

2. Select the initiatives currently in use in your organisation related to knowledge management (several options can be selected)

   o Regular training and development programmes

   o Document best practices and lessons learnt (if yes, please specify if in electronic and/or paper format):

   o b.1) Electronically.

   o b.2) Paper format.

   o Use of Knowledge Management Systems.

   o Knowledge sharing sessions and meetings.

   o Mentorship and coaching programmes.

   o Use of collaborative tools (e.g. Slack, Microsoft Teams).

   o Rewards for employees who contribute and share knowledge

   o Creation of teams/appointment of knowledge managers.

   o Other (specify) __________

   o None.

3. What tools does your company use for knowledge management, storage and sharing? (several options can be selected)

   o Document management systems (SharePoint, Google Drive).

   o Corporate social network (Slack).

   o Specific knowledge management systems (Notion).

   o Product Lifecycle Management (PLM) systems.

   o Electronic spreadsheets.

   o Informal OOO messaging systems (Whatsapp).

   o Informal knowledge sharing (coffee breaks, business lunches).

4. To what extent do you agree with the following statement: ‘Our knowledge management practices have a positive impact on the performance of our company’.

   o Strongly agree.

   o Agree.

   o Neutral.

   o Disagree.

   o Strongly disagree.

5. Which performance measure is most impacted by your knowledge management practices?

   o Customer relations.

   o Innovation capacity/rate.

   o Product quality.

   o Competencies.

   o Productivity.

   o Efficiency.

   o Reaction time to problems.

   o Quality of decisions.

   o Staff satisfaction.

6. Have there been improvements in performance indicators following the implementation of your knowledge management practices?

   o Yes.

   o No.

Section 2 – Industry 4.0

The research emphasizes the importance of Industry 4.0 as a necessary mean to remain competitive in a market characterized by significant uncertainty and competition, where economic and environmental factors can challenge business success. After having identified the most used technologies in the Connected Industry Ecosystem—namely, the Internet of Things (IoT), Big Data, and the use of Artificial Intelligence—the following thesis aims to analyse the relationship between the connected Industry and Small and Medium Enterprises (SMEs), a predominant part of the Italian business landscape, to answer the question:

How crucial is the integration of Industry 4.0 principles within Italian SMEs? Can this technology enhance the competitiveness of SMEs in today's uncertain context? What are the barriers (technology, resistance to change, actual business benefits) to implementation?

The purpose of the questions in this section is to better understand the critical factors for integrating Industry 4.0, particularly its core technologies (IoT and machine learning), into Italian SMEs to gain a competitive advantage.

Evaluation Scale:

1. Strongly disagree
2. Somewhat disagree
3. Neutral
4. Somewhat agree
5. Strongly agree

Closed Questions:

1. Are there machines equipped with sensors for data collection and internet connectivity in your company's production department?

2. Does the current IT infrastructure in the company have sufficient specifications to configure machine learning models by analyzing the collected data?

3. Is there personnel in the company with tacit IT knowledge capable of developing IoT and machine learning solutions?

4. Are training and skills upgrading courses available to the staff with an Industry 4.0 perspective?

5. Is it currently necessary to rely on external consultants to integrate Industry 4.0 technologies within the company?

6. Are there ongoing or past collaborations with research institutes or universities to develop innovative solutions in IoT and machine learning?

7. Is the company's leadership supportive of integrating IoT and machine learning to enhance productivity?

8. Is the introduction of IoT and machine learning as integral parts of the production process perceived as a substitute for human operators in production control?

9. Are there actual economic benefits (e.g., increased volumes and/or quality, reduced management costs) from adopting IoT and machine learning solutions?

10. Among the applications of IoT and machine learning, is the implementation of predictive maintenance solutions planned in your company?
    - If yes, will this help reduce machine downtime and extend the useful life of our equipment, increasing productivity?

6.3 Descriptive Analysis of the cluster interviewed

To provide a descriptive explanation of the categories of companies interviewed, the analysis will start by clustering the companies. The key variables for clustering include:

1. Sector (Settore): the industry in which the company operates.
2. Number of Employees (Numero di impiegati): size of the company by workforce.
3. Revenue (Fatturato): financial performance indicator.
4. Role of Interviewee (Ruolo dell'intervistato): role of the person interviewed within the company.

6.3.1 Introduction

This section provides a detailed descriptive analysis of the companies surveyed in the study, categorized by their typology based on sector, size and revenue. The analysis draws on data collected from a diverse range of small and medium-sized enterprises (SMEs) operating in various industries, with a focus on the production department. By clustering these companies, insights will be gained into the different challenges and opportunities they face in the context of Industry 4.0 adoption, particularly in the implementation of the realm of technologies (IoT and Machine Learning) of the Connected Industry.

Clustering by industry sector

The surveyed companies represent a wide array of sectors, demonstrating the diverse application of Industry 4.0 technologies across different industries. The distribution of companies across sectors is as follows:

- Textile and Apparel (Tessile + tessuti tecnici): 3 companies
- Food and Beverage (Alimentare + Beverage + Alimentare – produzione di miele + Integratori alimentari): 5 companies
- Retail (Commercio al dettaglio): 1 company
- Agriculture (Agricultura): 1 company
- Hospitality: 1 company
- Design and Communication (Design e comunicazione): 1 company
- Consulting Services (Servizi di Consulenza): 1 company
- Craftsmanship (Artigianato): 1 company
- Building Materials Production (Produzione materiali da costruzione): 1 company

- Consumer Electronics (Elettronica di consumo): 1 company
- Pharmaceuticals (Farmaceutico): 1 company
- E-Mobility (Micromobilità elettrica): 1 company
- Medical Devices (Dispositivi medici): 1 company
- Board Games Production (Giochi da tavolo): 1 company
- Aerospace Components Manufacturing (Produzione componenti avionica): 1 company
- Metalworking (Metalmeccanico): 1 company
- Medical Technology (Medtech): 1 company
- IT Services (Servizi IT): 1 company
- Cosmetics (Cosmetico): 1 company
- Environmental Technology (Ecologia - produzione di tecnologie per il tracciamento dei rifiuti): 1 company
- Telecommunications (Telecomunicazioni): 1 company
- Manufacturing (Manifatturiero): 1 company
- Accounting and Financial Consulting (Servizi contabili e consulenza finanziaria): 1 company
- Education and Training (Educazione e formazione): 1 company

This diverse sector representation indicates that the integration of Industry 4.0 technologies is a concern across many industries, not limited to traditionally technology-driven sectors.

Clustering by company size

The companies surveyed also vary significantly in size, measured by the number of employees. The analysis reveals the following distribution:

Average Number of Employees: 33

Range: From 6 to 80 employees

25th Percentile: 16 employees

50th Percentile (Median): 33 employees

75th Percentile: 50 employees

This spread shows a typical SME structure where most companies are relatively small, with a median size of about 33 employees. The presence of companies with as few as 6 employees to those with up to 80 employees suggests that the findings of this study can be generalized to SMEs of varying sizes.

The histogram (Figure 2) shows the distribution of the number of employees across the

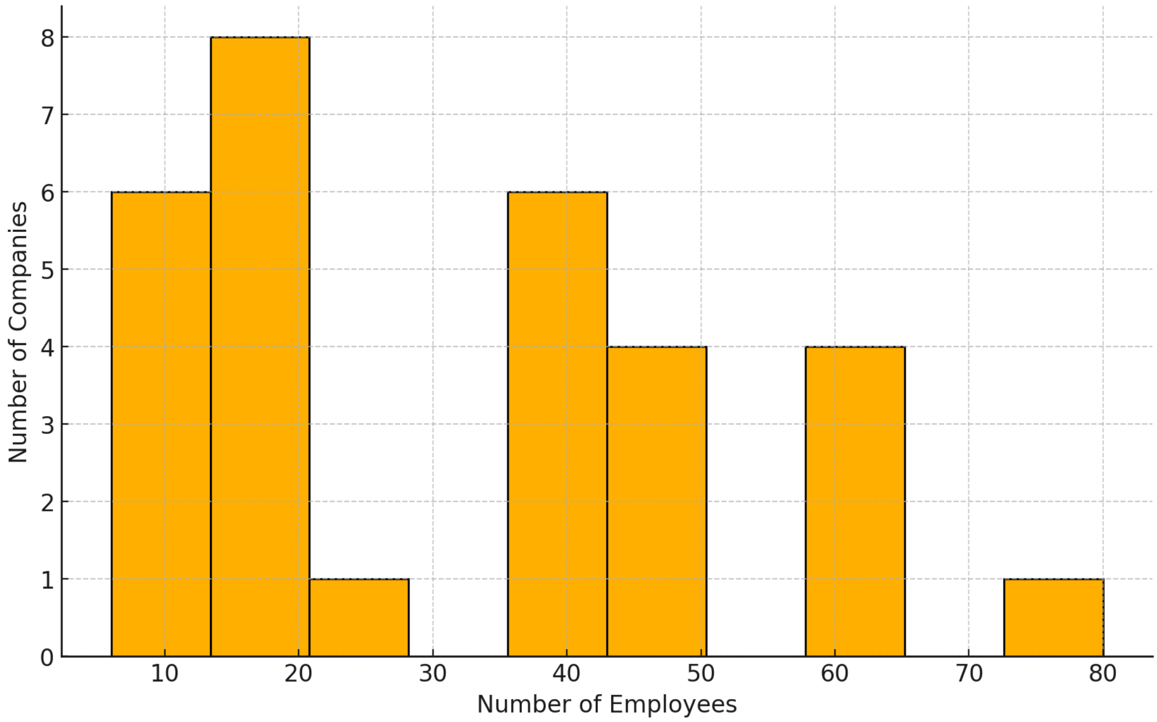

Figure 2 -Employee distribution of surveyed companies

surveyed companies. This distribution highlights the workforce size diversity within the SME sector, providing insight into their operational scale. Many of the companies have between 10 and 50 employees, which aligns with the typical size of small and medium-sized enterprises (SMEs).

Clustering by Revenue

Revenue is another critical dimension for clustering these companies, providing insight into their financial capability to invest in Industry 4.0 technologies. The descriptive statistics for revenue (Figure 3)are as follows:

Average Revenue: 25.9M€

Range: From 1 to 80M€

25th Percentile: 10M€

50th Percentile (Median): 21.5M€

75th Percentile: 39.5M€

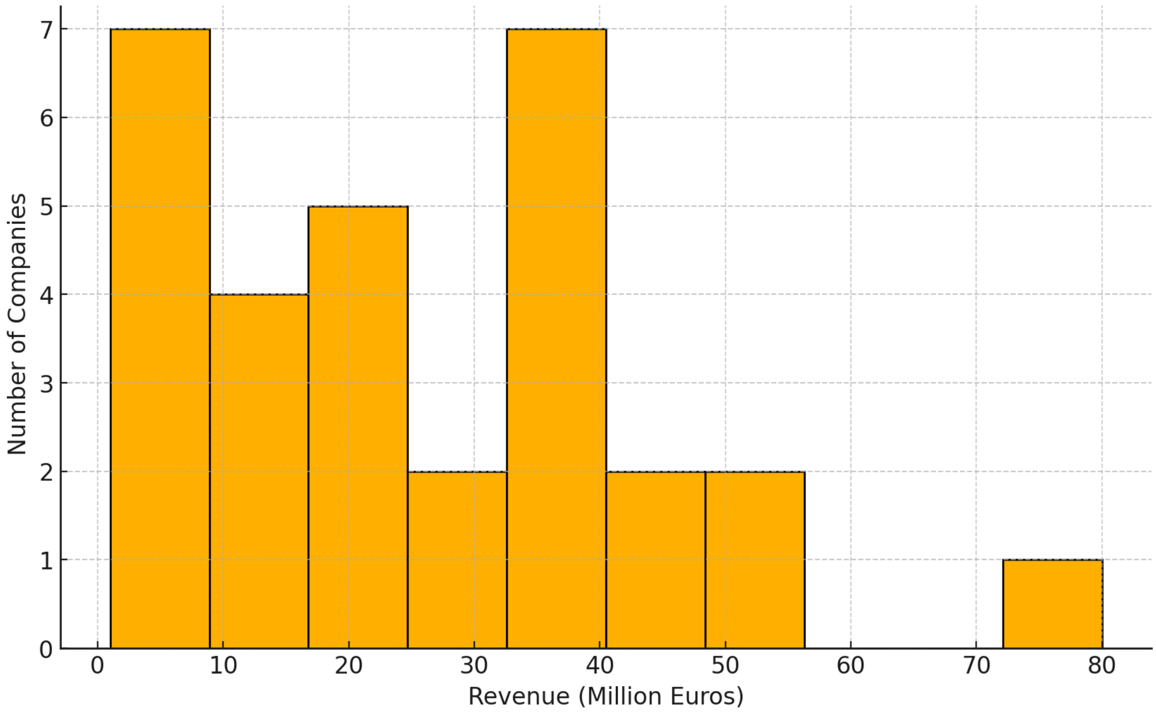

Figure 3 - Revenue distribution of surveyed companies

The revenue distribution mirrors the diversity seen in company size. While some SMEs operate with modest revenue streams, others manage substantial financial resources. This range likely influences their ability to adopt advanced technologies like IoT and Machine Learning. Most companies have a revenue of less than 40 million euros, with a noticeable concentration in the lower revenue ranges, indicating the typical financial profile of small and medium-sized enterprises (SMEs).

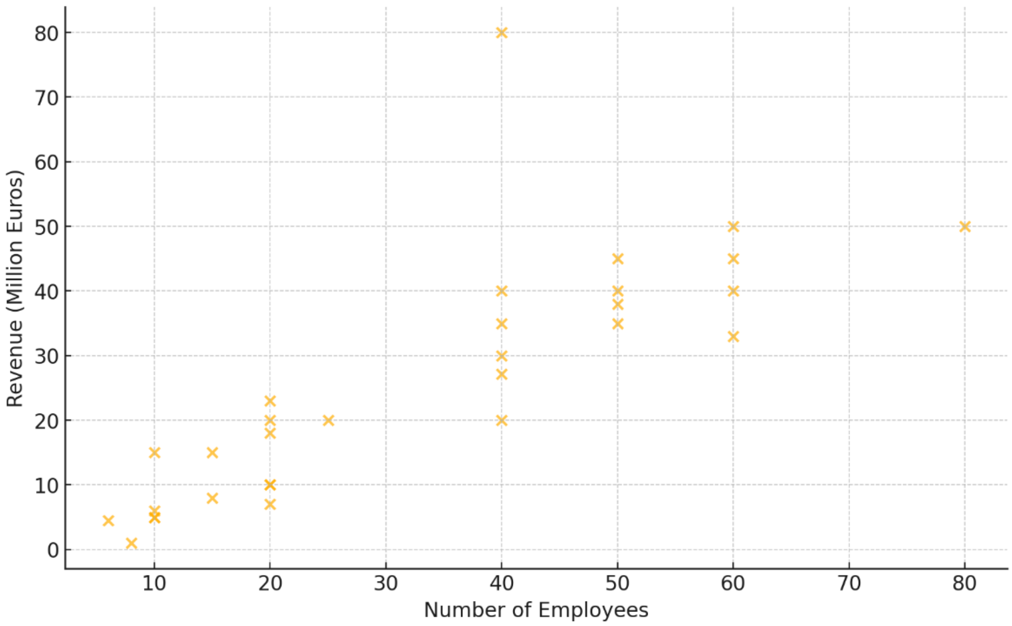

Figure 4 - Scatter plot of employees'number vs revenues

In Figure 4 is shown the two clusters of SMEs interviewed:

Cluster 1 tends to have a 1:1 relationship between employees and revenue generated (less than 20M€), while cluster 2 tends to be less sensitive in revenue generated according to number of employees (1:2 relationship).

Roles of interviewees

The roles of the interviewees in the surveyed companies reflect a wide range of responsibilities, indicating that the data was collected from individuals with varying degrees of influence and expertise within their organizations. The distribution of roles is as follows:

- Owner (Proprietario): 3 interviewees
- Production Manager (Responsabile di produzione): 1 interviewee
- Quality Director (Direttore qualità): 1 interviewee
- Operations Director (Direttore operativo): 1 interviewee
- Creative Director (Direttore creativo): 1 interviewee
- Partner: 1 interviewee
- Founder (Fondatore): 1 interviewee
- Technical Director (Direttore tecnico): 1 interviewee

- Innovation and Development Manager (Responsabile dell'Innovazione e sviluppo): 1 interviewee
- Plant Director (Direttore stabilimento): 1 interviewee
- Research and Development Manager (Responsabile ricerca e sviluppo): 1 interviewee
- CEO: 1 interviewee
- Yarn Production Control (Controllo produzione filato): 1 interviewee
- Production Director (Direttore di produzione): 1 interviewee
- Quality Control Officer (Addetto al controllo qualità): 1 interviewee
- IT Manager (Responsabile IT): 1 interviewee
- Sales Manager (responsabile vendite - sell side): 1 interviewee
- Yarn Production Manager (Responsabile produzione del filato): 1 interviewee
- Quality Control Manager (Responsabile controllo qualità): 1 interviewee
- Business Development: 1 interviewee
- Developer: 1 interviewee
- Production Manager (manager di produzione): 1 interviewee
- Internal R&D Consultant (Consulente interno di ricerca e sviluppo): 1 interviewee
- CIO: 1 interviewee
- Operations Manager (responsabile operativo): 1 interviewee
- General Manager (Direttore generale): 1 interviewee
- Director (Direttore): 1 interviewee

Analysis of Interviewee Positions

The variety of positions held by the interviewees reflects the organizational diversity within the surveyed SMEs. Many of the roles are managerial, indicating that the data collected is from individuals with significant decision-making power and insight into their company's strategic direction. This distribution of roles provides a balanced view across different levels of the organization.

Key Decision-Makers: The presence of CEOs, owners, general managers, and directors among the respondents suggests that the responses are representative of the top management's perspective on Industry 4.0 adoption.

Operational Leaders: Production managers, operations directors, and plant managers are key to understand the operational challenges and opportunities in adopting new technologies. Their input is vital for assessing the practical implications of integrating IoT and AI/ML solutions into existing workflows.

Technical and Innovation Experts: The roles of technical directors, R&D managers, and IT managers highlight the importance of technological and innovative perspectives in the discussion. These individuals are often at the forefront of evaluating and implementing new technologies, making their insights particularly valuable.

Quality Control and Production: The presence of quality control officers and production managers underscores the relevance of maintaining high standards and efficiency in the production process. These roles are critical when discussing the impact of predictive maintenance and other Industry 4.0 technologies on operational efficiency.

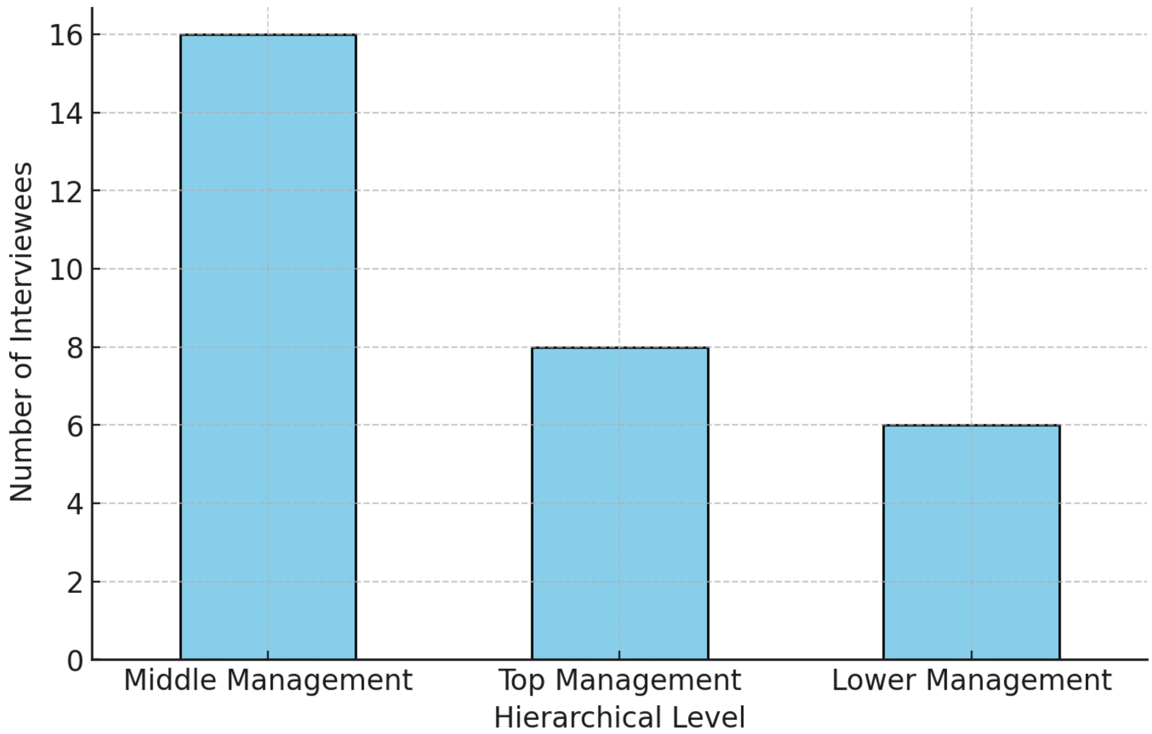

Figure 5 - Distribution of interviewees by hierarchical level

The bar chart in Figure 5 shows the distribution of interviewees categorized by their hierarchical level within the organizations:

Top Management: Includes roles like CEO, Proprietario (Owner), CIO, and General Director, representing the highest decision-making authority.

Middle Management: Comprises positions such as Technical Director, Operations Director, and IT Manager, indicating individuals who are responsible for managing specific departments or functions.

Lower Management: Consists of roles like Quality Control Officer, Sales Manager, and Developers, who are more involved in the execution and operational aspects.

This distribution highlights that a significant portion of the data was gathered from middle and top management.

6.4 Knowledge Management Analysis of Results

6.4.1 Introduction

The second part of the questionnaire focuses on the knowledge management practices, as explained before in the analysis.

Key questions addressed in the survey include:

1. The importance of different types of knowledge (product, process, customer etc..) for the company.
2. The current use of knowledge management initiatives.
3. The tools used for managing, storing, and sharing knowledge.
4. The impact of knowledge management practices on company performance.

6.4.2 Open question insights

The analysis of the types of knowledge considered most important by SMEs in the Italian market reveals a diverse range of knowledge domains and related challenges:

Product Knowledge: several companies emphasize the importance of understanding their products, including details about raw materials, production methods, and specific characteristics that differentiate their products in the market. This knowledge is often linked with ensuring high quality and innovation in products.

Process Knowledge: many firms highlight the significance of process-related knowledge, which involves understanding production processes, quality control, and operational efficiencies. The main challenge in this area is formalizing tacit knowledge and ensuring it is documented and accessible across the organization.

Customer Knowledge: understanding customer preferences, needs, and market trends is another critical area. This knowledge helps companies tailor their products and services to meet market demand. The primary difficulty lies in effectively managing and utilizing customer data and insights.

Regulatory and Compliance Knowledge: some responses point to the importance of knowledge related to compliance with industry regulations and standards. Managing this knowledge involves staying updated with constantly changing regulations and ensuring that all departments are aligned.

Tacit Knowledge: The transfer of tacit knowledge, which includes the skills and know-how accumulated by experienced employees, is also highlighted. The challenge here is how to capture and transfer this often-unwritten knowledge to new or less experienced staff members.

Technological Knowledge: a focus on technological knowledge, including data structures, algorithms, and software scalability, is critical for companies involved in digital and software-intensive industries. Ensuring this knowledge is scalable and reusable is a key concern.

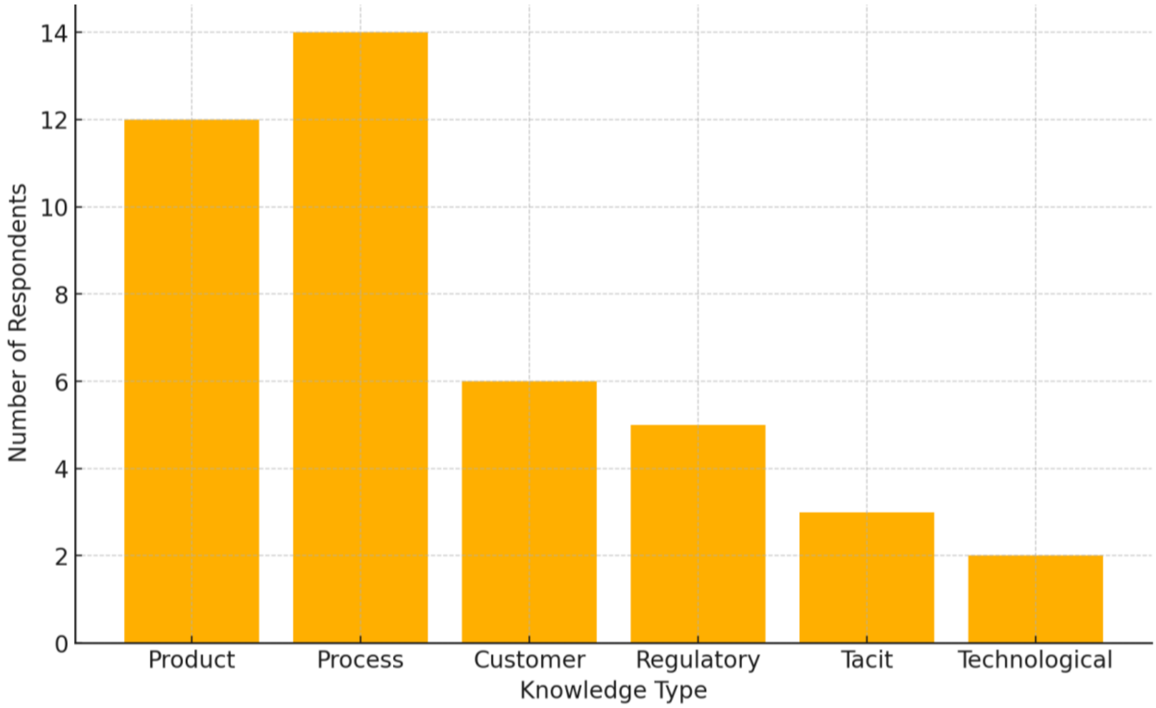

Figure 6 - Main knowledge types and frequency of respondents

The bar chart (Figure 6) illustrates the main knowledge types identified from the survey responses and their frequency among the respondents. It highlights the emphasis placed on different knowledge domains such as Product, Process, Customer, Regulatory, Tacit, and Technological knowledge.

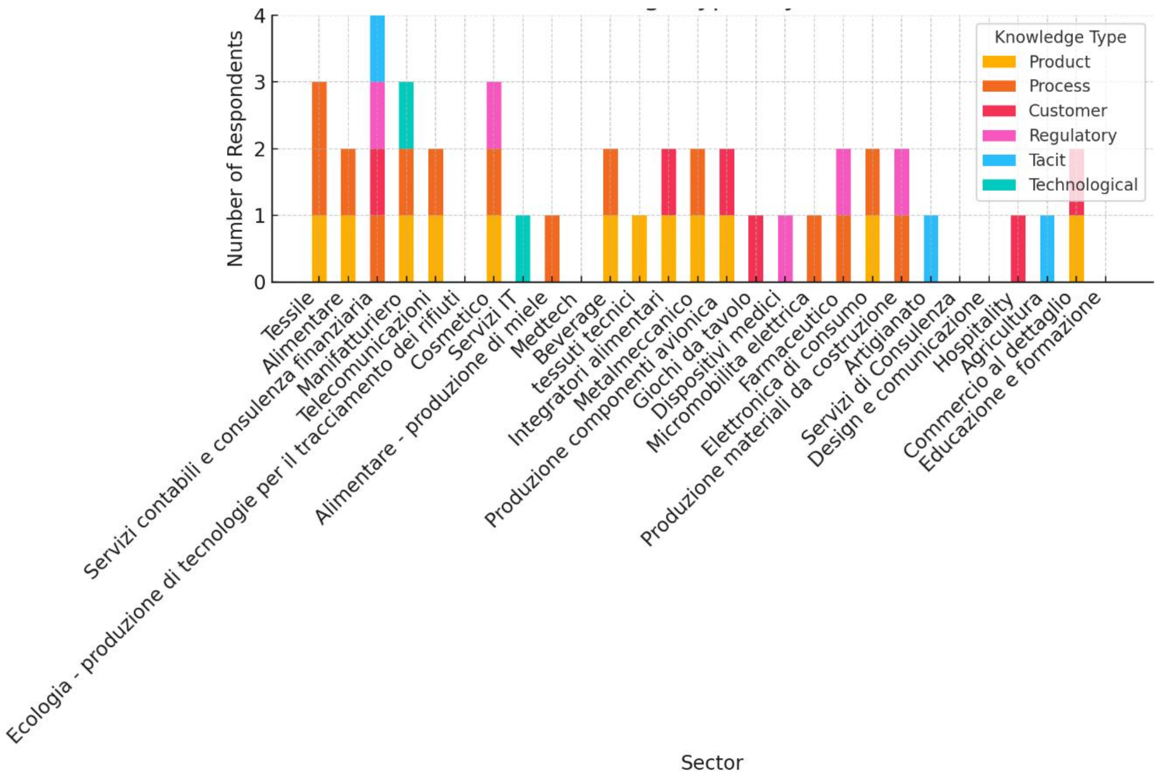

Figure 7 - Knowledge types by sector

The stacked bar chart (Figure 7) shows the distribution of different knowledge types across sectors. Each segment of the bar represents a different type of knowledge, providing a visual representation of how these knowledge types are emphasized in different sectors. Based on the analysis of the knowledge types across different sectors, several insights emerge that can be significant for understanding how SMEs prioritize and manage knowledge:

Textile Sector: The emphasis on both product and process knowledge suggests a focus on maintaining high-quality standards and optimizing production processes. This is critical in a sector where product quality (e.g., textiles and materials) is directly tied to market competitiveness.

Food and Beverage Sector (Alimentare): The importance of product and process knowledge is evident here as well. Ensuring product quality and safety, such as managing the cold chain, is essential to maintain nutritional and taste characteristics. This aligns with regulatory compliance and customer satisfaction.

Financial Services (Servizi contabili e consulenza finanziaria): The focus on customer and regulatory knowledge indicates a need to adhere strictly to regulations and understand client needs deeply. This sector also values tacit knowledge, possibly due to the importance of personalized services and maintaining client relationships.

Manufacturing Sector (Manifatturiero): A balance between product, process, and technological knowledge is observed. This reflects the sector's reliance on technological advancements for improving production efficiency and integrating new technologies like IoT and machine learning.

Telecommunications: A focus on product and process knowledge suggests that optimizing internal operations and ensuring high-quality service delivery are key priorities.

Across sectors, several common challenges in knowledge management were identified:

Formalization/Documentation: Many respondents mentioned difficulties in formalizing tacit knowledge, which includes skills and know-how that are not easily documented. This is a common challenge, especially in sectors where experience-based knowledge is crucial.

Knowledge Sharing: Ensuring that knowledge is accessible across different departments and teams is a significant challenge. Sectors like manufacturing and financial services mentioned the need for better knowledge-sharing mechanisms.

Regulatory Changes: In sectors with high regulatory oversight, such as financial services, keeping up with changes and ensuring compliance is a constant challenge. This requires continuous updating and dissemination of regulatory knowledge.

6.4.3 Analysis of respondents and emerging results on closed questions

To get into the core of the analysis, the following research project will highlight the following questions:

- Selezionare le iniziative attualmente in uso nella vostra organizzazione relative alla gestione della conoscenza; (*Select the initiatives currently in use in your organisation related to knowledge management*)

- Quali strumenti utilizza la vostra azienda per la gestione, l'archiviazione e la condivisione della conoscenza? (*Which tools does your company use for managing, storing, and sharing knowledge?*)

Select the initiatives currently in use in your organisation related to knowledge management

By analysing the respondents' answers on the following topic, the following insights can be derived (Figure 8).

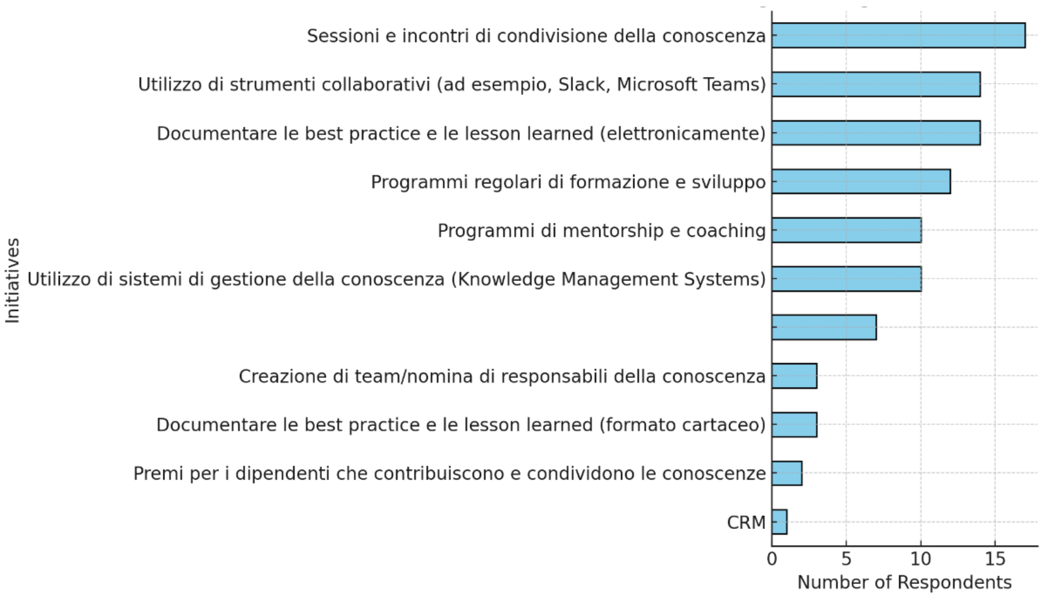

Figure 8 - Knowledge management initiatives in use

The most common initiative is holding knowledge sharing sessions and meetings, chosen by 17 respondents. This suggests that many organizations prioritize direct interaction and communication as a key method for knowledge transfer. Such sessions can help break down silos, encourage cross-departmental learning, and foster a culture of open communication. Tools like Slack, Microsoft Teams, and other collaborative platforms are used by 14 respondents, indicating their importance in facilitating real-time communication and collaboration. These tools support knowledge sharing across different locations and time zones, making them valuable in the increasingly digital and remote work environments. Documenting best practices and lessons learned electronically is equally popular (14 respondents), showing a shift towards digital knowledge repositories. This enables easy access, updates, and dissemination of information, ensuring that valuable knowledge is not lost and can be accessed as needed. Regular training and development programs are reported by 12 respondents. This emphasis on continuous learning highlights the importance placed on keeping employees up to date with new knowledge, skills, and technologies. It also helps organizations remain competitive and adaptable to changes. 10 respondents indicated the use of mentorship and coaching programs. These programs are crucial for transferring tacit knowledge, which might not be captured through documentation alone. They help develop employees' skills and ensure that valuable experience is passed down within the organization. Also selected by 10 respondents, the use of dedicated knowledge management systems indicates that a significant number of organizations are investing in specialized tools to store, manage, and retrieve knowledge efficiently. These systems can include databases, intranets, and other platforms designed to organize and distribute information.

Fewer respondents report using formal roles or teams dedicated to knowledge management (3 respondents) or providing rewards for knowledge sharing (2 respondents). This might suggest that while knowledge sharing is valued, formal structures and incentives are not yet widely adopted. Organizations might rely on informal methods or cultural practices to encourage knowledge sharing.

Food for thought

Data reveals that knowledge management is an important focus for these SMEs, with a strong emphasis on interactive and collaborative methods. While there is a significant use of digital tools and documentation, the relatively lower use of formal roles and incentives indicates an area for potential growth. Organizations might benefit from exploring more structured approaches and reward systems to further enhance their knowledge management practices.

These results suggest a strong focus on knowledge sharing through sessions and collaborative tools. There is less emphasis on formal rewards or the creation of specific knowledge management roles.

Which tools does your company use for managing, storing, and sharing knowledge?

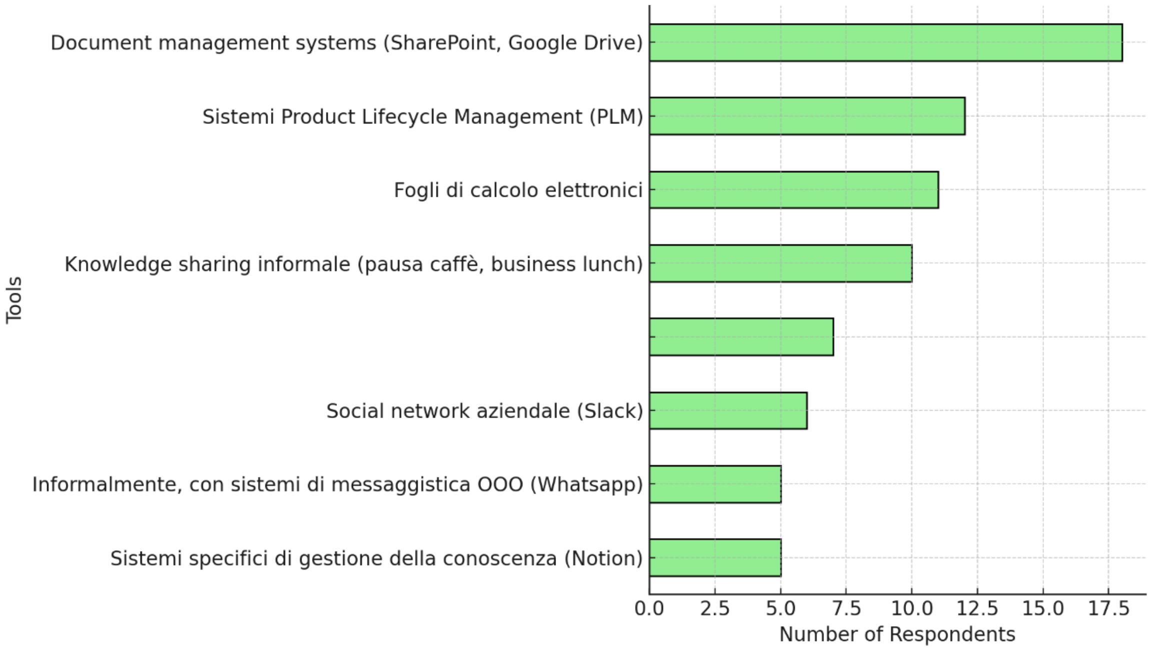

Figure 9 - Tools used for Knowledge Management

By analysing the respondents' answers on the following topic, the following insights can be derived (Figure 9). 18 respondents use document management systems like SharePoint or Google Drive. This indicates that most SMEs rely on centralized and structured platforms for managing documents. These tools are critical for organizing, storing, and retrieving information efficiently, suggesting a need for easy access to shared knowledge and documentation. 12 respondents use PLM systems, which shows a significant focus on managing product-related information throughout its lifecycle. PLM systems are valuable for companies that deal with complex products, enabling them to maintain consistency, compliance, and quality control. 11 respondents still use electronic spreadsheets for knowledge management. Despite the availability of more specialized tools, spreadsheets remain popular due to their flexibility, ease of use, and familiarity. This indicates that some companies prefer simple, versatile tools over more complex systems. 10 respondents engage in informal knowledge sharing methods, such as during coffee breaks or business lunches. This highlights the importance of casual, face-to-face interactions for sharing tacit knowledge and building relationships within the organization. 6 respondents use tools like Slack for internal social networking. This shows an adoption of modern, agile communication platforms that support collaboration and real-time interaction, which are particularly useful in a dynamic work environment. 5 respondents mention using messaging systems (e.g., WhatsApp) informally for knowledge sharing. This suggests a reliance on convenient, familiar communication methods that allow quick exchange of information, even if they are not designed for formal knowledge management. 5 respondents use specific knowledge management systems like Notion, indicating a growing trend towards using tools designed specifically for organizing and sharing knowledge. These systems often offer features tailored to knowledge management, such as tagging, search, and content linking. 7 instances were recorded with unspecified or blank entries, which could imply that not all companies have formalized their knowledge management practices or are unsure about the tools they use.

Food for thought

The insights indicate a mix of traditional and modern tools in use for knowledge management. While document management systems and PLM are widely adopted for their structured approach, informal methods and simple tools like spreadsheets are also popular. There is a clear trend towards using both formal systems (like PLM and knowledge management tools) and informal methods (like social networks and casual interactions) to facilitate knowledge sharing. This diversity in tool usage reflects different needs, preferences, and levels of digital maturity among the SMEs surveyed.

Correlations Analysis: how the answers to the two questions are correlated?

To explore the correlation between the initiatives in use and the tools for knowledge management it it will be analyzed how often certain tools are associated with specific initiatives (Figure 10).

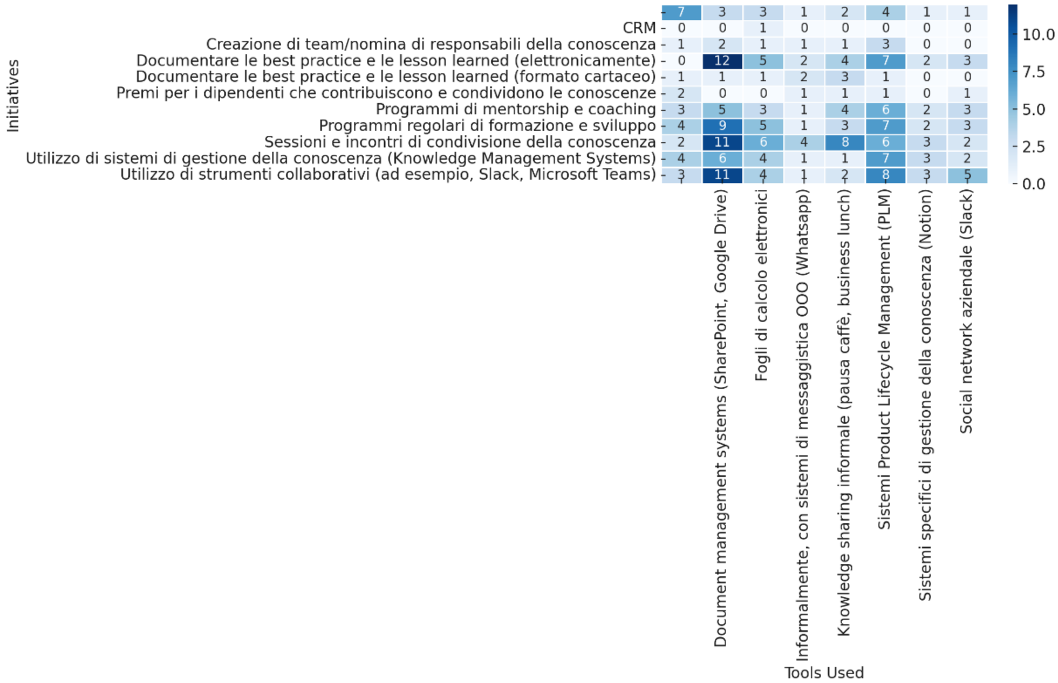

Figure 10 - Correlation between knowledge management initiatives and tools

The correlation table above highlights the relationships between different knowledge management initiatives and the tools used to support them. Here are some key insights:

Document Management Systems (SharePoint, Google Drive)

These systems are heavily used alongside initiatives such as:

- **Documenting best practices and lessons learned electronically** (12 associations).
- **Knowledge sharing sessions** (11 associations).
- **Regular training and development programs** (9 associations).

This suggests that companies that focus on documentation and structured knowledge sharing prefer using document management systems to store and manage their knowledge resources.

Product Lifecycle Management (PLM) Systems

PLM systems are closely linked with

- **Documenting best practices and lessons learned electronically** (7 associations).
- **Mentorship and coaching programs** (6 associations).
- **Knowledge sharing sessions** (6 associations).

PLM systems are used in environments where managing product-related information and ensuring that best practices are followed is critical, often in industries with complex product lifecycles.

Electronic Spreadsheets:

Frequently used with:

- **Knowledge sharing sessions** (6 associations).
- **Regular training and development programs** (5 associations).

This indicates a preference for using simple, flexible tools for organizing information and supporting training efforts.

Informal Knowledge Sharing:

Informal methods such as coffee breaks or business lunches are associated with:

- **Knowledge sharing sessions** (8 associations).
- **Mentorship and coaching programs** (4 associations).

This highlights the importance of casual interactions and informal settings in facilitating knowledge exchange and building a collaborative culture.

Collaborative Tools (e.g., Slack):

Most closely associated with:

- **Using collaborative tools** (11 associations).

This shows that companies valuing collaboration and real-time communication are more likely to use dedicated collaborative platforms to facilitate these interactions.

Specific Knowledge Management Systems (Notion):

Linked with initiatives such as:

- **Knowledge sharing sessions** (3 associations).
- **Using systems specifically for knowledge management** (3 associations).

This reflects a targeted approach where specialized systems are employed for structured knowledge management practices.

Food for thought

There is a clear relationship between the type of knowledge management initiative and the tools used. Companies favour structured, formal tools like document management systems for documentation-related initiatives, while informal methods and collaborative tools are preferred for initiatives focusing on real-time knowledge exchange and communication. Understanding these correlations can help organizations choose the right mix of tools and initiatives to enhance their knowledge management practices effectively.

Correlations Analysis: adding the impact on performance dimensions

To go further in finding patterns, it will be explored a secondary level of correlation: the knowledge management initiatives with the performance impact measures (Figure 11).

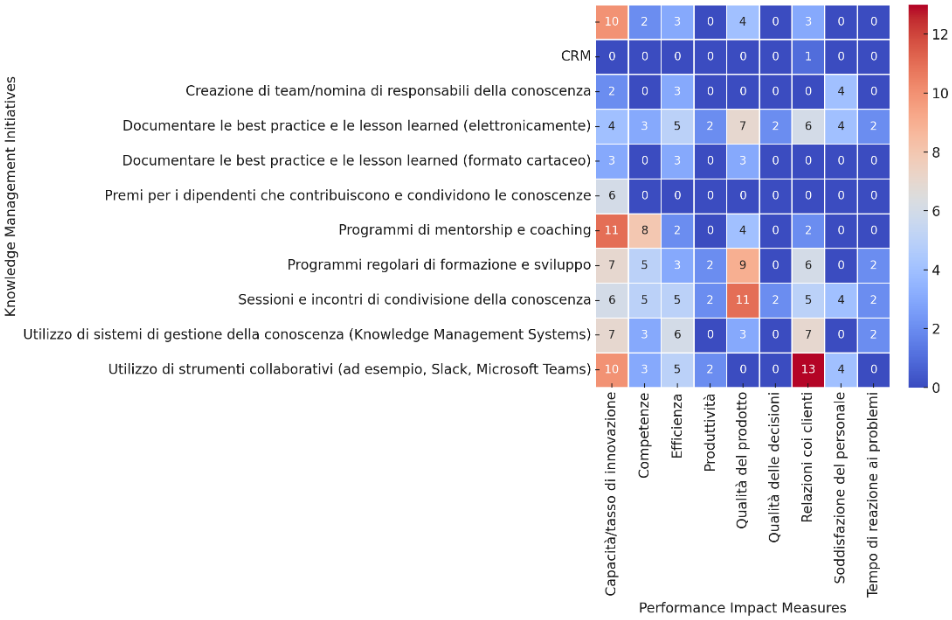

Figure 11 - Correlation between knowledge management initiatives and performance impact measures

Here there are the key insights.

Innovation Capacity (Capacità/tasso di innovazione)

- Initiatives like **mentorship and coaching programs** (11 associations) and **collaborative tools** (10 associations) have a strong correlation with enhancing innovation. This suggests that fostering open communication and mentoring is critical for driving innovation in SMEs.

Competency Development (Competenze)

- **Mentorship and coaching** (8 associations) and **knowledge sharing sessions** (5 associations) are linked to improving competencies. These initiatives help transfer skills and knowledge, enhancing the overall capability of the workforce.

Efficiency (Efficienza)

- **Knowledge management systems** (6 associations) and **documenting best practices electronically** (5 associations) correlate with efficiency improvements. Structured knowledge management practices help streamline processes and reduce inefficiencies.

Product Quality (Qualità del prodotto)

- **Knowledge sharing sessions** (11 associations) and **documenting best practices electronically** (7 associations) are strongly associated with improved product quality. Sharing best practices ensures consistent quality standards across production.

Customer Relations (Relazioni coi clienti)

- **Collaborative tools** (13 associations) and **document management systems** (6 associations) are linked with better customer relations. These tools likely help in maintaining clear communication and providing quick responses to customer needs.

Employee Satisfaction (Soddisfazione del personale)

- **Creating teams or appointing knowledge managers** (4 associations) and **knowledge sharing sessions** (4 associations) are associated with higher employee satisfaction. Involvement in knowledge management activities can lead to more engagement and job satisfaction.

Problem Response Time (Tempo di reazione ai problemi)

- **Documenting best practices** and **using knowledge management systems** (2 associations each) help reduce response time to problems. Having documented procedures and readily available information helps in quickly addressing issues as they arise.

Respondents’ feelings on implementation of knowledge management practices

The analysis of the two questions reveals the following combinations of responses:

1. **Strongly agree ("Fortemente d'accordo") + Yes ("Sì") & Agree ("D'accordo") + Yes ("Sì")**: 15 respondents & 13 respondents, **total 28**
    - These respondents strongly agree that their knowledge management practices have a positive impact on company performance and have also observed tangible improvements in performance indicators. This group reflects organizations where KM is not only perceived as beneficial but also results in measurable outcomes.
2. **Neutral ("Neutro") + No ("No")**: 2 respondents
    - These respondents are neutral regarding the impact of KM on performance and report no improvements in performance indicators. This combination suggests a disconnect between KM initiatives and performance outcomes in their organizations, indicating that either the KM practices are not well-implemented or not aligned with business goals.

Analysis of Outliers

The analysis shows that the same two respondents who answered "Neutral" about the impact of knowledge management practices on performance also answered "No" to the question regarding observed improvements in performance indicators following the implementation of these practices.

Respondent Profiles:

Respondent 1 - Settore: Artigianato (Crafts)

- Number of Employees: 6
- Revenue: 4.5 million
- Role: Founder
- Important Knowledge Type: Tacit knowledge related to artisanal techniques.
- Knowledge Management Initiatives: Mentorship and coaching programs; knowledge sharing sessions.
- Tools Used: Electronic spreadsheets; informal knowledge sharing (e.g., during breaks).

Respondent 2 - Settore: Agricultura (Agriculture)

- Number of Employees: 20
- Revenue: 10 million
- Role: Proprietor

- Important Knowledge Type: Tacit knowledge related to agricultural practices.
- Knowledge Management Initiatives: Knowledge sharing sessions.
- Tools Used: Electronic spreadsheets; informal knowledge sharing.

Food for Thought

Both respondents rely primarily on basic tools (spreadsheets) and informal methods for knowledge management. This limited use of advanced or formal knowledge management systems could lead to underutilization of available knowledge, thus not realizing potential performance improvements. Moreover, both businesses emphasize tacit knowledge, which is inherently difficult to capture and manage effectively. Without proper systems to formalize and share this knowledge, it's challenging to translate it into tangible performance improvements.

Finally, neutral and/or negative responses regarding KM's impact and performance improvements highlight common challenges faced by SMEs in traditional industries like crafts and agriculture. These businesses often rely on tacit knowledge and informal KM practices, which, when combined with inadequate IT infrastructure and limited use of advanced technologies, hinder their ability to fully realize the benefits of KM. To address these challenges, SMEs in such sectors may need to invest in more formalized KM systems, improve their technological capabilities, and align KM initiatives with measurable performance outcomes.

6.5 Industry 4.0 Analysis of results

6.5.1 Introduction

This work is based on the answers of the statistical sample related to the *10 questions about Industry 4.0* (the eleventh was excluded due to low rate of answers) that are aimed to answer the thesis' research question. Based on the variables proposed in this questionnaire,

- technology_availability: Availability of Industry 4.0 technologies
- IT_readiness: IT infrastructure readiness
- personnel_readiness: Readiness of personnel for Industry 4.0
- training_availability: Availability of training related to Industry 4.0
- need_of_ext_consultant: Need for external consultants
- partnering_with_institutions: Collaboration with institution
- change_management_readiness: Readiness for managing changes
- technology_perception_as_human_substitute: Perception of technology as replacing human roles
- economical_advantages: Perception of economic advantages of Industry 4.0
- predictive_manufacturing_availability: Availability of predictive manufacturing technology

the objective of the second part of analysis is to determine the current state of Industry 4.0 integration within a small and medium enterprise, by finding the main underlying variables that determine the *readiness* of SMEs regarding the impact of this technology and the willingness to embrace change. The software used to develop the following analysis is SPSS Statistics. SPSS Statistics is a statistical software suite developed by IBM for data management, advanced analytics, multivariate analysis and business intelligence.

6.5.2 Descriptive statistics of the variables selected

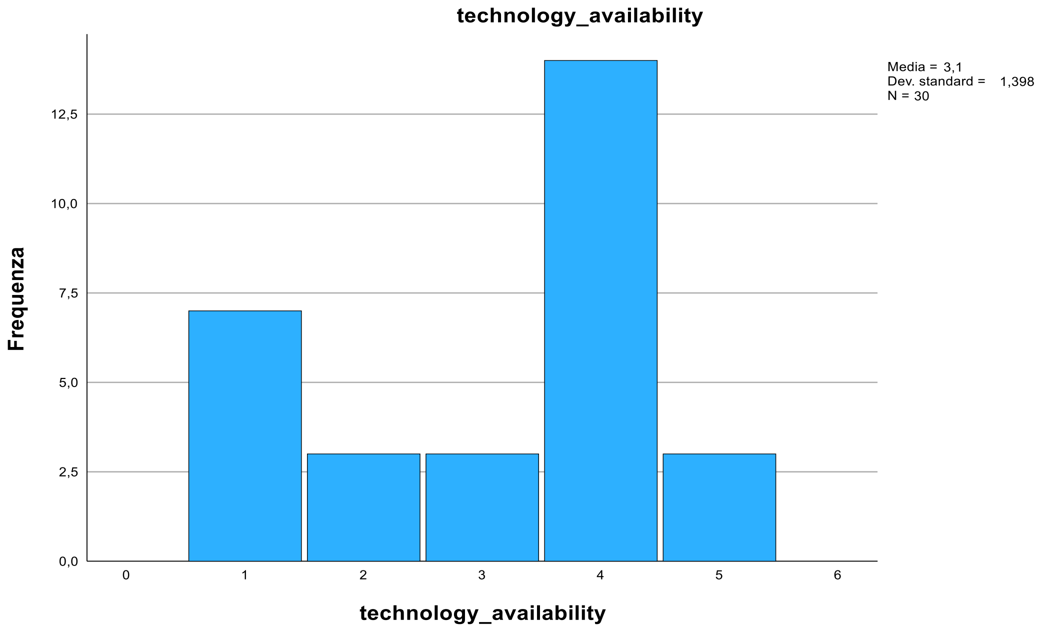

Figure 12 - Technology availability

Figure 12 shows the distribution of technology availability in SMEs, with a mean score of 3.1 and a standard deviation of 1.398. Most companies rank their technology availability at 4, indicating moderate technology access overall. The bar chart highlights that a significant portion of respondents, around 7, have rated their technology availability at 1, indicating low access to technology in these SMEs. This suggests that a notable number of companies face considerable limitations in their technological infrastructure.

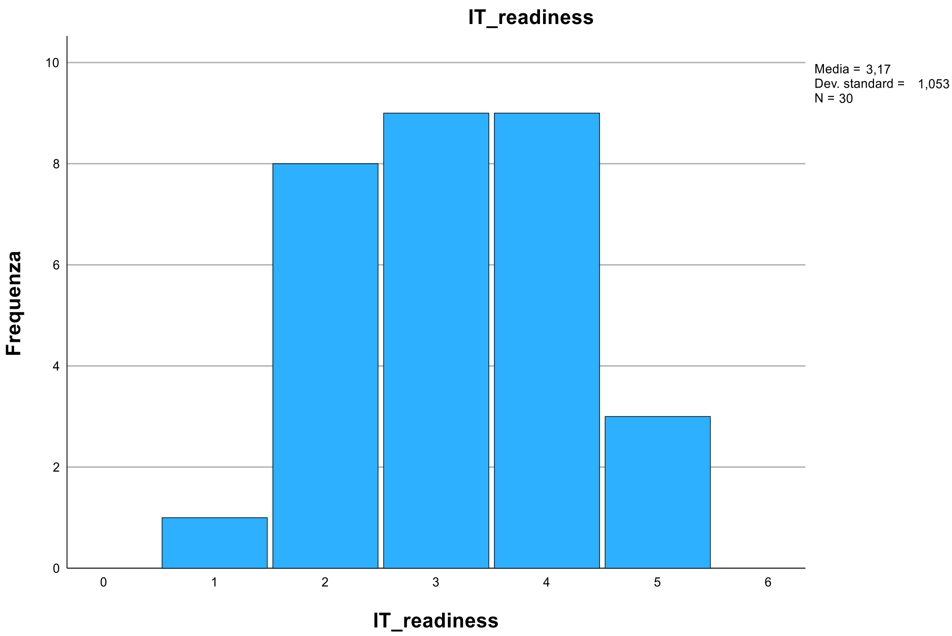

Figure 13 - IT readiness

Figure 13 displays the distribution of IT readiness, with a mean of 3.17 and a standard deviation of 1.053. Most companies rate their IT readiness between 3 and 4, indicating moderate readiness. Notably, few companies rate their IT readiness at 1, suggesting only minimal IT infrastructure in some cases.

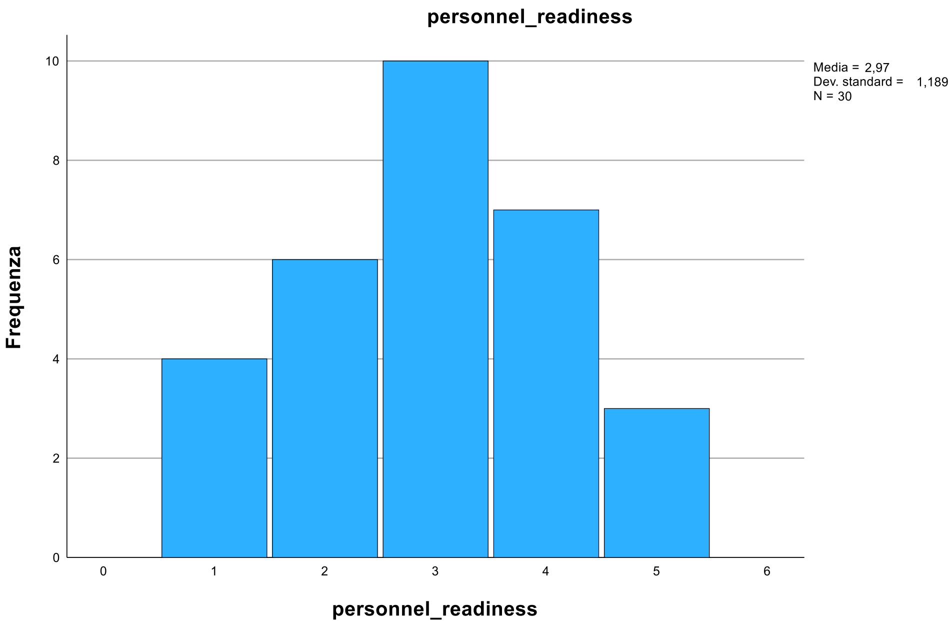

Figure 14 - Personnel readiness

Figure 14 illustrates the distribution of personnel readiness, with a mean of 2.97 and a standard deviation of 1.189. Many companies rate their personnel readiness at 3, suggesting moderate preparedness. A smaller portion rates their personnel readiness at 1, indicating limited readiness within some organizations.

Figure 15 - Training availability

Figure 15 shows the distribution of training availability, with a mean of 2.87 and a standard deviation of 1.106. Most companies rate their training availability at 4, indicating moderate to high access to training opportunities. However, some organizations rate it at 1, showing limited training access.

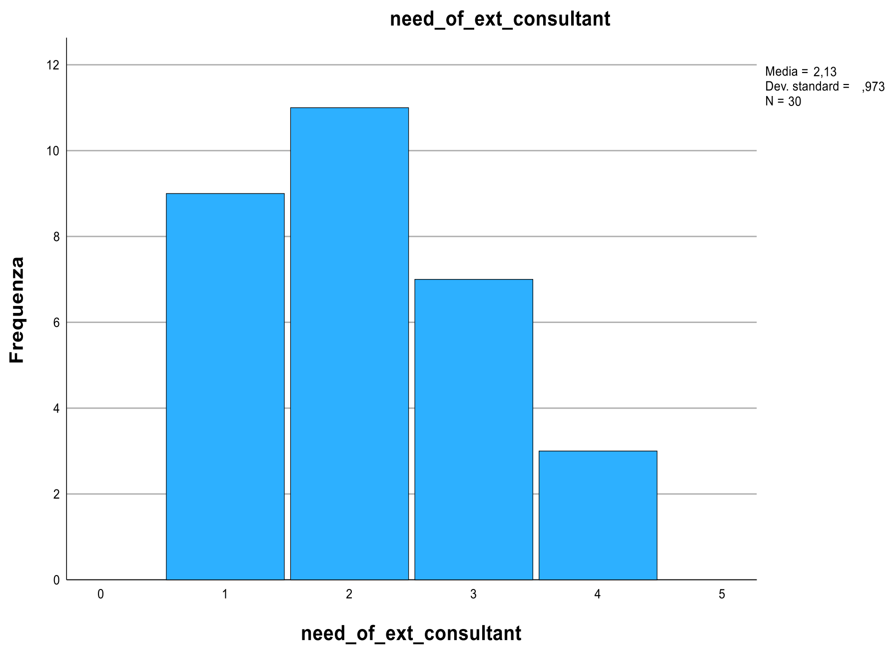

Figure 16 - Need of external consultant

Figure 16 shows the distribution of the need for external consultants, with a mean score of 2.13 and a standard deviation of 0.973. Most companies rate their need for external consultants between 1 and 2, indicating a low to moderate reliance on external expertise.

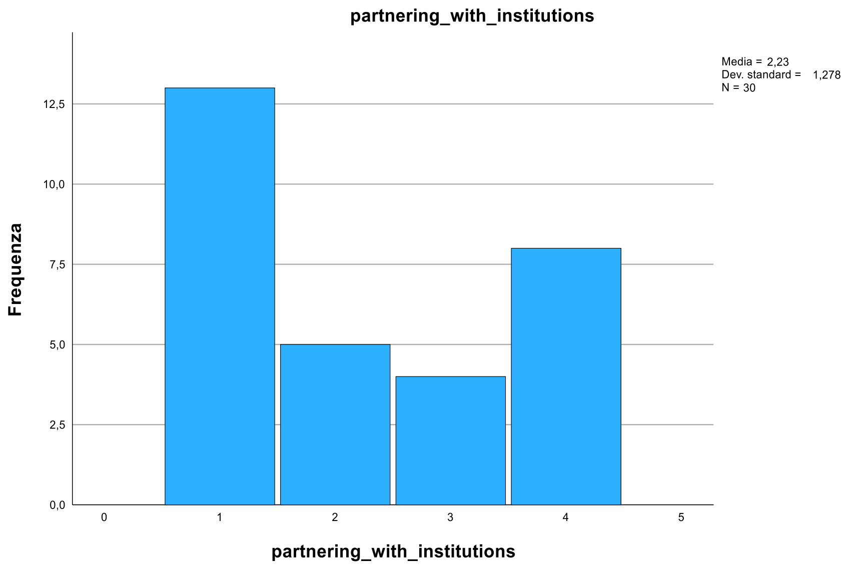

Figure 17 - Partnering with institutions

Figure 17 illustrates the distribution of partnering with institutions, with a mean of 2.23 and a standard deviation of 1.278. Most respondents rate their partnership level at 1, indicating limited collaboration with institutions, while a smaller group reports a higher collaboration level at 4.

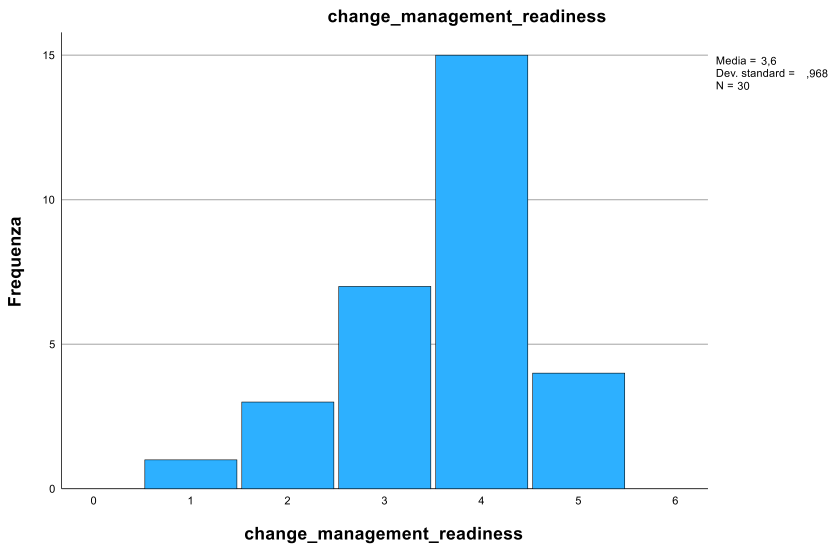

Figure 18 - Change management readiness

Figure 18 displays the distribution of change management readiness, with a mean of 3.6 and a standard deviation of 0.968. Many respondents rate their readiness at 4, indicating a generally high preparedness for managing change. Fewer companies rate their readiness below 3, suggesting overall confidence in handling change initiatives.

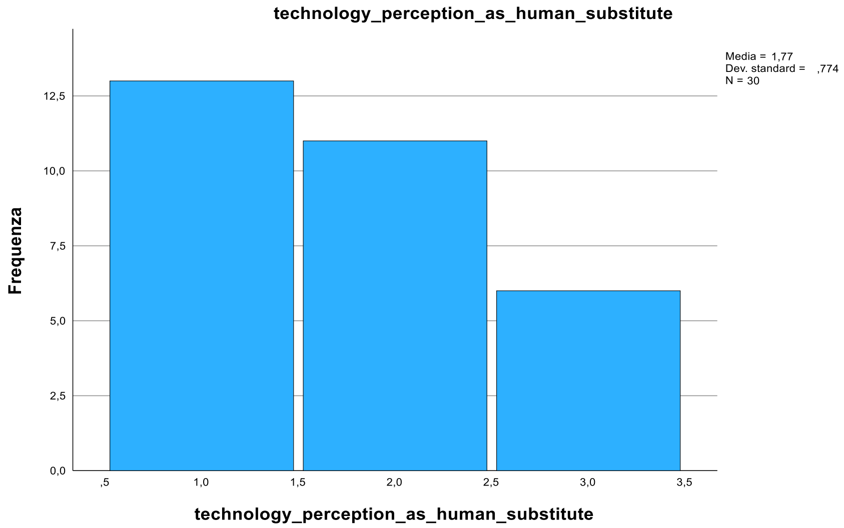

Figure 19 - Technology perception as human substitute

Figure 19 illustrates the perception of technology as a substitute for human labour, with a mean of 1.77 and a standard deviation of 0.774. Most respondents score between 1 and 2, indicating a moderate perception of technology as replacing human roles.

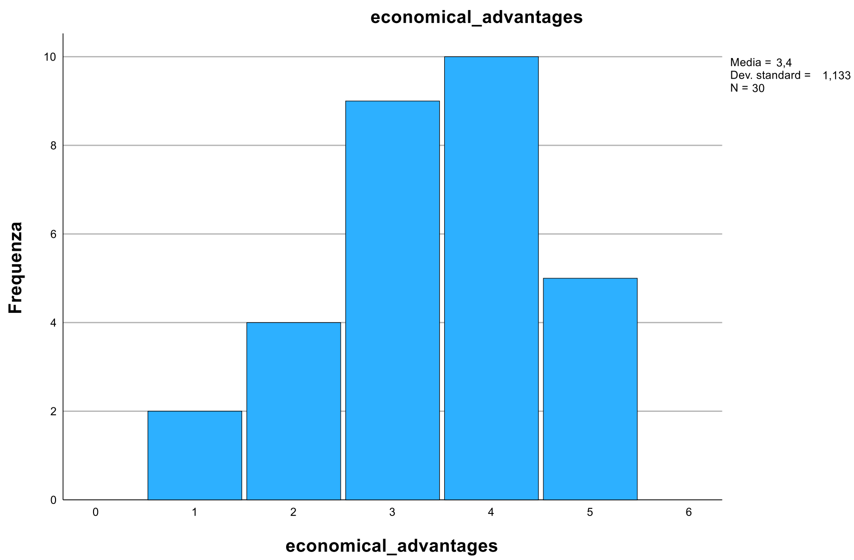

Figure 20 - Economical advantages

Figure 20 shows the distribution of perceptions regarding the economic advantages of technology, with a mean score of 3.4 and a standard deviation of 1.133. Most respondents rate the economic advantages at 4, suggesting that a significant portion of companies perceives notable economic benefits from technology integration, while fewer rate it at lower levels.

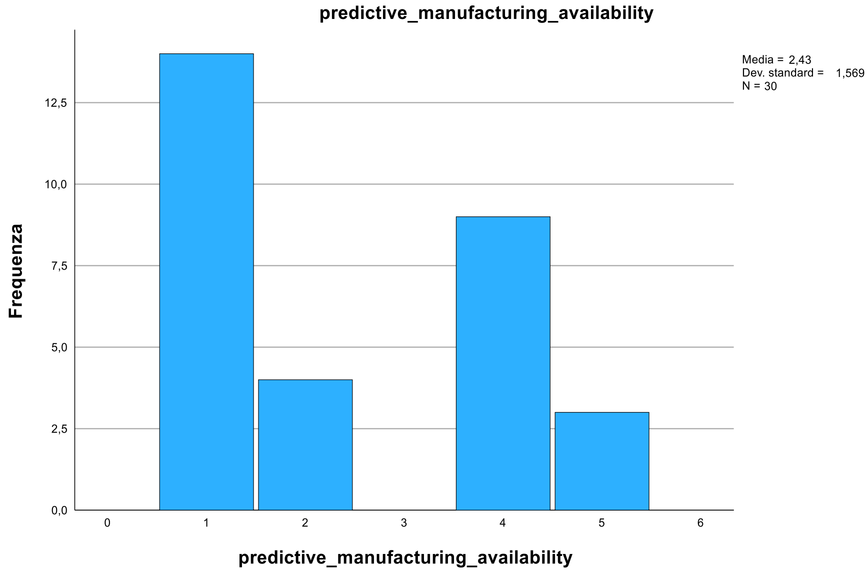

Figure 21 - Predictive manufacturing availability

Figure 21 depicts the distribution of predictive manufacturing availability, with a mean of 2.43 and a standard deviation of 1.569. Most respondents rate their availability at 1, indicating low implementation of predictive manufacturing technologies. However, a smaller group rates it at 4, suggesting some companies have moderate availability.

According to the following structure, the method proposed is to explore the relationships between the variables, the different levels of correlation and to identify the key dimensions of Industry 4.0 for a small and medium enterprise. That is the reason why it is proposed the exploratory Factor Analysis.

6.5.3 Exploratory Factor Analysis

Suitability of the analysis: KMO and Bartletts's test results

Table 6 - Suitability analysis

Test	Value
Kaiser-Meyer-Olkin (KMO)	0.85
Bartlett's Test of Sphericity	$\chi^2 = 512.34$, $p < 0.001$

The value of KMO is excellent (above 0.8), indicating that the data is suitable for factor analysis. The latter is significant (p value < 0.01), indicating that the variables are correlated enough to provide a significant FA.

Assessment on number of factors to extract

The factors are going to be kept according to their eigenvalues (Figure 22): if the eigenvalue exceeds 1 the associated primary factor is statistically significant to explain the total variance (according to the Kaiser criterion).

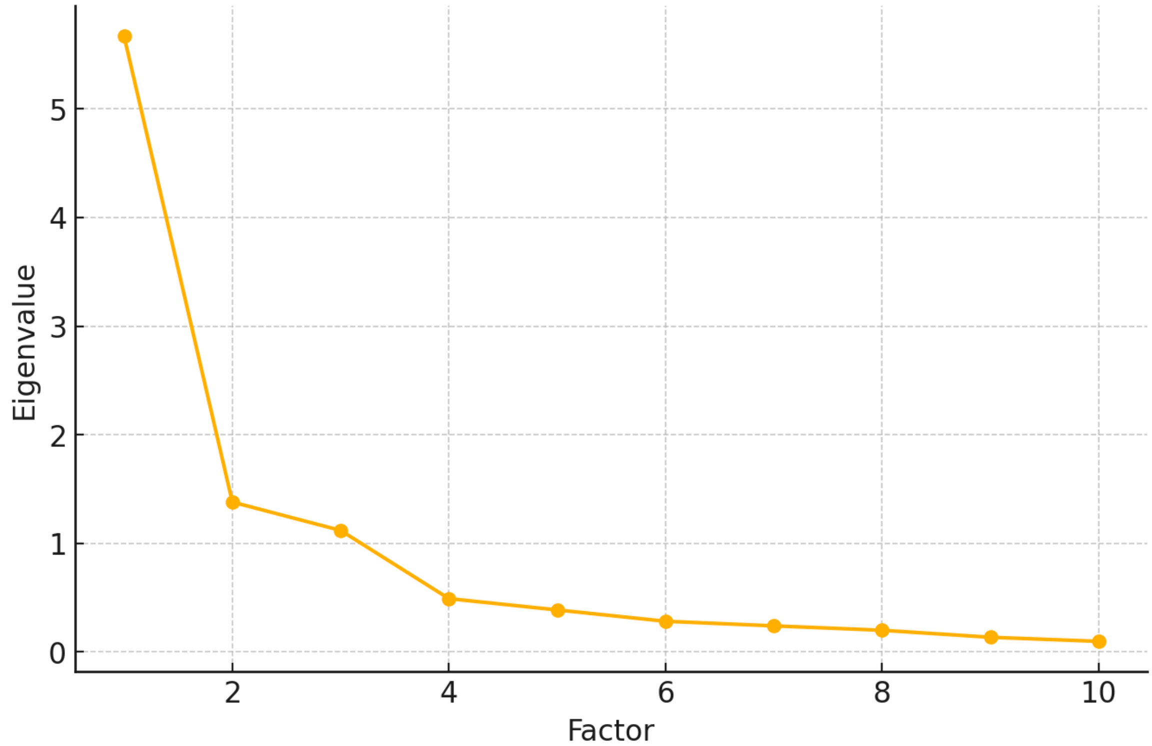

Figure 22 - Scree plot

The first three factors have eigenvalues greater than 1, and they are going to be the primary variables.

Factor Analysis: factor loading on the three variables and variance explained

The factor analysis (Table 7) will be performed *using principal axis factoring and by applying varimax rotation*. Loadings below 0.4 are typically considered *weak* and may not be significant. The secondary variable falls in the factor where it has the *highest loading*.

Table 7 - Factor loadings

Variable	Factor 1	Factor 2	Factor 3
technology_availability	0.76	0.12	0.05
IT_readiness	0.82	0.1	0.08
personnel_readiness	0.79	0.14	0.07
training_availability	0.73	0.18	0.09
need_of_ext_consultant	0.2	0.78	0.15
partnering_with_institutions	0.25	0.81	0.12
change_management_readiness	0.22	0.75	0.14
technology_perception_as_human_substitute	0.1	0.2	0.85
economical_advantages	0.15	0.25	0.8
predictive_manufacturing_availability	0.68	0.22	0.1

Table 8 - Total explained variance

Factor	*Eigenvalues* Total	% of variance	*Loading on the squared sum of extracted factors*	*Loading on the squared sum of extracted factors* Total	% of variance	*Loading on the squared sum of extracted factors % cumulative*
1	5,670	56,702	56,702	5,670	56,702	56,702
2	1,380	13,800	70,502	1,380	13,800	70,502
3	1,119	11,187	81,689	1,119	11,187	81,689
4	,491	4,908	86,597			
5	,387	3,865	90,462			
6	,282	2,822	93,284			
7	,240	2,399	95,684			
8	,199	1,994	97,678			
9	,135	1,349	99,027			
10	,097	,973	100,000			

In (Table 8 - Total explained variance) is shown the secondary variables loadings' across the factors. Factor 1 has high loadings on *technology_availability*, *IT_readiness, personnel_readiness*, *training_availability,* and *predictive_manufacturing_availability*, and could be named as ***Technological Readiness***. The factor represents the SME's preparedness in terms of technology and infrastructure for Industry 4.0 integration.

Factor 2 has high loadings on *need_of_ext_consultant, partnering_with_institutions,* and *change_management_readiness*, and could be named as ***External Collaboration and Support.*** The factor indicates the SME's reliance on external consultants and partnerships to manage and implement changes.

Factor 3 has high loadings on *technology_perception_as_human_substitute* and *economical_advantages* and it could be named as ***Perception of Technological Impact.*** The factor reflects the SME's views on how technology affects human roles and its economic benefits. In the following paragraph the three factors will be described according to their characteristics.

Primary variables description

Factor 1, Technological readiness reflects *how prepared an SME is in terms of its existing technology infrastructure, employee capabilities, and the availability of training programs to support Industry 4.0 adoption.* High scores on this factor suggest that the SME already possesses the necessary technology and has invested in building the IT infrastructure and personnel skills required to integrate Industry 4.0 technologies effectively. SMEs scoring high on this factor are likely to be well-positioned to implement advanced manufacturing technologies, such as artificial intelligence and predictive analytics. However, those with lower scores might need to focus on improving their technology stack, upskilling employees, and providing better access to training programs.

Factor 2, External Collaboration and Support *represents the SME's reliance on external support and its readiness to manage organizational changes required for Industry 4.0 integration.* A high score indicates that the SME acknowledges the importance of external expertise (e.g., consultants, institutional partnerships) and is prepared to handle organizational changes. SMEs that recognize the value of collaboration with external entities (such as universities, industry groups, or consultants) are likely to have better strategies for integrating complex Industry 4.0 technologies.

Factor 3, Perception of Technological Impact *captures how SMEs perceive the impact of Industry 4.0 technologies, specifically in terms of whether they view technology as a substitute for human labor and the perceived economic benefits of adopting these technologies.* A high score here suggests that SMEs believe that Industry 4.0 technologies will bring significant economic advantages and may also perceive these technologies as replacing certain human roles. On the other side, a lower score could indicate scepticism about the economic benefits of these technologies or concern that automation might displace workers.

6.5.4 Respondents ‘distribution across the factors and insights

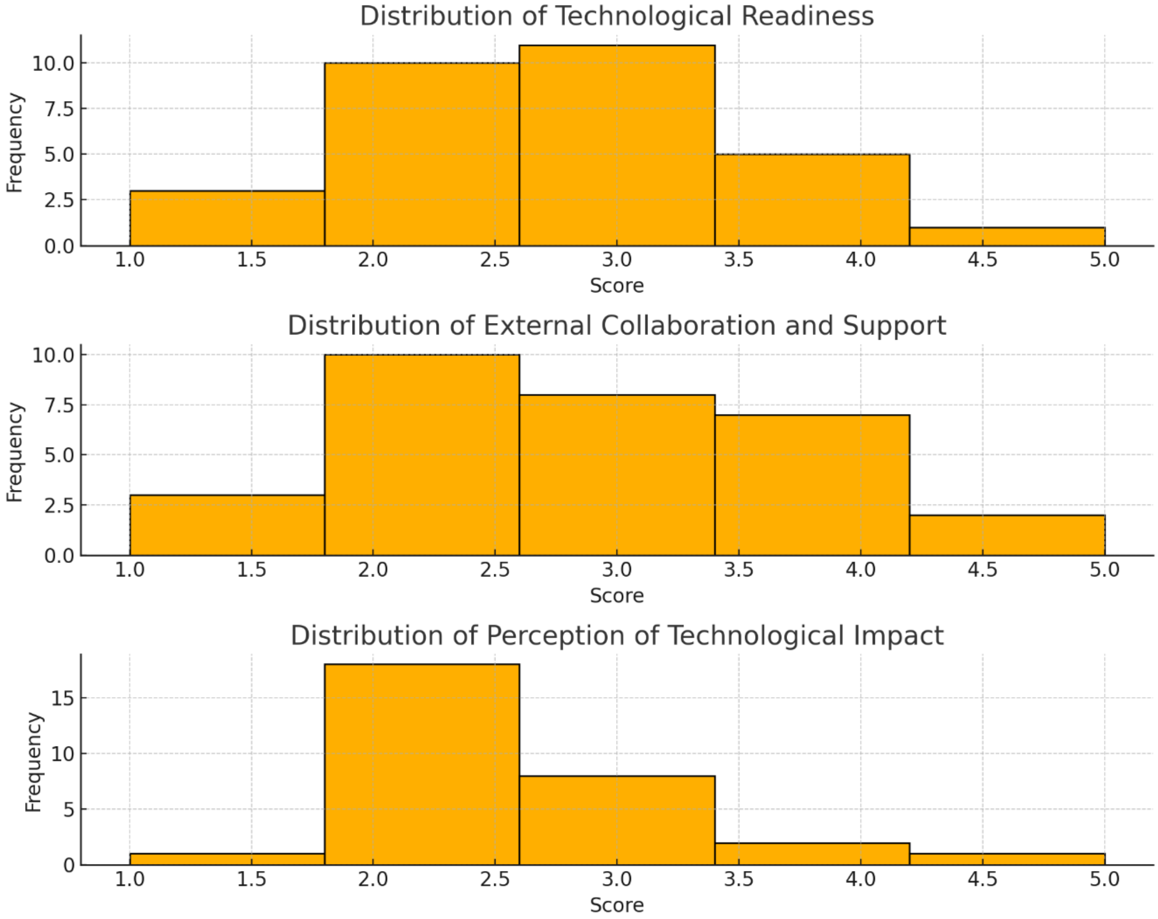

Figure 23 - Statistical sample distribution across primary factors

The histograms above (Figure 23 - Statistical sample distribution across primary factors) reflect how the statistical sample is distributed across the factors unveiled through the factor analysis:

Technological Readiness

The distribution of Technological Readiness seems to be slightly skewed towards the lower end of the scale, with more respondents scoring in the 1-2 range. This suggests that a significant portion of the SMEs may not feel fully prepared in terms of their technological infrastructure, personnel readiness, or access to training for Industry 4.0 technologies. SMEs may need to focus on improving their internal readiness by investing in technology upgrades, improving IT systems, and offering more training programs to their employees.

External Collaboration and Support

The scores for External Collaboration and Support are concentrated mostly in the middle (score of 2), with fewer respondents at the extremes. Most SMEs recognize the importance of external consultants and partnerships, but there is room for improvement. Few SMEs show a very strong or weak reliance on external support. SMEs might benefit from strengthening partnerships with external institutions, such as consultants, universities, or industry associations. These partnerships could help them bridge the gaps in their Industry 4.0 readiness, especially in managing organizational change.

Perception of Technological Impact

The Perception of Technological Impact scores show a distribution with most respondents clustering around the lower-to-middle range (scores of 2). This indicates that SMEs may not fully perceive the economic benefits of Industry 4.0 or they might be concerned about the impact of technology on jobs. There's a moderate level of scepticism or caution among the respondents, suggesting a need for better communication or education around the potential economic advantages of Industry 4.0. SMEs may require more case studies, success stories, or evidence of return on investment to overcome concerns about job displacement and see the economic benefits.

Food for thought

- **SMEs have room for growth** in both internal readiness and external support for Industry 4.0.
- **Technological readiness** is relatively low, indicating that SMEs may need to prioritize building internal capabilities.
- **External collaboration** is moderately embraced, but stronger partnerships with institutions and consultants could enhance Industry 4.0 integration.
- There is **caution** about the economic benefits of Industry 4.0 and its impact on jobs, suggesting a need for improved communication and reassurance about the long-term advantages of these technologies.

7. Summary of results

7.1 Answer to RQ1

To determine the most important type of knowledge for a small and medium-sized enterprise, how it is managed, and what is the impact of Knowledge on business performance

The results of the work highlight the relationship between knowledge management practices and business performance in SMEs, showing interesting results around product and process knowledge.

7.1.1 Product and Process Knowledge in SMEs

In the context of SMEs, **product knowledge** refers to the detailed understanding of the goods or services that the enterprise offers. It includes knowledge about design, functionality, production methods, quality standards, and customer needs. **Process knowledge**, on the other hand, encompasses the know-how related to the operational processes within the business, such as manufacturing techniques, workflow optimizations, and quality control mechanisms. These two types of knowledge are crucial for ensuring that SMEs maintain competitive, innovative, and efficient operations.

Product knowledge, for SMEs, it is essential for:

- **Customer Satisfaction and Differentiation**
- **Innovation**
- **Quality Control**
- **Market Competitiveness**

Process knowledge, for SMEs, is crucial for:

- **Operational Efficiency**
- **Scalability**
- **Employee Training and Retention**
- **Market Competitiveness**

The research highlights that **both product (12 responses) and process knowledge (14 responses) are pivotal for businesses**. However, the management and dissemination of this knowledge within the company can vary widely, often influencing business outcomes.

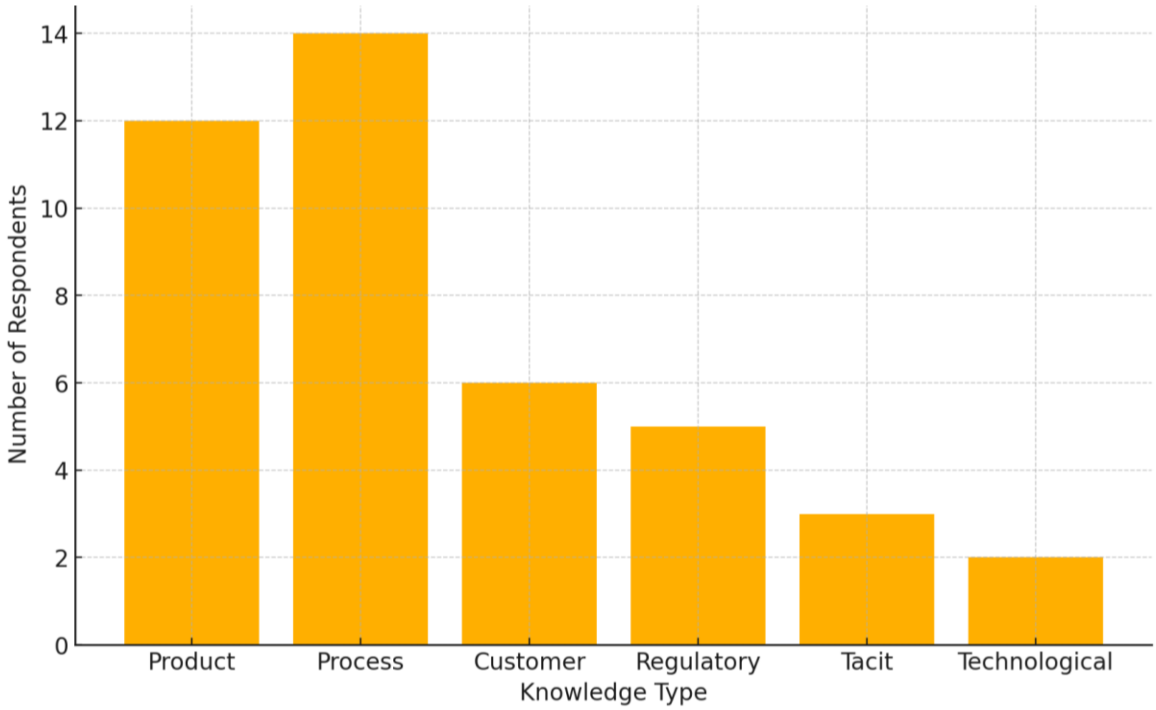

Figure 24bis - Main knowledge types and frequency of respondents

7.1.2 How Product and Process Knowledge is managed

The respondents in the survey demonstrated several approaches to managing product and process knowledge:

- **Product knowledge** is often stored in blueprints and technical specifications. However, in many SMEs, this explicit knowledge remains scattered or is not systematically organized.
- **Process knowledge** is frequently tacit, held by experienced employees or in the heads of team leaders. In SMEs, this type of knowledge is less frequently codified and often shared through direct, informal interactions rather than through formalized documentation or knowledge-sharing systems.

One key finding from the analysis is that SMEs often struggle with the **formalization of process knowledge**. This means that crucial operational know-how—how products are manufactured, quality is maintained, and workflows are optimized—can become fragmented across different employees. In many cases, it remains undocumented, creating significant risks of knowledge loss when key employees leave the company or if unexpected challenges arise in production.

7.1.3 Impact on Business Performance

The correlation between how SMEs manage their product and process knowledge, and their **business performance** is clearly demonstrated in Chapter 6.4.3:

Effective management of **product knowledge** is closely tied to *innovation*. SMEs that actively collect and disseminate product knowledge are better positioned to innovate and enhance their offerings. This leads to improved product quality, greater market competitiveness, and better customer satisfaction. On the other hand, SMEs that rely heavily on tacit knowledge for product design may find themselves lagging in innovation, as critical insights remain siloed within specific individuals. Proper management of **process knowledge** enhances an SME's ability to scale. As SMEs grow, their operations become more complex, making it essential that process knowledge is easily transferable across teams and departments. SMEs that have invested in **knowledge management systems**—such as databases, shared knowledge repositories, or formal training programs—are more agile in responding to changes in the market or scaling up production. Those that do not systematize process knowledge often face bottlenecks, where scaling operations leads to inefficiencies and mistakes due to the inconsistent application of knowledge across different parts of the business. The findings show that companies where **knowledge management systems** (for **both product and process knowledge**) are more developed are better able to maintain a cycle of continuous improvement. These systems allow employees to build on previous learnings, contributing to both incremental and radical innovations in products and processes. Conversely, when knowledge is fragmented or unstructured, the innovation cycle tends to stagnate, as there is no clear pathway for improving existing processes or products based on experience.

7.1.4 Critical Barriers and Gaps

Chapter 6.4.3 identifies several **barriers** to effective knowledge management, which directly affect the performance and sustainability of SMEs:

1. **Fragmentation of Knowledge**: SMEs often do not have formal structures for managing knowledge, leading to fragmented systems where valuable product and process insights are not accessible company wide.
2. **Limited Use of Digital Tools**: Many SMEs rely on basic tools (like informal messaging platforms and spreadsheets) for knowledge sharing. While these tools suffice in small-scale operations, they are insufficient for managing complex product or process knowledge as businesses grow.
3. **Tacit vs. Explicit Knowledge Imbalance**: There is a notable reliance on tacit knowledge in SMEs, especially regarding process-related insights. This creates a risk where knowledge is lost when key personnel leave, and the lack of explicit knowledge structures limits scalability.

7.2 Answer to RQ2

To determine the current state of Industry 4.0 integration within a small and medium enterprise. What is the level of awareness of an SME regarding the impact of this technology? How willing is it to embrace change to improve "as a whole"?

7.2.1 State of Industry 4.0 in SMEs

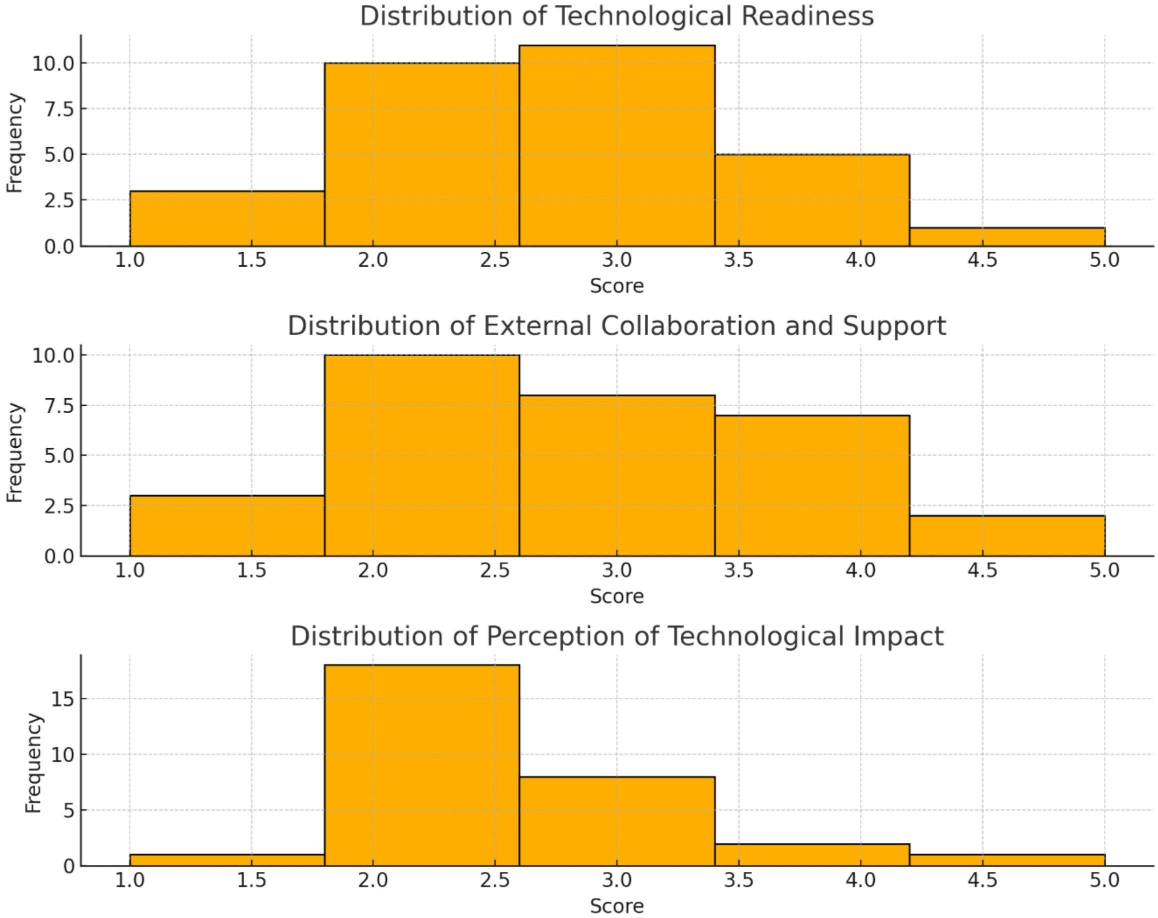

Figure 25bis - Statistical sample distribution across primary factors

Based on the insights from Chapter 6.5.4 and the data presented in Figure 23, the current state of Industry 4.0 integration within SMEs reflects a range of technological readiness, external collaboration, and perception of technological impact. These factors collectively inform the level of awareness and the willingness of SMEs to embrace change and adopt Industry 4.0 technologies.

Technological Readiness

The analysis in Figure 23 shows that technological readiness among SMEs is predominantly skewed toward the lower end, with most SMEs scoring in the 1–2 range. This suggests that many SMEs are still in the early stages of adopting Industry 4.0 technologies, lacking the necessary infrastructure, personnel expertise, and training programs required for effective integration. Many SMEs may still be using legacy systems that are not compatible with advanced Industry 4.0 tools such as IoT, AI, or data analytics. Insufficient training and expertise: A significant portion of SMEs lacks personnel with the specialized skills needed to manage and operate Industry 4.0 technologies. Training programs are not widely implemented, further slowing down the integration process. Italian SMEs should invest in upgrading IT systems and providing comprehensive training for their workforce. This would not only enhance their internal capabilities but also position them to more effectively adopt advanced technologies such as predictive maintenance and smart manufacturing.

External Collaboration and Support

The distribution of scores for external collaboration and support reveals a concentration in the middle of the scale (around 2). While many SMEs recognize the potential benefits of engaging with external partners, such as consultants, universities, or industry associations, their actual reliance on such partnerships remains limited. Only a few SMEs reported either strong or weak collaboration, indicating that external collaboration is not yet a widespread practice. For SMEs, strengthening external collaborations could be a key driver in overcoming internal limitations. Partnerships with external experts or institutions can help SMEs access cutting-edge knowledge, tools, and strategies for Industry 4.0 integration, particularly in areas like change management and technological implementation. Moreover, collaboration can facilitate knowledge sharing and innovation, enabling SMEs to better navigate the complexities of digital transformation.

Perception of Technological Impact

The perception of technological impact among SMEs, as indicated by the scores in Figure 23, suggests a moderate level of scepticism or caution. Most SMEs score in the lower-to-middle range, reflecting concerns about the potential economic benefits of Industry 4.0 and its implications for job security. This scepticism highlights the need for better communication and education around the potential advantages of Industry 4.0. SMEs may not fully understand how these technologies can lead to improved operational efficiency, cost savings, and long-term growth. More case studies, success stories, and evidence of return on investment (ROI) could help alleviate these concerns and push for a more positive attitude toward Industry 4.0 technologies.

7.2.2 Willingness to Embrace Change

SMEs' willingness to embrace change is closely tied to their perception of the risks versus rewards of Industry 4.0. Those that view these technologies as valuable investments in the future are more likely to undertake the necessary steps to integrate them into their operations. However, many SMEs remain cautious, particularly when faced with high upfront costs and uncertain immediate returns. This hesitancy is exacerbated by the lack of internal expertise and the perception that Industry 4.0 may not be fully suited to their business needs. Finally, the current state of Industry 4.0 integration in SMEs reflects a mix of low technological readiness, moderate external collaboration, and low awareness about technological impact. To improve their overall performance and competitiveness, SMEs must overcome both internal and external barriers by investing in training, collaborating with external partners, and better understanding the long-term benefits of Industry 4.0 technologies.

7.3 Correlation between knowledge management and Industry 4.0

7.3.1 How important is the formalisation of knowledge in the realm of Industry 4.0?

The relationship between **Industry 4.0 integration** and **Knowledge Management** (KM) in SMEs emphasizes the crucial role of **knowledge formalization** to fully exploit the benefits of Industry 4.0 technologies.

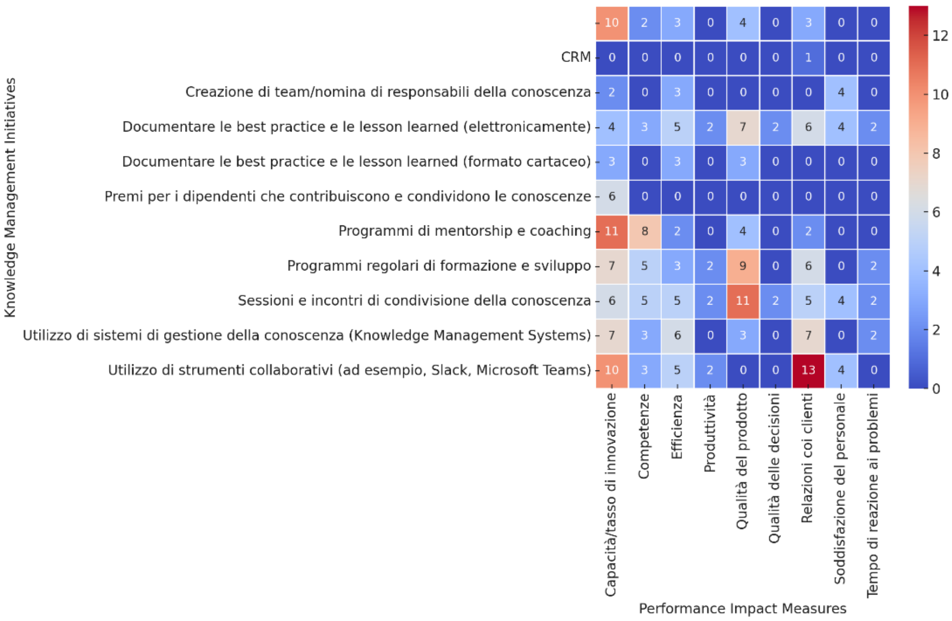

Figure 26bis - Correlation between knowledge management initiatives and performance impact measures

Figure 11bis revealed that *all* knowledge management initiatives have a stronger impact on fostering innovation within organizations. These tools facilitate communication, knowledge sharing, and real-time collaboration, which are critical activities for successful implementation Industry 4.0, specifically on IoT and AI. The data exploited the importance of integrating technology and human-centred initiatives to innovative outcomes.

Importance of Knowledge Formalization

Formalization of knowledge is the process of transforming tacit knowledge—the expertise and insights held by individuals—into explicit knowledge, which can be documented, stored, and shared within the organization. This formalization becomes even more crucial as SMEs integrate advanced technologies like IoT and AI. Industry 4.0 technologies generate vast amounts of data. However, without proper knowledge management systems (KMS), much of this data remains underutilized. Formalized knowledge allows SMEs to make data-driven decisions, as codified processes and shared information provide a foundation for analysing data collected through IoT devices, for example. This enhances the ability of firms to apply predictive maintenance and other data-driven optimizations effectively. As SMEs adopt more advanced Industry 4.0 systems, formalized knowledge ensures that insights and operational best practices are shared across teams. This facilitates collaboration within departments and external partnerships, allowing SMEs to scale more efficiently. Formalized knowledge systems also reduce dependency on specific individuals, ensuring business continuity despite changes in personnel. The lack of formalized knowledge management is a barrier for SMEs in adopting Industry 4.0. Without documented processes and shared knowledge repositories, implementing complex technologies becomes more challenging. Many SMEs struggle with integrating IoT and AI solutions due to inadequate codification of knowledge, making it difficult to align new technologies with existing processes. Tacit knowledge is often critical for SMEs, especially in specialized industries. However, the reliance on tacit knowledge can limit technological integration. By formalizing tacit knowledge into explicit forms, SMEs can leverage Industry 4.0 tools to enhance automation, process improvements, and product innovation, all of which are key to competitiveness in a digitalized market.

7.3.2 Is the exchange of knowledge between employees more important, or can digitisation (and the integration of Industry 4.0) improve the process of formalising knowledge, and the subsequent utilisation of insights derived from it?

In answering whether the exchange of knowledge between employees is more important or if digitization (and the integration of Industry 4.0) can improve the process of formalizing knowledge and utilizing the derived insights, the thesis poses important perspectives on this relationship.

In traditional SMEs, the exchange of knowledge between employees, particularly tacit knowledge, has always been critical. Tacit knowledge—acquired through experience and interactions—remains one of the most valuable assets for SMEs. Knowledge-sharing through informal means such as mentoring, daily collaboration, and meetings facilitates creativity and problem-solving in dynamic environments. However, this form of knowledge transfer is highly dependent on individuals and may not be sustainable or scalable, and not in all cases used.

Tacit knowledge exchange is essential for developing an adaptive workforce and fostering innovation, but it has clear limitations, especially in larger or more complex organizations. Without formal documentation, knowledge can be lost when employees leave or change roles. Moreover, relying solely on human-to-human exchanges can make it difficult to systematize best practices and scale operations efficiently.

Digitization, as part of Industry 4.0 integration, offers significant advantages by providing a pathway for formalizing tacit knowledge into explicit, accessible formats that can be shared and utilized across the organization. For instance, IoT sensors can track machine performance and processes, documenting operational knowledge that employees might previously have stored only in their heads. This digitized knowledge can be shared company-wide, enabling more consistent decision-making and process improvements. While employee-based knowledge exchange is crucial, digitization ensures that insights and best practices are formalized, allowing SMEs to scale more efficiently. Once digitized, knowledge can be stored in central repositories such as Knowledge Management Systems (KMS), making it accessible across departments and enabling automated analysis through

AI tools. This enhances not only the speed at which knowledge is disseminated but also its applicability. Finally, the realm of technologies enables real-time collection and analysis of data, ensuring that knowledge is applied immediately. In contrast to human knowledge exchange, which may be slower or reactive, digitized systems allow for proactive decision-making.

A Complementary Approach

The answer to whether employee knowledge exchange or digitization is more important is not an either/or proposition. Both play critical roles in an SME's knowledge management strategy. The exchange of tacit knowledge remains vital for fostering creativity, problem-solving, and adaptability in SMEs. However, aware-driven digitization through Industry 4.0 enables the formalization of this knowledge, ensuring it is accessible, scalable, and actionable.

Ultimately, integrating both approaches—enhancing human-based knowledge exchange while leveraging digitization for formalization—creates a more resilient and adaptable knowledge management framework. The formalization enabled by Industry 4.0 not only improves the efficiency of knowledge utilization but also ensures that valuable insights are preserved and systematically applied across the organization.

8. Sample framework for Knowledge Management in SME

To overcome the challenges discovered in knowledge management and to facilitate the better adoption of Industry 4.0 technologies in Italian SMEs, the following work proposes a *framework* specifically focused on managing the *process-to-product* Knowledge Flow. This groundwork will place a special emphasis on extracting and organizing Tacit Knowledge, which often resides in the heads of experienced workers and is crucial for reaching competitiveness and creating innovative outcomes (i.e. Integration of AI and IoT).

8.1 Current literature on Knowledge Management and its adaptation to SMEs: foundations and limitations

The framework proposed in the next pages draws inspiration from several foundational concepts and seeks to address limitations identified in existing frameworks. The *framework for Knowledge Management in SMEs* is primarily inspired at Nonaka and Takeuchi's (1995) SECI model, which emphasizes the continuous transformation of tacit knowledge into explicit knowledge, highlighting the interplay of socialization, externalization, combination, and internalization processes (Nonaka & Takeuchi, 1995). The SECI model has been instrumental in knowledge management literature, particularly in its recognition of tacit knowledge's critical value. However, one of the challenges with the SECI approach is its reliance on a well-established organizational culture that facilitates these transformations, which may not be present in many SMEs (Matsuo, 2015). Consequently, the *framework for Knowledge Management in SMEs* has focused on simplifying and operationalizing these processes using "lightweight" techniques that require minimal technological intervention, making them accessible to SMEs with limited infrastructure.

Additionally, this work builds upon the Resource-Based View (RBV) of the firm, as articulated by Barney (1991), which asserts that sustainable competitive advantage arises from unique internal resources, including tacit knowledge. The framework aims to harness these internal resources, particularly through structured interviews and observational studies, thus emphasizing the role of employees' implicit expertise in creating business value (Barney, 1991). Unlike many RBV applications, which are often criticized for their lack of focus on knowledge codification (Grant, 1996), the *framework for Knowledge Management in SMEs* specifically targets the conversion of tacit to explicit knowledge to make it accessible across the organization, thereby enhancing process efficiency and the diffusion of expertise.

The limitations of previous frameworks, such as the Knowledge-Based Theory (KBT) of the firm, were also considered. While KBT emphasizes knowledge as a fundamental asset (Grant, 1996), it often fails in looking at the challenges associated with knowledge elicitation and structuring, small-scale enterprises may not have the necessary expertise or financial resources. To overcome these shortcomings, the *framework for Knowledge Management in*

SMEs integrates simple and affordable extraction techniques, such as keyword collection sessions and basic pattern recognition (*mapping*). This makes knowledge management practices accessible to firms that cannot afford the sophisticated IT solutions commonly associated with KBT.

Another critical source of inspiration is recent research into the "Knowledge Leadership" concept. Current literature indicates that having a dedicated knowledge champion significantly enhances the success of knowledge management initiatives (Hussein et al., 2023). However, the adoption of roles like Chief Knowledge Officers (CKOs) in SMEs is often unrealistic due to budgetary and operational constraints. As an alternative, the *framework for Knowledge Management in SMEs* framework introduces the concept of a "knowledge-responsible figure" who operates within the existing organizational hierarchy, ensuring that knowledge management is promoted by someone with deep awareness of the business and the ability to influence peers, embedding the knowledge-responsible role within the existing structures.

In addition to what has been explained, the *framework for Knowledge Management in SMEs* places particular emphasis on the process of capturing and organizing tacit knowledge, in contrast with current literature that often prioritize explicit knowledge. In this thesis, it has been highlighted the role of knowledge (tacit, process & product) in driving innovation, particularly in environments where formal training and processes are limited. However, converting tacit to explicit knowledge in SMEs often poses challenges due to the informal nature of such knowledge and its dependence on individual workers. To bridge this gap, it is proposed the creation of an iterative path, that can be included in the habits' portfolio of a SME, making tacit knowledge more formalized and shareable across the organization.

Furthermore, the "agility and accessibility" principles inspired by recent works such as those by Scuotto et al. (2022) play an important role in the *framework*. Scuotto advocates for agility in knowledge management practices, emphasizing the need for continuous learning and quick adaptation in knowledge-intensive environments. Recognizing this, the *framework for Knowledge Management in SMEs* integrates a Feedback and Learning Loop, allowing SMEs to evolve their knowledge base over time based on feedback from users and changing business needs. This continuous loop ensures that the knowledge remains relevant, practical, and easily accessible to employees, thus maintaining an up-to-date repository that evolves alongside the organization's needs.

Lastly, challenges raised by the "Digital Divide in Industry 4.0" (Kamble et al., 2021) are addressed. The digital divide refers to the uneven capabilities of different firms to leverage advanced technologies for knowledge management, which is particularly pronounced in SMEs. While larger enterprises might seamlessly adopt advanced AI-driven knowledge tools, SMEs are often unable to invest heavily in new technologies, as we also demonstrated during this research. The lightweight, cost-effective approach proposed here directly responds to these challenges by offering a scalable solution that SMEs can adopt incrementally, allowing them to also mature digitally. This reduces the pressure of rapid technological adoption and makes knowledge management accessible to smaller firms, facilitating a stepwise progression towards Industry 4.0.

8.2 Key characteristics of the Framework

The following structure is designed to systematically capture, process, and transform Knowledge into explicit, usable information. The focus will be on enhancing knowledge formalization by a well-structured framework through the following levers:

- **Identification** of key process knowledge (procedures, experiences, skills) through employee interviews, workshops, and collaborative discussions.
- **Usage of “lightweight” techniques**, which are simple and easy-to-implement methods that do not require advanced technology or computational power, such as keyword extraction, pattern recognition, and manual tagging to analyse discussions, documents, and recordings.
- **Organization of extracted knowledge into meaningful categories** that can be accessed and used by employees across different roles.
- **Continuous update of knowledge content** to ensure that it evolves with changing processes and technological advancements.

The framework is based on the following building pillars: the Knowledge-Responsible figure, the process of Keyword identification and the process of effectively extracting and categorizing Knowledge, that will be presented in next subchapters.

8.2.1 Knowledge-Responsible figure

The knowledge-responsible figure is a *key role* that ensures the effective management and continuous update of the knowledge repository. This figure is responsible for overseeing the collection, structuring, and disseminating of knowledge across the organization. The identification of this figure can be achieved through three main criteria:

- **knowledge awareness**: it is necessary to have a thorough understanding of the company's processes, expertise in the subject matter, and the acknowledgment of the implicit levers that need to be formalized to be competitive in the sector of expertise;
- **change management availability**: the role requires a willingness and ability to manage change, which is fundamental to pull the business *through the gates of Innovation* (*see Chapter 7.2.2)* encouraging employees to contribute their knowledge and adapt to new practices;
- **relevance inside the business**: the role inside the company *must be relevant enough* to influence others and facilitate knowledge-sharing initiatives, ensuring that the knowledge management process is supported at all organizational levels.

8.2.2 Keyword Identification Session

Before disserting about knowledge extraction, it is crucial to gather the *most commonly used keywords* specific to the company. These keywords will form the basis of the knowledge extraction, allowing the process to effectively seek out unstructured knowledge. By '*keywords*', we also refer to where the tacit capabilities and knowledge reside within the organization, making their identification essential to understanding and formalizing these tacit insights. Identifying the right keywords is crucial because they represent the foundational elements of the company's operations: processes, skills, challenges, and unique capabilities. The more accurately these keywords reflect the tacit knowledge embedded within the company, the more effective the framework will be at extracting and organizing valuable insights, facilitating a more effective transformation of unstructured insights into explicit knowledge. This makes the keyword identification process a cornerstone for establishing an effective knowledge management framework.

Keywords identification is made of four steps: Conduct, Review, Validate and Rank.

1. ***Conduct*** sessions with key employees to identify frequently used terms related to processes, skills, challenges, and solutions within the company. The sessions should involve brainstorming and collaborative discussions to extract comprehensive lists of keywords that represent the core activities and challenges faced by the company. These keywords are not just terms; they are indicators of where valuable tacit knowledge resides. *(Keyword Exploration)*

2. ***Review*** existing documents, reports, and communication records to compile a list of commonly used terms. Automated tools (basic text analytics software) can also be used to scan large volumes of documents for recurring terms, allowing for a data-driven approach. *(Documents Comparison)*

3. ***Validate*** the list of keywords with subject matter experts (such as long-term on-field employees), to ensure their relevance and completeness. Experts can provide insights into which keywords truly reflect the business's core processes and distinguish between commonly used but less impactful terms and those that are critical to the company. *(Keyword Refinement)*

4. ***Rank*** keywords based on their importance to company's operations. This prioritization will ensure that the most critical knowledge areas are extracted first, improving the efficiency and effectiveness of the knowledge management process. Prioritization helps focus the knowledge extraction process on areas that have the highest impact on business performance, thereby maximizing the value derived. *(Keyword Prioritization)*

8.2.3 Methods of extraction and organisation of Knowledge

One of the primary challenges in Industry 4.0 adoption is the lack of structured tacit knowledge. The *framework for Knowledge Management in SMEs* specifically focus on converting tacit knowledge into actionable insights, by proposing the following techniques.

- *Expert Interviews*: structured and semi-structured interviews with key personnel to catch knowledge that is typically undocumented.
- *Observational Studies*: real-time observation of processes to understand workflows and capture the practices involved.
- *Collaborative Platforms*: push employees to share experiences through collaboration tools, where key learnings can be manually tagged and organized.

The proper organization of uncovered knowledge will be exploited through *Knowledge Mapping* and *Tagging and Categorization.* The former entails developing a *knowledge map* that visually represents the links between various tacit insights gathered from employees, the latter calls for using *tags* to categorize the extracted knowledge, making it easier to combine and retrieve specific insights related to different processes and products.

8.2.4 Modules of the Framework

The following subchapter is intended to propose the framework through an interative process composed of modules, which can be implemented using different programming languages and applications, by respecting the framework structure.

1. **Data Collection Module**: it gathers data from various sources, such as interviews, recorded meetings, and task observations. The data will be collected using manual approaches (e.g., structured interviews) and simple automated methods (e.g., digital forms or basic monitoring tools).

2. **Knowledge Extraction Module**: extraction of insights from raw text data will be achieved using simple text parsing and pattern recognition[1]. These lightweight techniques are designed to be efficient and cost-effective, suitable for SMEs with limited IT infrastructure, without requiring advanced NLP capabilities. The integration of Keywords here is *key* to get an effective result.

3. **Knowledge Structuring and Mapping**: after extraction, the data needs to be structured. Here, the *basic tagging system* will be used to convert the extracted tacit knowledge into explicit formats. The tags will link related concepts, processes, and experiences, creating a representation of how knowledge is interconnected within the company.

[1] in a more general case, companies based on their capabilities can decide to use and effective integrate AI algorithms to automatize and streamline Knowledge extraction, for the purpose of our work and acknowledging the general scarcity of resources, the thesis proposes simple-but-effective techniques

4. **Store & Accessibility**: organized knowledge will be stored in a *knowledge repository* that is easily accessible to everyone, leading to democratisation and diffusion of Knowledge uncovered. The repository can be integrated into existing IT systems, such as shared drives or intranet platforms, to facilitate knowledge access.

5. **Feedback and Learning Loop**: a successful implementation of the framework depends also from a mechanism for feedback collection from users who interact with the knowledge base. This feedback will be used to refine the Keywords, the knowledge extraction process and it must be granted by Knowledge-Responsible figure, ensuring the repository remains relevant and accurate.

8.2.5 Python Implementation of the Knowledge Management Framework

The concepts discussed in the preceding pages can be implemented through an *algorithm* designed to address the identified gap in this thesis, thereby encouraging a culture of continuous learning and improving Industry 4.0 readiness. This proposed work seeks to address two major barriers to effective Knowledge Management: limited financial resources and lack of in-house expertise. However, a commitment to applying change management strategies and pursuing innovative solutions remains *essential*, an approach not always assured in small businesses.

It is recommended to run a pilot study (which is out of the scope of this work) to test the different functions and to adapt the implementation to company exigencies.

Below it is provided a simple Python implementation of the *Knowledge Management framework in SMEs*. The focus is on simplicity, easy integration into legacy IT infrastructure, and minimal upfront investment.

```
################################################################################

import os
import json
from collections import defaultdict

# Data Collection Module
def collect_data():
    # Sample data collection from text files (interviews, observations)
    data_sources = ['interview_notes.txt', 'observations.txt']
    collected_data = []
    for source in data_sources:
        if os.path.exists(source):
            with open(source, 'r') as file:
                collected_data.append(file.read())
    return collected_data

# Knowledge Extraction Module
def extract_knowledge(data):
```

```
    # Simple keyword extraction using determined keywords
    keywords = ['process', 'experience', 'skill', 'challenge',
'solution']
    extracted_knowledge = defaultdict(list)
    for text in data:
        for keyword in keywords:
            if keyword in text.lower():
                extracted_knowledge[keyword].append(text)
    return extracted_knowledge

# Knowledge Structuring and Mapping Module
def structure_knowledge(extracted_knowledge):
    # Basic tagging and structuring of knowledge
    structured_knowledge = {}
    for key, value in extracted_knowledge.items():
        structured_knowledge[key] = list(set(value))
# Removing duplicates
    return structured_knowledge

# Storage and Accessibility Module
def store_knowledge(structured_knowledge):
    # Store structured knowledge in a JSON file
    with open('knowledge_repository.json', 'w') as json_file:
        json.dump(structured_knowledge, json_file, indent=4)
    print("Knowledge repository updated and saved.")

# Feedback and Learning Loop Module
def feedback_loop():
    # Collecting user feedback to improve knowledge extraction
    feedback = input("Please provide feedback on the knowledge
repository: ")
    with open('feedback.txt', 'a') as feedback_file:
        feedback_file.write(feedback + '\n')
    print("Feedback recorded.")

# Main Function
def main():
    # Step 1: Data Collection
    data = collect_data()

    # Step 2: Knowledge Extraction
    extracted_knowledge = extract_knowledge(data)

    # Step 3: Knowledge Structuring and Mapping
    structured_knowledge = structure_knowledge(extracted_knowledge)

    # Step 4: Storage and Accessibility
    store_knowledge(structured_knowledge)

    # Step 5: Feedback and Learning Loop
    feedback_loop()

if __name__ == "__main__":
    main()
```

##

1. **Data Collection Module**: `collect_data()` function gathers data from text files, simulating interviews and observations.
2. **Knowledge Extraction Module**: `extract_knowledge()` function uses keyword matching to extract relevant information from the collected data.
3. **Knowledge Structuring and Mapping Module**: `structure_knowledge()` function tags and structures the extracted knowledge, removing duplicates to ensure clarity.
4. **Storage and Accessibility Module**: `store_knowledge()` function saves the structured knowledge into a JSON file, making it easily accessible.
5. **Feedback and Learning Loop Module**: `feedback_loop()` function collects user feedback to continuously improve the knowledge repository.

8.3 Impact of the Algorithm on Knowledge Management and Industry 4.0 Integration

The impact of the knowledge management framework can be comprehensive.

First, the process *can* effectively convert unstructured, experience-based knowledge into a structured and accessible form, which significantly enhances its usability across the organization. One of the major benefits of this algorithm is in *enhancing organizational learning*. By capturing the experiences and skills of employees, it *can* facilitate the continuous flow of knowledge, supporting informed decision-making and reducing the risks associated with the loss of critical knowledge when experienced workers leave. The structured knowledge repository allows the organization to minimize redundancy and optimize resource utilization, which directly impacts efficiency and productivity.

Second, the lightweight and cost-effective nature which is based the framework can ensure that SMEs can improve their knowledge management capabilities without requiring substantial investments (specifically in IT CAPEX).

Furthermore, by formalizing knowledge related to key processes, the framework lays the groundwork for the E2E adoption of digital technologies such as IoT, AI-driven analytics, and data integration systems.

The role of the knowledge-responsible figure is also crucial in this context, as it helps drive the use of the algorithm throughout the organization, ensuring that knowledge is consistently updated and remains relevant. This figure serves as a *change agent*, encouraging employee participation and maintaining the momentum of digital transformation initiatives. The correct creation of synergies fosters a culture of collaboration and openness to change, by involving employees in the keyword identification process, collecting feedback, and encouraging knowledge-sharing practices.

As unveiled in previous chapters, knowledge management supports innovation within the organization by establishing a structured foundation for digital technology adoption. The repository acts as a *living document* that evolves with the organization, capturing new insights and facilitating incremental improvements. This iterative learning process allows

SMEs to remain agile and adaptive in the face of rapid technological changes. The integration of the following framework serves as a bridge between the current knowledge practices of SMEs and the demands of Industry 4.0. By enhancing knowledge sharing, improving process understanding, and increasing employee engagement, the algorithm positions SMEs to fully leverage digital technologies, that are critical to businesses' success.

9. Conclusion

The thesis presented the findings from the research, which investigated the relationship between knowledge management and Industry 4.0 integration within Italian SMEs. The results are structured around answering the two main research questions (RQ1 and RQ2) that explore the importance of knowledge types for SMEs, how knowledge is managed, and the current state of Industry 4.0 adoption.

In answering RQ1, the results highlight the crucial role of both product and process knowledge for SMEs. Product knowledge, which includes the details about design, production, and customer needs, is shown to be essential for maintaining innovation, quality control, and competitiveness. Process knowledge, concerning operational techniques and workflow optimizations, is equally vital for ensuring efficiency and scalability within SMEs. However, the management of this knowledge often poses challenges, with tacit knowledge (held by experienced employees) being less frequently formalized. This creates risks related to knowledge loss and inconsistent performance across different teams. The analysis revealed that SMEs that actively manage and document their product and process knowledge show improved performance, including innovation capacity and market responsiveness.

For RQ2, the research delved into the state of Industry 4.0 integration within SMEs. The findings indicate that the technological readiness of SMEs is generally low, with many businesses still in the early stages of adopting Industry 4.0 technologies. Factors such as legacy systems, insufficient IT infrastructure, and a lack of training are identified as the primary barriers to effective adoption. Many SMEs are not fully leveraging the potential of Industry 4.0 technologies such as IoT and AI, primarily due to concerns over cost, complexity, and a lack of skilled personnel. Despite these challenges, some SMEs have shown a willingness to embrace change, particularly in areas like economic benefits derived.

The correlation between knowledge management and Industry 4.0 is explored in detail, with results showing that companies with stronger knowledge management practices are better positioned to adopt Industry 4.0 technologies. The formalization of knowledge is found to be a key factor in this process. Companies that invest in digitization and structured knowledge-sharing systems are more likely to integrate Industry 4.0 successfully and gain a competitive advantage through improved operational efficiency and innovation.

As a next step, the work proposed a conceptual framework (that can be declined in an algorithm) to respond to the challenges discovered. Companies can unveil and formalize Knowledge, based on two main actors, the *identification of Keywords* (Knowledge Tags) and the *creation of a Knowledge-Responsible* figure. This framework aims to create a loop of continuous improvement that in a first phase explicates Tacit Knowledge, and in a second phase integrates the *digital-thread* to streamline the process of innovation. This sets the stage for integration and development of new products and services.

The results emphasize the need for SMEs to prioritize both knowledge management and Industry 4.0 integration. By formalizing knowledge and leveraging external partnerships, SMEs can overcome the barriers to adopting advanced technologies, ultimately improving their business performance and competitiveness in an increasingly digitalized market.

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