Instituto Superior de Gestão e Administração de Santarém

Mestrado em Gestão de Empresas

Dissertação

Digital Twin in European Union Manufacturing Industry: A Systematic Literature Review

Os Gémeos Digitais na Indústria de Manufatura na União Europeia: Revisão Sistemática da Literatura

Filipe José Canha Esteves

Orientador:

João Carlos Gonçalves dos Reis

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Dissertação submetida para satisfação parcial dos requisitos do grau de Mestre em Gestão de Empresas sob a orientação do Professor Doutor João dos Reis

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Resumo

O estudo integra resultados de uma revisão sistemática da literatura e de uma meta-análise visando avaliar o estado atual, os desafios e perspetivas futuras inerentes às transformações tecnológicas e socioeconómicas, através de uma análise temática. A primeira parte é dedicada ao estudo dos Gémeos Digitais (DTs) na indústria de manufatura da UE, análise da a sua implementação, benefícios e barreiras, propondo um modelo conceptual para melhorar a recolha e partilha de dados em toda a UE. O estudo destaca a necessidade de modelos de referência padronizados e de uma maior colaboração entre academia, indústria e decisores políticos de modo a potenciar as capacidades dos DTs. A segunda parte investiga a Indústria 5.0 (I5.0) através de uma meta-análise temática, apresentando novas taxonomias e evidências consolidadas sobre as suas contribuições na produtividade, emprego e sustentabilidade. O estudo revela que os fabricantes europeus estão a adotar gradualmente os princípios da I5.0, mas a ausência de métricas e modelos de avaliação padronizados pode comprometer o envolvimento das partes interessadas. A UE deve continuar a fomentar a colaboração interdisciplinar para desenvolver standards éticos e regulatórios que reforcem as parcerias entre a indústria, a academia e os governos, bem como, agilizar o acesso a financiamento, especialmente para as PMEs, que são as mais afetadas pelas suas limitações técnicas e financeiras. Os líderes devem promover a adoção de tecnologias da I5.0, por forma a aumentar a competitividade através de modelos de negócio alinhados com a I5.0, privilegiando tecnologias centradas no ser humano. Investigações futuras devem focar-se em tecnologias centradas no ser humano, modelos de resiliência e de economia circular, bem como em standards éticos e políticos consensuais entre a academia, a indústria e os decisores políticos, de modo a garantir a adoção generalizada da I5.0 em toda a UE.

Palavras chave: Gémeos Digitais; Indústria de Manufatura; Industria 5.0; Competitividade.

Abstract

The rapid evolution of digital technologies and the transition toward more sustainable and human-centric industrial models are reshaping the manufacturing sector in the European Union (EU). The study comprises findings from a systematic literature review and a meta review to assess the current state, challenges, and future directions of these technological and socio-economic shifts through a thematic analysis. The first part of the thesis examines DTs in the EU manufacturing industry, analysing their implementation, benefits, and barriers, proposing a conceptual framework to enhance data collection and sharing across EU. The study highlights the need for standardized frameworks and greater collaboration between academia, industry, and policymakers to fully leverage DTs potential. The second part investigates Industry 5.0 (I5.0) in a thematic oriented meta-review, presenting new taxonomies and consolidated evidence on its contributions on productivity, employment and sustainability. This study reveals that EU manufacturers are gradually adopting I5.0 principles but the lack of standardized metrics and frameworks to assess I5.0 impact can compromise stakeholder engagement. EU should continue leveraging interdisciplinary collaboration to develop ethical and regulatory frameworks capable of tightening partnerships between industry, academia and government to expedite funding access, particularly for SMEs which are the most affected by technical and financial constraints. Furthermore, the adoption of I5.0 technologies should be promoted by leaders to enhance competitiveness through I5.0 aligned business models, prioritizing human-centric technologies. Future research should focus on human-centric technologies, resiliency and circular economy models, alongside with ethical and policy frameworks accepted by academia, industry and policy makers to ensure I5.0 adoption across EU.

Keywords: Digital Twins; Manufacturing Industry; Industry 5.0; Competitiveness.

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INTRODUCTION

Research Context

Since the first Industrial Revolution, technology has been the driver of change and progress in factories and society. The Fourth Industrial revolution has not yet reached its peak and manufacturing industries are still merging with newer, modern communication and information technologies (Haag & Anderl, 2018). Despite Industry 4.0 (I4.0) is still being implemented, European Commission was forced to move forward to speed up the digitalization and competitiveness in Industry, creating the Industry 5.0 Award. Moreover, a Community of Practice for industry 5.0 was launched on 16th of November of 2023 in response to evolving market demands and pressing sustainability imperatives (Industry 5.0 - European Commission, 2022). Industry 5.0 (I5.0) is portrayed as a pivotal development for Europe, enabling a transition beyond the techno-economic paradigm of Industry 4.0 towards an industrial future that is more closely aligned with European values and the pressing need for a sustainable, resilient, and human-centred society. I5.0 is regarded as essential for addressing inequality, environmental challenges, and social tensions, as well as for ensuring Europe's long-term prosperity and global leadership (Commission, 2022).

Emerging as the industrial evolution benchmark and, as a complement to I4.0, I5.0 presents a renewed vision for industry’s future (Mourtzis et al., 2022). Since the mid-2010s I5.0 has been gaining emphasis and formally leveraged by the European Commission, pivoting towards a transformative model that integrates the technological advancements of I4.0, prioritizing human-centricity, sustainability, and resilience (Konstantinidis et al., 2023). I5.0 is more than a technological leap, it is a re-orientation, seeking to place human well-being and planetary boundaries at the heart of industrial production (Zizic et al., 2022). Furthermore, I5.0 seeks to harmonise technological progress with societal and environmental well-being, positioning competitiveness within a broader socio-economic framework. A key enabler of this transition is the Digital Twin (DT) technology, providing a virtual representation of physical systems, enabling real-time monitoring, simulation, and optimisation, capable of merging new physical production systems to digital manufacturing. These innovations, together, are reshaping the competitive dynamics of EU’s industrial landscape, leveraging EU to become a world leader in smart, sustainable and socially responsible manufacturing (Hunkova & Haviernikova, 2024).

Global manufacturing competition is rapidly increasing, led by AI and automation innovations from EUA and China, while EU differentiates itself through sustainable and human-centric production approaches. To stay competitive EU must leverage I5.0 and DTs to strengthen supply chain resiliency in a post pandemic and geopolitical unstable panorama that exposed vulnerabilities in a globalized supply chain. For Small and Medium Enterprises (SMEs), I5.0 enhances localized and flexible production integration, driving sustainable manufacturing while fostering innovation, since they are the backbone of EU manufacturing sector (Mourtzis et al., 2022). Aligning new technologies and innovative manufacturing systems with ethical and regulatory standards, such as, data privacy, AI ethics and environmental compliance creates emphasis on transparent human-centric, ensuring customer trust in EU made products (Dhirani et al., 2023). In addition, EU has been actively promoting digital transformation in manufacturing through initiatives, such as the European Innovation Council (EIC) dedicated mainly to SMEs, recognizing DTs as the strategic tool for enhancing operational efficiency, reducing waste, and supporting circular economy objectives. However, and despite their potential, the adoption of DTs across EU manufacturing sector remains uneven, influenced by technological readiness, financial constraints, and workforce adaptability (Kritzinger et al., 2018). Moreover, the interplay between I5.0's core tenets and DTs deployment presents both opportunities and challenges to maintain EU's competitive edge in global markets (Krupas et al., 2024).

I5.0 and DT technologies are case sensitive, involving manufacturing processes, social acceptance, workforce readiness, data privacy and ethical compliance, these factors are generating large volumes of specific information, dispersed throughout several manufacturing sector. This information needs to be summarized in a way that academia, policy makers and industry may interpret together. Creating a knowledge framework perceivable for academia, business owners and professionals may leverage and accelerate I5.0 development and implementation, generating new highly skilled job roles and new business models capable of enhancing even further the already known advantages of I5.0 and DTs.

Despite the considerable obstacles associated with this transition, including the need for new skillsets, managing technological risks, and ensuring social acceptance, the EU is actively creating conditions to enable I5.0, leveraging the single market to set global standards and implement policies supporting I5.0 core principles.

Problematic and Research Questions

I4.0 implemented by Germany created a unique opportunity for Europe to lead the global manufacturing sector with innovative products and new technologies, however, EU is now struggling to maintain its position in a global and competitive economy. I5.0 and its human-centered, sustainable and resilient approach might be the new heading towards a new industrial era, bringing global competitiveness back to EU manufacturing sector centered in I5.0 core principles. Digitalization is being developed throughout the entire world and the EU must also pursue this objective. As I5.0 is being implemented, new challenges and opportunities arose, impelled by newer and innovative technologies, business owners, regulatory, political actors and all relevant stakeholders must adapt to a new paradigm. Due to their specific associated technologies, DTs are creating specific challenges and opportunities for each manufacturing sector, new professions have been created, and new skillsets are in high demand to try and respond to this new industrial revolution. At the same time, the knowledge remains scattered and interdisciplinary, making it difficult for researchers and business owners to assess whether to adopt DTs. To study and understand this newly created challenges, this study defines the following research questions:

(1) What are the key factors influencing the adoption and implementation of DTs in the European manufacturing industry, and how do these technologies contribute to operational efficiency, productivity, and sustainability goals?

This question addresses the barriers and enablers shaping DTs integration. While technical feasibility is a critical factor, organizational readiness, cost implications, and interoperability standards also play decisive roles. Moreover, the extent to which DTs enhance operational performance and alignment with EU sustainability remains underexplored, necessitating empirical validation of their long-term impact.

(2) What are the emerging trends and research directions of DTs within the European manufacturing sector?

Seeks to identify how DT can influence, what are the benefits, and what challenges may arise to redefine manufacturing processes in EU.

(3) What are the key thematic areas in I5.0 core tenets contributions towards a competitive EU manufacturing sector?

Examines how human-centricity, sustainability, and resilience intersect with technological innovation to foster a robust industrial ecosystem in a thematic analysis. Understanding these dynamics is essential for policymakers and industry stakeholders to strategize the EU's transition towards a more competitive and sustainable manufacturing future.

General and specific goals

Industry 5.0 is the newest industrial revolution, it represents a new paradigm for industry, governments and society in general, it is focused on human-centricity, sustainability and resiliency. This core tenets and their associated technologies are creating new research opportunities and data collection that must be synthesized. The general objective of this study is to gather, synthesize and create new taxonomies on DTs in EU manufacturing sector and I5.0 from an EU perspective. Previous research was focused on specific industry/manufacturing areas and in particular case studies, lacking research from a systematic point of view to gather, organize information and explore how DTs can connect to I5.0 core tenets boosting EU's competitiveness. Moreover, the level of implementation of DTs across different sub-sectors and companies differing in size needs be investigated to map the adoption level across EU and, how it impacts on competitiveness and resiliency in EU manufacturing sector.

In the pursuit of answers to the research questions, two articles were created. Firstly, a systematic literature review (SLR) was carried out, resulting in the elaboration of a theoretical article. This SLR followed PRISMA guidelines, and the research was conducted in Web of Science (WoS) core collection database to investigate the benefits, and challenges of DTs in EU manufacturing sector. Concept's complexity, technologies used, and the range of applications raised several challenges, culminating in a framework proposal to organize the existing body of knowledge. This framework involved categorising the concept into themes—adoption, implementation, productivity, efficiency, and sustainability—with the aim of contributing to a productive, efficient, and competitive EU's manufacturing sector. Through the elaboration of the first article, I5.0 became significantly relevant due to its capabilities to enhance DT technologies as a transformational technology for EU's industry sectors and society as the new paradigm to pursue.

A second article was created with the purpose of exploring the EU perspective on I5.0 and its industrial policies, presenting new taxonomies to organize the concept and consolidate knowledge on productivity, employment and sustainability. The article follows a meta-review methodology as a research strategy, conducted in WoS core collection database, aiming to present a new perspective in EU industrial policies and state of knowledge. To organize the concept and consolidate evidence, new thematic taxonomies were created. I5.0 is focused on human-centric, sustainable and resilient principals and, to accomplish it, industries must adopt and develop the already existing technologies, introduced by I4.0, to leverage competitiveness while placing humans, sustainability and societal consciousness as primary focus. Conducting the thematic analysis 6 themes emerged comprising competitiveness, sustainability, resiliency, technology, organizational adoption and strategic planning and, policy and regulatory frameworks. Research highlights how crucial for EU industries technology is, not only as an efficient resource to enhance production capacity and competitiveness but also as a societal revolution enabler, centered in humans, sustainability and resiliency. DTs play a particular role in I5.0 revolution since it is considered a key enabler alongside Cobots to substantially transform the EU manufacturing industry. Despite financial and technological constraints, early-stage market development and regulatory challenges, DTs remain a foundational driver of efficiency, productivity and sustainability. It is also in evidence that organizations, company owners, workers and policy makers must be aligned to adopt and develop responsibly I5.0 core tenets, as the new industrial paradigm. Hence, the relevancy of this article with the potential to enhance the creation of robust ethical guidelines and policy frameworks capable of providing regulatory standards in a comprehensible and equitable manner.

This master thesis is composed of a brief introduction presenting a general overview of the topics, two articles, the first one a systematic literature review and the second one being a meta-review and, a conclusion containing the main findings, identified gaps and future research suggestions.

CHAPTER I

Digital Twins in European Union Manufacturing Industry: A Systematic Literature Review

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Abstract. Technologies have advanced significantly since the First Industrial Revolution, and digital twins, which have existed for several decades, have only become widely implementable across various manufacturing industries with the adoption of the Internet of Things (IoT). As Industry 4.0 continues to evolve, digital twins have had a major impact on organizations, compelling them to remain competitive, resilient, and sustainable to succeed. Each manufacturing industry has its own challenges and opportunities implementing digital twins due to specific associated technologies, creating new skillsets and professions. In the broader context of business and technology, the rapid increase in data complexity and volatility has resulted in knowledge production at an unprecedented speed. However, this knowledge often remains scattered, fragmented, and interdisciplinary, making it difficult to keep up with state-of-the-art research and assess collective evidence in specific areas. In response to these challenges, the European Commission is encouraging organizations to transition to Industry 5.0 as a global competitive strategy aimed at making Europe resilient, socially responsible, and ecological. This study is a Systematic Literature Review using PRISMA guidelines and research in Web of Science database to assess the influence, benefits, and challenges of digital twins in European Union manufacturing Industries. The complexity of the concept, technology used, and range of application raised several challenges. The systematic review of the selected literature culminated in a framework to organize literature context in five themes, adoption, implementation, productivity, efficiency and sustainability. Utilizing full potential of digital twins, European manufacturing can leverage productivity, efficiency and competitiveness, involving both theoretical and practical approaches.

Keywords: *Digital Twins; Manufacturing Industry; European Commission; Systematic Literature Review.*

I.1. Introduction

Since the first Industrial Revolution, technology has been the driver of change and progress in factories and society. The Fourth Industrial revolution (also called Industry 4.0) has not yet reached its peak, manufacturing industries are still merging with newer, modern communication and information technologies (Haag & Anderl, 2018). However, several challenges must be addressed to achieve the full potential of Industry 4.0. These include skill gaps, workforce development (Ruzsa, 2021), lack of maturity in some technologies (Böttjer et al., 2023), complexity and cost of implementation (Timperi et al., 2023), cybersecurity concerns (Borangiu et al., 2020) and ethical and social implementations (Nick et al., 2024). Taking these key factors into priority, industries can explore the industry 4.0 full potential, leading to a higher level of competitiveness, efficiency, sustainability and at the same time contributes to a more resilient ecosystem beneficial for both businesses and society (Moreno et al., 2023). The foundation of Industry 4.0 has been made possible by advancements in information technologies such as the Industrial Internet of Things (IIoT), cloud computing, cyber-physical systems (CPS), and artificial intelligence (AI), which focus on automation and the digitalization of manufacturing operations(Böttjer et al., 2023).

The European Commission has taken a step forward to accelerate digitalization and competitiveness in Industry by creating Industry 5.0 award and also a Community of Practice for Industry 5.0 was launched on 16th of November of 2023 (*Industry 5.0 - European Commission*, 2022). These initiatives are driving the digital transformation of the manufacturing sector, enabling the availability of high-volume data across all devices and levels, including tool sensors, machines, actuators, robots, CAD/CAM systems, and physical networks. Among the tools enhancing productivity and efficiency, Digital Twins (DTs) stand out as an important innovation (Zhou et al., 2018).

Manufacturing digitalization enables complex data systems to become available online and in real-time, perceiving various benefits such as real-time monitoring, simulation, optimization and even accurate forecasting (Ranaboldo et al., 2024). All this capabilities merge together into DTs (Jiang et al., 2021). A Digital Twin is essentially a digital replica of a physical product, process, or service (Schleich et al., 2017). DTs concept consists in three instances: the digital entity; the physical entity and the third one is the communication between both entities (Moreno et al., 2023). Physical entity refers to a process, a product or a system, while the digital entity refers to the digital representation (Möller et al., 2021) (Chávez et al., 2022).

DTs offer numerous benefits, including reducing the cost of prototype production, enabling extreme and destructive testing without the need for physical laboratories, absorbing data from these tests, delivering accurate predictions, and providing real-time monitoring of physical assets (Ruzsa, 2021). These capabilities allow humans to analyse meaningful real-time information, making timely, informed, and efficient decisions that would be impossible without DTs (Sharma et al., 2022).

The EU is actively working to reindustrialize Europe, with DTs playing a fundamental role in this effort. By directly impacting manufacturing sustainability, resilience, and competitiveness, DTs are essential for companies that successfully digitalize their processes and train their workforce, positioning them for success in this new production paradigm(Nour & Arbussà, 2024).

The concept of DTs has evolved significantly since its first application by Vickers and Grieves during the Apollo 13 mission, where it was used primarily for structural mechanics, long-term prediction, and material science in aerospace engineering(Haag & Anderl, 2018). From the 1970s to the present day, various DT concepts have emerged, driven by technological advancements and diverse applications. Today, DTs are utilized across multiple sectors, including healthcare, smart manufacturing, aviation, energy, social media, agriculture, and education.

In the manufacturing sector, DTs are a key component of the digital transformation driven by Industry 4.0 and the Internet of Things (IoT). These technologies enable companies to enhance sustainability, respond to faster customer profile changes, and meet new market demands while addressing ecological and human-centric challenges (Timperi et al., 2023).

IoT also holds significant potential for exploitation. Through IoT, devices can be monitored and managed remotely via network infrastructures, facilitating a seamless integration between physical environments and virtual systems. This integration sets the pace to enhanced efficiency, precision, and economic advantages. Despite being a relatively recent phenomenon, the concept of Industry 4.0 has garnered widespread attention, with its fundamental technologies delineated in existing literature(Gordon et al., 2018),(Negri et al., 2017). As a result, Cyber-Physical Systems (CPS) have emerged as crucial components, representing intelligent embedded and interconnected systems within production frameworks (Negri et al., 2017).

DTs can be found in areas such as Healthcare, Smart Manufacturing, Aviation, Energy sector, Social Media, Agriculture and Education (Warke et al., 2021). As a part of digital transformation that manufacturing industry sector is undergoing since industry 4.0 started, DTs has been, among others, an essential tool to digitalize and provide conditions for industry 5.0 (Negri et al., 2017).

DTs can be used to predict manufacturing misconceptions and enhance processes, it also has benefits such as obtaining real-time data allowing automatic adjustments and process control, resulting in improved productivity and energy efficiency (Kurvinen et al., 2022).

Not only technology, competitiveness and sustainability are impelling manufacturing organizations to adopt and thrive using and implementing new technologies, but also, new European Commission policies such as Industry 5.0 Community of Practice was created to leverage Europe's Industry. European Commission has taken a step forward to speed up the digitalization and competitiveness in Industry by creating a new policy for research and innovation aiming for Industry 5.0. Recognizing the importance of Industry 4.0 as a key driver in economic and societal prosperity, European Commission issued a new approach to improve efficiency, boosting productivity, reinforcing digital and greener transitions. European commission policy initiatives approach industry in 3 main priorities, sustainability, human-centric and resiliency (*Industry 5.0 - European Commission*, 2022).

By researching and analysing the literature exclusively from EU manufacturing industry, a direct and standardized approach is established regarding policies, laws and regulations underlining a structured base to study organizations operating under the same social and economic conditions governed by the same EU legislation.

Since its inception, the Digital Twin concept has evolved significantly, and it began as a simple digital copy of a physical object for testing purposes only. At the time the biggest limitation was the lack of a real-time connection or data stream between the physical object and the virtual copy as the historical example of NASA's use of a virtual copy of Apollo 13 in 1970 (Ruzsa, 2021).

DTs concept has evolved and led to four main types of development stages according to Ruzsa (Ruzsa, 2021). Testing model was the first stage consisting in a digital copy of a physical object used for testing purposes without continuous data flow from the physical object into the digital copy. In the second stage, the surveillance modelling stage, the DTs receives data inputs from the physical object but has no interactive control over it, only acts as a supervisory tool. When the third stage started, was possible to change data between the physical object and the DTs enabling it to control the physical object, it was the Control

Twin-Interactive connection stage. Fourth stage is known as the simulation twin and is possible to provide data to the DTs from the physical object and use it for simulations in the virtual world where circumstances can be manipulated. It allows product development optimization and cost reduction during testing because it is possible to use customer insights and feed it into the design process simulations.

Nowadays Digital Twin concept emphasizes bi-directional data flow between physical and virtual spaces (Layer et al., 2023), enabling real-time updates and feedback for decision-makers to take action based on the information provided by the system (Chávez et al., 2022).

With Industry 4.0 starting as an integrated manufacturing transformation policy-driven by Germany’s high-tech economic strategy in 2011 (Brauner et al., 2022). The use of digital technologies became integrated and fundamentally linked to all kinds of manufacturing companies. Technologies such as cloud computing, Internet of Things (IoT), artificial intelligence, autonomous robots, augmented reality, blockchain were linked to create smart factories (Barata & Kayser, 2023). With these advanced technologies integration a newer concept of DT is being shaped (Ranaboldo et al., 2024), enabling real-time monitoring, analysis, prediction and optimization of processes and physical objects (Borangiu et al., 2020).

Given all the technologies and different development platforms, complex and counterintuitive challenges arose while existing engineering disciplines weren´t sufficient. There are already some examples of newly created disciplines and professions to cope with these new challenges and knowledge. As an example, “Equipment Systems Engineer” was recently created as a profession and obtained development funding from the Irish Higher Education Authority (Gordon et al., 2018).

Adopting and implementing DTs in the European manufacturing industry can present both significant opportunities and complex challenges. DTs have been increasingly recognized and associated for their potential to boost productivity, drive sustainability, enhance operational efficiency, but there are still big challenges to overcome. Barriers such as high implementation costs, skill shortages and technological complexity are contributing for an uneven adoption (Reim et al., 2023). Moreover, DTs are known by their capacity to optimize the use of resources and to support the achievement of environmental goals but still lacks measurable results in real world manufacturing and sustainability contexts. To address such a complex problem a systematic exploration of the factors that influence adoption and implementation, as well as evaluating how DTs are influencing efficiency, productivity and sustainability. At the same time, it is desirable to understand how crucial DTs are for guiding policy, innovation, and investment across European manufacturing sector. This research aims to collect insights in the literature about these complex challenges of DTs in EU manufacturing. Considering how scarce and spread facts are in the literature, this study has the purpose to answer the following questions:

RQ1: What are the key factors influencing the adoption and implementation of DTs in the European manufacturing industry, and how do these technologies contribute to operational efficiency, productivity, and sustainability goals?

RQ2: What are the emerging trends and research directions of DTs within the European manufacturing sector?

To address RQ1 and RQ2, the research is organized into themes: adoption, implementation, efficiency, productivity, and sustainability. This structured approach will provide insights into the complex challenges and opportunities associated with DTs in the EU manufacturing sector, guiding policy, innovation, and investment decisions.

I.2. Methodology

I.2.1. Study Scope

In this study and taking into consideration the complexity and applicability of DTs concept and their various applications, research should be done through a Systematic Literature review.

Nowadays, in manufacturing industry, machine builders and component suppliers are being forced to sell not only physical products but also combining it with services and offering product–service systems (Olivotti et al., 2019).

In business and technology, new data have been increasing, becoming more complex and more volatile, resulting on knowledge production at a tremendous speed but, at the same time it remains scattered, fragmented and interdisciplinary. Thus, making it difficult to keep up with state-of-the-art research and assessing collective evidence in a particular area. This is why literature review has becoming more and more relevant as a research method (Snyder, 2019).

In this research a Systematic Literature Review will be used to better understand and appraise relevant research on how European manufacturing companies are adopting DTs, what are their benefits and challenges. What are the potential DTs advantages to help companies to become more innovative and resilient to deliver efficiently their products in time.

I.2.2. Search Strategy

In this section articles and database selection are the main subjects. DTs is a broad and disperse concept used in multiple manufacturing areas, Web of Science (WOS) database was selected due to its wide coverage of peer-reviewed quality articles of scientific journals in engineering and computer sciences as well as manufacturing. Research was conducted through the European Union official website to retrieve any important piece of information regarding DTs, European companies and any relevant policy documents that might contribute with different insights. As a result, four documents were considered in this SLR.

A systematic review can be explained as a research method and process for identifying and critically appraising relevant research, as well as for collecting and analysing data from said research (Liberati et al., 2009a).

To increase quality, credibility and minimize bias on a SLR, methodology is of paramount importance and PRISMA guidelines were applied. While PRISMA predominantly concentrates on reporting reviews assessing intervention effects, it can also serve as a foundational framework for documenting systematic reviews addressing objectives beyond intervention evaluation (Page et al., 2021).

PRISMA 2020 statement includes the checklists, explanation and elaboration, and flow diagram that replaces PRISMA 2009 statement. The checklist is divided in sections (Title, Abstract, Introduction, Methods, Results, Discussion and other information) and made of 27 questions distributed by the respective sections (Page et al., 2021). A three phase “PRISMA 2020 flow diagram for new systematic reviews which included searches of databases and registers only” was chosen (Page et al., 2021).

I.2.3. Inclusion and exclusion criteria

During extraction and synthesis PRISMA framework was applied and a systematic method was created to perform data screening and in figure 1 the steps made to complete the process are graphically represented.

In identification phase, research was conducted in Web of Science (WoS) database using as keywords “Digital Twins” AND “Manufacturing industry” considered only on “Topics”. Only 2019 and onwards documents were selected justified by possible outdated concepts and facts that might mislead the outcome and the results of the study. Last research was conducted on the 17th of December of 2024. By using the “AND” operator in WoS search engine only the documents with both keywords were selected to reduce the number of documents that were only affected by one of the two keywords, thus becoming not relevant for this study. As a result of using only WoS database there were no duplications in the identification phase and there were 96 documents selected.

Screening phase was conducted in three steps. First step included the retrieval of documents using filters to refine the search, such as, only English written documents were accepted to standardize language and minimize the risk of mistranslations and misinterpretations. Only documents form within the European Union were considered. The second step consisted in retrieving the documents and only full text access was deemed eligible of which 7 were not retrieved. One document was excluded although indexed in 2019, its publication date was 2018. A second document was excluded because the document was in Spanish despite the information in WoS research was in English.

The third step consisted in reading the title, topics, abstract and introduction of all selected documents to assess the relevance to the current study and as a result, 3 were excluded due to lack of content related to study subject. As a result, 35 documents met the eligibility criteria and were included for final analysis.

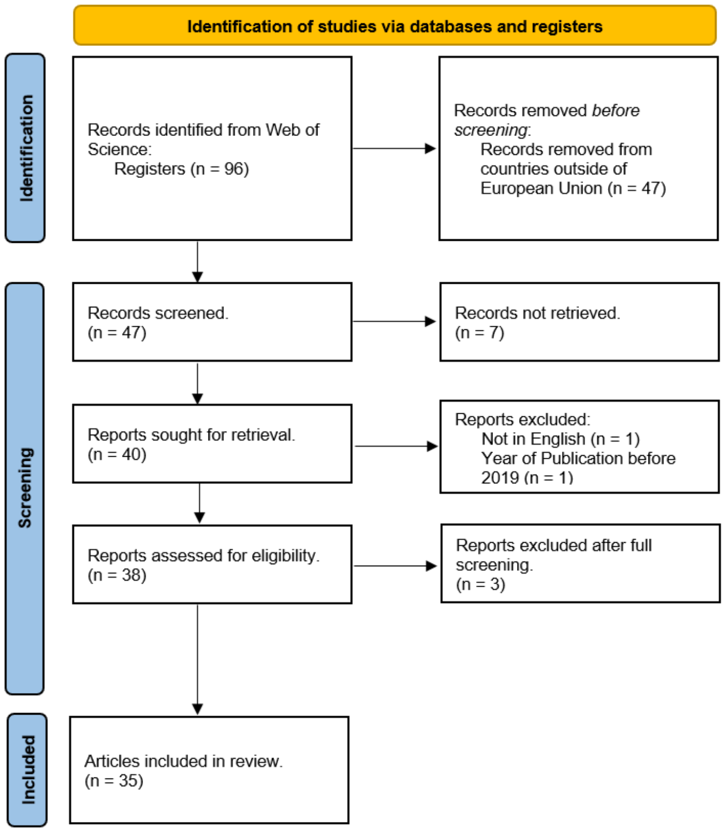

Fig. 1. *Prisma 2020 flow diagram for new systematic reviews (adapted from PRISMA 2020, Page et al. (2021)).*

I.2.4. Descriptive analysis

A descriptive analysis was made to assess the number of published documents and their citations in WoS database. Figure 2 shows the number of publications and their respective citations from 2018 until 2024 for keywords related to digital twin and manufacturing industry. By analysing it, the number of citations and publications have been increasing substantially since 2019 and more abruptly after 2021, this fact indicates how recent and that this topic attention is growing among researchers. Using this quantitative analysis of counting and tracking keywords occurrence in literature proves how substantial and influential this topic is and, at the same time, with this data-driven point of view, it is possible to understand how important and relevant it is for the field of investigation.

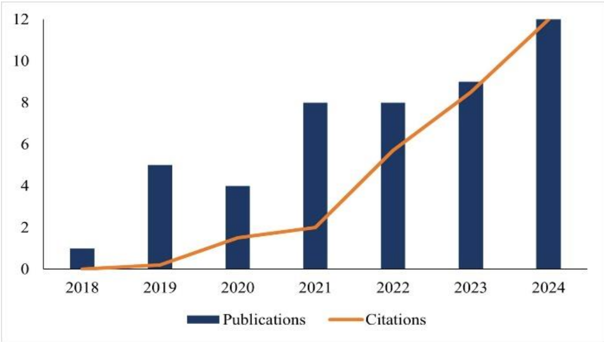

Fig. 2. *Number of published documents and their citations from 2018 to 2024 collected from WoS database.*

Selecting the top five publication document categories given by WoS, figure 3 shows the number of documents published per category. Categories “Engineering Industrial” and “Engineering Manufacturing” have 9 published documents both, followed by “Automation Control Systems”. “Computer Science Interdisciplinary” with 6 published documents each, and “Engineering Electric Electronic” is the last category with 5 published documents.

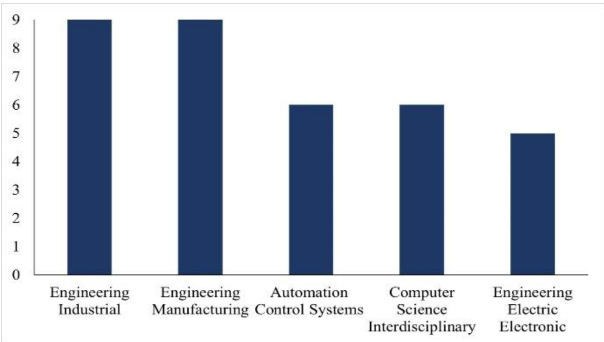

Fig. 3. *Top five fields of document publications from WoS database categories.*

Using VOSviewer software, is possible to create a co-occurrence network of keywords included in the documents selected for the study as displayed in figure 4. The co-occurrence of related keywords is indicated by a link between two nodes in the visualization of the keyword co-occurrence network. The thickness of a link is proportional to the number of articles in which the linked keywords occur, and a node's size is correlated with the quantity of articles that contain the related keyword. Examining the co-occurrence network presented in figure 4 three most common terms associated to DTs are “industry 4.0”, “framework” and “design” with 12, 9 and 7 occurrences, respectively. The main term “Digital Twin” is the biggest node with 21 occurrences making it the central topic.

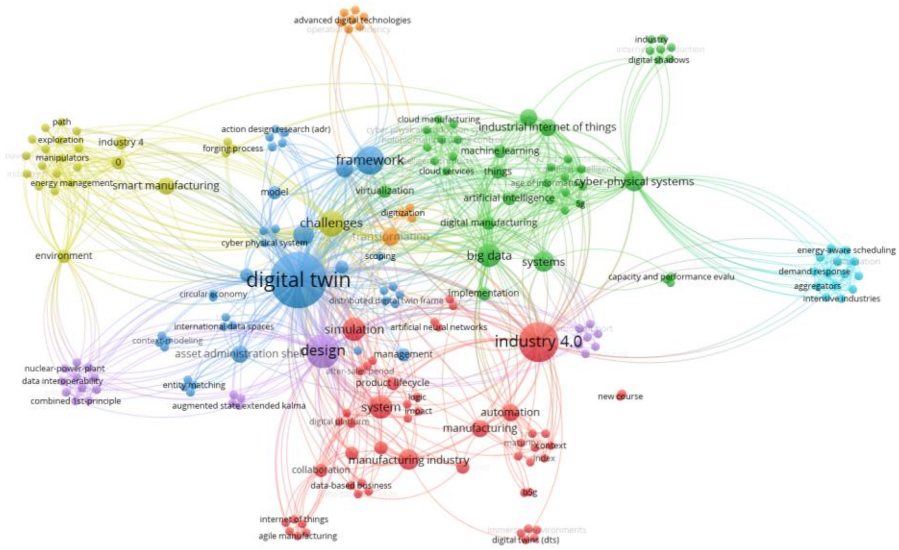

Fig. 4. *Network visualization of keyword co-occurrence of the selected studies using VOSviewer software.*

The descriptive study shows that researchers are becoming more interested in the topic of DTs in European union manufacturing industry, as shown by the rapid increase in research studies and related citations since 2019 and more abruptly after 2021. Engineering Industrial, Engineering Manufacturing, Automation Control Systems, Computer Science Interdisciplinary Applications and Engineering Electric Electronic are among the interdisciplinary domains drawing more attention from research studies and scholars. According to the bibliometric study on DTs in European union manufacturing industry indicates close association with industry 4.0, framework and design.

I.2.5. Thematic analysis

After final screening, 35 documents were eligible for thematic analysis presented in this section with the objective of summarizing the main themes of DTs in European manufacturing industry. Document type, author and year of publication were also considered in this summary. Themes were adopted to synthetise selected documents content to answer the research questions proposed and to provide an overview of how European manufacturing industry is cooping and implementing DTs to achieve competitive advantage by increasing productivity, efficiency and sustainability. The themes considered for this analysis are adoption, implementation, productivity, efficiency, sustainability and future trends as shown in figure 5.

Author	Year	Adoption	Implementation	Productivity	Efficiency	Sustainability	Future trends
Chavez et al.	2022					✓	✓
Ranaboldo et al.	2024	✓	✓	✓			
Brauner et al.	2022	✓	✓	✓	✓		
Morabito et al.	2021	✓	✓	✓			✓
Del real torres et al.	2022			✓			✓
Bottjer et al.	2023	✓	✓				✓
Nick et al.	2024		✓	✓	✓		
Sahlab et al.	2021	✓		✓	✓		
Binder et al.	2021		✓	✓	✓		
Olivotti et al.	2019		✓	✓	✓		
Lermer, m; reich, c.	2019		✓		✓		
Layer et al	2024	✓	✓	✓	✓		
Perno, m.; hvam, l.	2020	✓	✓	✓	✓		
Borangiu et al	2020		✓	✓			
Khalaj et al	2023		✓			✓	
Timperi et al	2024		✓	✓		✓	
Muegge et al	2024					✓	✓
Ruzsa et al	2021	✓	✓				✓
Baldassarre et al	2024	✓	✓		✓		
Nour, s.; arbussa, a.	2024	✓		✓	✓		
Shi et al	2025		✓				
Reim et al	2023	✓	✓				
Tinnes et al	2024	✓	✓				✓
Timperi et al	2023		✓	✓	✓		
Simoes et al	2024	✓	✓	✓	✓		
Zeb et al	2022		✓	✓	✓		
Feng et al	2022		✓				
Moeller et al	2021	✓	✓		✓		
Villalonga et al	2020				✓		
Vrchota, j.; pech, m.	2019		✓				
Moreno et al	2023	✓	✓		✓		
Azevedo, a.; almeida, a. H.	2024						✓
Harjula et al	2021		✓				
Denisa et al	2023		✓				
Ng, a. H. C.; bandaru, s.	2020				✓	✓	✓

Fig. 5. *Overview of relations between authors and themes per document.*

I.3. Results

Results section will present the main results obtained from all eligible documents considered previously. A critical analysis was conducted to identify the main findings to answer the research questions and to find possible future research. DTs are a very complex and broadly used concept, it has correlations to many manufacturing industry areas that make it complex to systematize and to gather concrete information. As a result, a conceptual framework proposal was elaborated to summarize and clarify the findings according to the relevant topics found in literature.

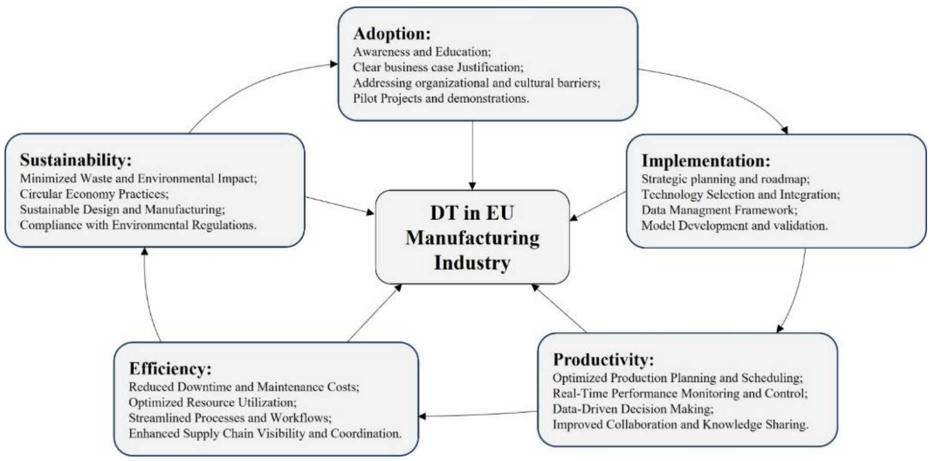

Fig. 6. *Conceptual Framework proposal for enhancing data collection and sharing standardized knowledge across European manufacturing industry sector.*

I.3.1. Adoption

Awareness and education – The widespread acceptance of DTs technology in the manufacturing sector is based on enhancing knowledge of its advantages and possibilities and how it can be used in their operations. Efforts in education, industry events, and examples of successful implementations can show the value of DTs and help clarify common misconceptions in real applications.

Business case justification – There is a need to establish clear business case for organizations that demonstrates the return on investment (ROI) for DTs implementation. To do so, they must identify specific pain points, quantifying potential benefits (e.g., cost savings, productivity gains), and compare the implementation costs against the expected returns. DTs adoption should be strategically aligned with business strategy.

Organizational and cultural barriers – The success of adoption often implies changes to organizational structures, workflows, and decision-making processes. It is fundamental to encourage a data-driven culture, open to adopt innovation and collaboration across different departments. A culture of innovation is essential for successful implementation, backed up by a strong leadership.

Pilot projects and demonstrations – Starting with smaller pilot projects focusing on specific use cases can be a starting point to help organizations gain practical experience, demonstrate feasibility, and build internal support for wider adoption. These pilot projects can also provide valuable insights for refining the implementation strategy. Moreover, organizations should invest to develop skills and knowledge for DTs adoption.

I.3.2. Implementation

Strategic planning and roadmap – It are of critical importance to elaborate a comprehensive plan outlining goals, objectives, timelines, resource allocation, and key performance indicators (KPIs) for a successful implementation. This roadmap should be aligned with the organization's overall digital transformation strategy, determine all stakeholders involved and their specific requirements.

Technology selection and integration – Choosing the most suitable technologies is essential for a successful implementation depending on the organization’s workforce skill limitations and asset limitations to technological improvements and integration possibilities.

Data management framework – Data management is both critical and essential, establishing a robust data management framework is of paramount importance and it should enclose data acquisition, storage, processing, quality control, security, and governance. With this framework, organizations be able to address the challenges of handling large volumes of data, different data formats, and ensuring data integrity.

Model development and validation – Developing accurate and reliable models that represent the physical twin's behaviour is critical for the DTs effectiveness. Model validation using real-world data and continuous improvement through machine learning techniques are necessary to maintain model fidelity. Modelling scope is essential to define the level of detail and accuracy of the DTs, they are not static models, instead they require continuous updates and new datasets from physical world. Most of the times, implementing a DTs means integrating it in existing models or multiple models and combining these models may provide extensive and broad representation of the respective physical system. Validated models can provide real-time data connecting, simulation and testing, performance metrics and iterative refinement.

DTs implementation poses a wide range of challenges and barriers covering technical, organizational, economic and collaborative aspects.

Technical challenges like the lack of modelling standardization and data fusion techniques undermine interoperability and comparability between DTs implementations. Data management for large volumes of data from different sources can lead to difficulties in data collection, storage and real-time processing. Creation of accurate and comprehensive models is difficult and, realistically, models tend to be a simplification of the real asset, decreasing accuracy and data quality. Interoperability achievement between different domains is a big challenge across various applications, making DTs integration more difficult. Integrating DTs in existing legacy systems can be costly, complex and could result in separated environments. To make this large volume of data available in real-time, significant computational resources and infrastructure are require, making it another challenge to overcome.

Organizational and collaborative challenges can pose threats from different backgrounds including data sharing between several stakeholders and data sharing is a sensitive subject and organizational structures involved may be reluctant contributing to incomplete DTs models. There are several specific challenges to collaboration, dependency issues, lack of documentation and unsuitable payment models ending in a decrease of influential actors that may become dependent on others, creation of platform providers dependency and payment can become less attractive for some stakeholders.

Organizational readiness is required for successfully deploy DTs, organizations lack on technology, suitable planning and resources.

Economical and business challenges can also be determinant, high development costs can directly impact in their final cost-effectiveness leverage. Return of investment need to be carefully considered, despite DTs potential benefits, business viability can be threatened by high implementation costs. Develop an entire factory floor DTs can present scalability challenges typical for large case scenarios. Hour-based payment makes competitiveness difficult and may not be suitable for DTs implementation.

Other important barriers to consider are data security and data ownership, lack of physical fidelity, limited real-world testing and structured data transition.

Facing these challenges imply data management, a robust strategy for standardization, collaboration, and investment. A clear understanding of the specific use cases and requirements of the manufacturing environment must be taken into consideration.

I.3.3. Productivity

Optimized Production Planning and Scheduling – DTs enable the simulation and optimization of production schedules, considering real-time data on machine availability, material flow, and potential disruptions. This leads to improved production planning, minimize maintenance, reduced lead times, and increased overall productivity. DTs leverage enhanced process efficiency allowing organizations to respond quicker to customer demands, adjust production standards, increasing flexibility and agility. Design changes can be made in a risk-free virtual environment reducing the need for physical testing.

Monitor and control real-time performance – By continuously monitoring physical twin's performance through the DTs, allows real-time adjustments to process parameters, resource allocation, and production sequences. This helps maintaining optimal operating conditions, minimize downtime, and improve overall output, enabling real-time optimization. Virtual commissioning is also possible allowing to test and validate new processes before being implemented.

Data-driven decision making – DTs are seen as a decision support tool by generating insights of the system behaviour, performance and potential issues based. This way, stakeholders can make more informed decisions related to process optimization, capacity planning, quality control, and maintenance scheduling. This data-driven approach leads to better informed and more timely adjusted decisions, resulting in increased productivity and profitability.

Improved collaboration and knowledge sharing – Collaboration between different teams, such as, design, engineering, production, and maintenance can be improved by providing a shared platform for communication, data visualization and analysis. As a result, knowledge sharing is encouraged, reduces communication barriers, and leads to better problem solving and decision making. With data being shared, training and education of operators can be leveraged, leading to a higher skill level in manufacturing workforce.

Summarizing, DTs have a profound impact in manufacturing through enabling real-time monitoring, enhanced decision making and predictive maintenance, as a result, manufacturers can reduce costs, optimize processes, improve product quality and increase operational efficiency.

I.3.4. Efficiency

Reduced downtime and maintenance costs – Predictive maintenance, enabled by DTs allows a proactive identification of potential failures and optimize maintenance scheduling, hence, minimizes unexpected downtime which is the main source of inefficiency in manufacturing and reduces associated costs, optimize resource allocation and potentiates minimum levels of maintenance for maximizing equipment availability.

Optimized resource utilization – DTs can help optimize the use of energy, materials, and other resources, they contribute with data for more sustainable consumption patterns, identifying areas for improvement, and simulating the impact of different operating scenarios. DTs can improve quality control in real-time directly from the production process, helping identify potential issues reducing waste created by defective products. This leads to reduced operational costs and continuous improvement in resource efficiency.

Simplified processes and workflows – Automation of some tasks and decision-making processes can be provided by DTs, reducing human interventions and eliminate redundant, repetitive or unnecessary workflows. Consequently, organizations can improve their processes efficiency, reduce human error and reduce turnaround time.

Enhanced supply chain visibility and coordination: DTs can be implemented with supply chain management systems to produce real-time visibility into the status of orders, inventory levels, and logistics operations. This improved transparency improves overall supply chain efficiency, enables better coordination and reduces delays.

I.3.5. Sustainability

Waste and Environmental Impact – Minimizing waste generation, reducing energy consumption, lower emissions lead to production process optimization with DTs. Triggering a more sustainable manufacturing operation and lowers environmental footprint.

Circular Economy Practices – With data enabling a better product lifecycle management, DTs can support circular economy principles facilitating reuse and recycling and the optimization of end-of-life disposal processes.

Sustainable Design and Manufacturing – DTs can be used in the product design phase to simulate and evaluate the environmental impact of materials, manufacturing processes, and product configurations. Contributing to more sustainable choices for an eco-friendlier product lifecycle.

Environmental Regulations Compliance – Tracking and monitoring organization's environmental performance against regulatory requirements can be done through DTs ensuring compliance and reducing reputation damage and penalty risk.

I.4. Discussion and findings

I.4.1. Answers to research questions

Since 2019 DTs publications and citations grown considerably specially after 2021. Although DTs are being implemented across various manufacturing industries, they are technology dependant and industry specific key factors must be considered for their successful implementation. This research analysed 35 studies, and the results were identified as a thematic framework to better understand and segregate how DTs contribute for adoption and implementation in EU manufacturing industries.

Recent growth in research and publications in manufacturing is also seen in electronic and computer communities, especially in applications related to AI modelling DTs. Assuming a leading role, Manufacturing and Industrial Engineering are the impelling force of DTs adoption and implementation, while Automation control Systems, Computer Science and electric/electronic engineering are the enablers for a successful DTs implementation, use and interaction with different stakeholders. Several studies suggest that the development and use of standardized frameworks regardless of manufacturing areas help identifying stakeholders, facilitate implementation and standardize DTs application areas. In European manufacturing industry, knowledge is fragmented due to regulatory differences, different adoption rates, sector-specific advances and factories dimension.

Documents based in empirical studies suggest DTs implementation can improve operational efficiency, productivity and leverage conditions to achieve sustainability goals, competitive advantage and resiliency. The development of DTs should be data driven, focusing on real-time applications and simulation modules to improve flexibility and adaptability to enhance competitiveness and sustainability. This contributes to an improved decision making and monitoring efficiency, via remote diagnostics, reducing errors and failures. The organization reduces operational costs and improves capacity to deal with larger customers. Product life cycle data can lead to a strategic circular economy implementation throughout the entire product life cycle, helping manufacturing industries becoming more eco-friendly and optimizing resources to contribute to a more energy consumption efficiency.

Research to compare the state of DTs adoption and implementation in Europe with other continents or economic areas might be useful to understand how DTs are being used and investigate their benefits. The organization's dimension is also an area of interest because costs, standardization and regulatory compliance may change according to manufacturing areas or economic areas and directly influence DTs adoption decision to pursue a data driven manufacturing. Emerging topics such as circular economy or sustainable practices, are gaining recognition among professional and academia, becoming a fundamental tool for analysing product lifecycle data and organization's competitiveness.

I.4.2. Limitations

The use of a single database to search and screen studies can be a limitation of present research, since other databases might have studies that could contribute with more knowledge and empirical data. Although the analysis was carried out through full reading of each article, flaws may be present due to language subjectivity and researcher background. Given that current research was made only in a European context, lacks other economic areas point of view and state-of-the-art for DTs applications and studies, comparative studies can provide new insights. As technology advances, so does frameworks and manufacturing to stay competitive, making this research relevant for a short period.

Synthesizing, future research should focus on cost reduction strategies, workforce training to maximize benefits and standardization.

I.5. Conclusions

The existing scientific literature is still very dispersed and case specific, this literature review proposes an initial framework to gather and standardize DTs information to guide subsequential studies in both empirical and scientific studies, aiming for newer and broader adoption and implementation standards creation.

The adoption and implementation of DTs provide substantial advantages for improving productivity, process optimization, predictive maintenance efficiency and sustainability efforts. The complexity of the concept, technology used and range of application raised several challenges. The systematic review of the selected literature culminated in a framework to organize literature context in five themes, adoption, implementation, productivity, efficiency and sustainability. Both theoretical and practical findings focus on the same conclusion that DTs are transformative for European manufacturing industry as a hole, despite financial constraints, technological and regulatory challenges, DTs are the driver of efficiency, productivity and sustainability for European manufacturing industries.

As a conclusion, the adoption and implementation of DTs in European manufacturing industry is limited by several factors, data-related challenges, technological barriers, collaboration issues, economic factors and early stage of market development. By adequately tackling these issues through secure data practices, standardization, collaboration, reskilling, additional study and development, could unleash full potential of DTs in manufacturing. Utilizing full potential of DTs, European manufacturing can leverage productivity, efficiency and competitiveness, involving both theoretical and practical approaches resulting in a more resilient Europe bringing policy makers and manufacturers closer together.

CHAPTER II

Industry 5.0: Towards a competitive European Union manufacturing sector

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Abstract. Emerging economies and technological powerhouses have been increasing its competitiveness alongside the European Union (EU) manufacturing sector. Research into Industry 5.0 (I5.0) concept is crucial and considered the next challenge EU will embrace to regain its competitive edge, ensuring its manufacturing sector remains globally relevant, innovative and sustainable. Industry 4.0 (I4.0) represented an automation centered paradigm that has now changed with I5.0 to a human centered approach. Being more productive, focusing on sustainability and societal consciousness is the primary focus of I5.0 specifically highlighting Human-Machine Collaboration (HMC), Artificial Intelligence (AI), Robotics, and Internet of Things (IoT). I5.0 concept aligns with EU's sustainable and greener future, focused on circular economy, efficiency and sustainability, while remaining competitive. Research can provide new insights on how to improve the use of emerging technologies to satisfy new customer demand for personalized products, leveraging the creation of highly skilled jobs, stimulating economic growth to establish long term prosperity. Researching on I5.0 is a technological need and a strategic necessity for the EU to claim manufacturing leadership. This paper aims to bring a new perspective that will use a meta-review as a research strategy. First, we will conduct a review using the term "Industry 5.0" in Elsevier Scopus, identifying knowledge gaps and future research suggestions. Following, we will explore the EU perspective on I5.0 and its industrial policies, presenting new taxonomies organize the concept and consolidate evidence on its impacts on productivity, employment and sustainability.

Keywords: *Industry5.0; Manufacturing Industry; Competitiveness; European Commission.*

II.1. Introduction

Since the beginning of the fourth industrial revolution the transformation and innovation of technology in manufacturing processes have witnessed a growing complexity in many areas, such as, technological (Mourtzis et al., 2022), organizational (Zizic et al., 2022), logistical (Mourtzis et al., 2022), and environmental (Alves et al., 2023), (Mhatre et al., 2021). Technology created more complex networks and data records to secure and manage (Mourtzis et al., 2022), at the same time, industries became more decentralized (Zizic et al., 2022), delegating decision-making to lower-level managers revealing the need for a shift in organizational models (Zhang et al., 2023). Logistics also went through a pivotal transformation with an increased complexity, introduced by machine interconnectivity, storage systems and supply chain management (Mourtzis et al., 2022), (Leng, Zhu, et al., 2024).

These transformations also introduced some concerns, leading organizations to consider environmental and social criteria to adopt new technologies (Zhang et al., 2023), (Leng, Zhu, et al., 2024), particularly with higher energy demand, provoked by new technology implementation (Zizic et al., 2022). In I4.0 implementation, engineers and organizations were focusing their efforts in the evolution of manufacture and production systems towards innovation and through technologies (Alves et al., 2023). Among I4.0 technologies, sources highlights the most impactful ones, including IoT (Alves et al., 2023), cloud computing allied to AI, to assist and implement Cyber-Physical Systems (CPS) (Zizic et al., 2022), Digital Twins (DT) (Mourtzis et al., 2022), Augmented Reality (AR) (Zhang et al., 2023) and autonomous robots (Zizic et al., 2022). Previous mentioned technologies offered a wide range of opportunities and advances but, there were still limitations. Engineers sole focus on technology were no longer competitive and I5.0 presented an holistic approach, seeking to integrate human-centric technology focus, driving innovation and encouraging a more sustainable and equitable industry system boosting EU economy (Mourtzis et al., 2022).

I5.0 supposedly supersedes I4.0, changing the engineering paradigm focus from human-machine interactions and organizations strategy to a new digitalized decision-making process (Pereira & dos Santos, 2023). With I5.0, humans and machines are required to collaborate, boosting productivity of manufacturing industry, making digitalization and smart manufacturing a reality (Adel, 2022).

Moreover, academic researchers contribute with essential knowledge through their analyses and concept architectures, enabling technologies to shape the body of knowledge around I5.0 principles, making it crucial for a transformative EU manufacturing competitive sector (Zhang et al., 2023). In EU countries, I5.0 concept is setting the benchmark for a responsible and sustainable transformation, maintaining manufacturing industry's key role in EU economy (Matthews et al., 2021).

EU manufacturing sector is known as a fundamental driver for economic growth and resiliency composed by 2 152 042 enterprises, employing 30 026 436 workers registered in the detailed European Community Standard Classification of Industrial Activity (NACE). Contributing to one-quarter of the EU's business economy with a net turnover of 9 785 619 million euros in 2023 (*Statistics | Eurostat*, n.d.). According to Eurostat (Eurostat, 2025), manufacturing was the biggest NACE section contributing to employment with 18,7% share, becoming the major contributor to business economy value added with 24.1% share (Eurostat, 2025). Recognizing its economic contribution, EU proposed I5.0 to achieve a resilient European industry, approaching workers requirements, preferences and interests, as the centre of manufacturing processes, as a path to circular processes development and to resource recycling. Moreover, I5.0 adoption introduces a societal paradigm shift capable of achieving a higher resource efficiency, reducing environmental impact and waste generating, leading to a more conscious society capable of generating new circular economy loops (Leng, Zhu, et al., 2024). Ambitious strategies are being adopted to accomplish it, the Circular Economy Action Plan or the European Green Deal are examples of policies aiming to transform EU economy, emphasizing reuse, recycling, waste reduction and sustainable products promotion (Cifuentes-Faura, 2022).

Given the dynamics of I5.0, a synthesis overview of existing research is critical to understand its potential contribution to EU manufacturing competitiveness. This meta-review objective is to systematically analyse and synthesize findings of relevant studies, identify key themes and highlight research gaps to provide an overview of the current state of knowledge.

This study seeks to inform researchers, industry leaders and policymakers on the following research question: What are the key thematic areas in I5.0 core tenets contributions towards a competitive EU manufacturing sector?

The following section will shed some light on I5.0 concept, contextualization and its relevant related terms, followed by an explained PRISMA selection process and data collection explanation and analysis.

II.2. Conceptual overview

The expression "Industry 5.0" was first used in 2016, associating I5.0 with the emergence of disruptive technologies, as an example, bionics or synthetic biology (Coelho et al., 2023) and Michael Rada (Mourtzis et al., 2022) is particularly linked as a founder and leader of I5.0 organization (Madsen et al., 2023). I5.0 is considered the newest industrial paradigm with the objective of complementing I4.0 limitations. I4.0 focussed on technological evolution and industrial flexibility (Zizic et al., 2022), while I5.0 complements it by prioritizing research and innovation to aid and enable a transition to a sustainable, human-centric and resilient industry (Zhang et al., 2023). Technology is of paramount importance for I5.0 involving, AI, autonomous manufacturing and human intelligence, as cornerstones, leveraging collaboration between humans and machines, increasing the innovative solutions, the human potential and machinery accuracy with the use of DT, cybersecure data analysis and bio-inspired technologies (Mourtzis et al., 2022).

Literature focus on three fundamental aspects to define I5.0, Human-centricity, Sustainability and Resilience.

I5.0 literature highlights human-centricity as a core principle, placing human needs and interests at the centre of production processes, driven by Human-Machine Interaction (HMInt) to enhance efficiency, improved quality and cost reduction in production processes [1], [2]. The human-centric design solution allows the creation of shared working environments with adaptable and flexible technologies capable of fostering talent, diversity and empowerment to retain talent and leverage competitiveness (Mourtzis et al., 2022).

Sustainability emphasizes sustainable development by reusing natural resources, reducing waste and environmental impact as a path to create new loops of circular economy improving resource efficiency (Leng, Zhu, et al., 2024). It is also expected that manufacturing industry can adjust current resources requirements in order to develop sustainable systems that runs on renewable energy (Adel, 2022).

Resiliency is the ability to persevere through disruptions and catastrophic events and build robust and adaptable systems capable of recovering quickly and with the ability to proactively respond to challenges (Leng, Zhu, et al., 2024). In order to maintain employment rates and financial stability, I5.0 is accomplishing it by increasing responsiveness of the manufacturing system and strengthen resilience of value chains (Mourtzis et al., 2022).

With every industrial revolution, a societal transformation was inherited and in turn, I5.0 is reshaping the working and living standards in a way that concepts like Society 5.0 and Government 5.0 (G5.0) are gathering more attention from researchers and company owners. The society 5.0 is a new societal transformation caused by I5.0 focused on social economy to create a people-centric and super-smart society (Alves et al., 2023). According to Mourtzis et al. (Mourtzis et al., 2022), some authors describe it as a futuristic super-smart society where individuals can comfortably live with high quality of life brought by the fusion of both cyberspace and physical space. The EU sees I5.0 as an evolution of I4.0, integrating a broader vision, benefiting a wider range of stakeholders, surpassing the shareholder value to embrace a regenerative purpose, ranging all individuals in a given society (Mourtzis et al., 2022).

To ensure a completely fulfilled transition to I5.0, governments are considered a fundamental stakeholder and are required to rapidly evolve their roles. A crucial change in how public sector operates and interacts with citizens, industries and other stackholders is needed. G5.0 is about creating a strategic aligned, more agile and collaborative public sector capable and balanced to cope with the ambitious goals of I5.0 for the people, the planet and for prosperity (Commission, 2022).

Political and international organization's initiatives also marked and boosted industrial revolutions, I5.0 is no different. European Commission (EC), United Nations Environment Programme, World Economic Forum and Green Economic Conferences are creating events to evolve to a greener society and greener economy. Supported by strategies and laws, they incentivise organizations and governments to adopt newer and greener technologies to boost circular economy, sustainable development, prioritizing social value instead of economic value. Some examples in EU are the presentation of the European Green Deal in 2019, the adoption of the European Industrial Strategy in 2020 and climate target plan for 2030 in 2021 (Hlushchenko et al., 2023). In March of 2020 the EC release a framework document named "A New Industrial Strategy for Europe" concerning the guidelines for European industry to remain an industry powerhouse, leading both ecological and digital transitions, driving competitiveness through innovation and adaptation (Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions A New Industrial Strategy for Europe, 2020).

To successfully transition to I5.0, governments within the EU must update and innovate in public policy, interactions between governments and industry should be improved and G5.0 is needed. The adopted strategy is centred in an imperative commitment from all EU member states and industry to accomplish the desired industrial transformation (Commission, 2022). There are some initiatives created by the EU to persuade and attract manufacturing organizations to innovate and become competitive, such as the "Industry of the future award" (*Industry of the Future Award 2022*, n.d.) or the creation of the European Innovation Council Work Programme in 2024, presenting funding opportunities worth over 1200 million Euros for scaling up companies or investments in strategic technologies mainly dedicated to Small and Medium Enterprises (SMEs), or selected start-ups operating on predefined game-changing innovations with major impact on EU future objectives (*EIC Accelerator Challenges - European Commission*, n.d.).

II.3. Materials and methods

Following a meta-review approach, this chapter contains and explains the materials and methods used to study the existing body of knowledge produced by the researchers and synthesize it carefully. Meta-reviews are known and widely accepted, considered as the strongest level of evidence in research papers and capable of gathering significant literature to contribute to research, practice and policies (Hennessy et al., 2019). A methodology was followed according to guidelines from Preferred Reporting Items for Systematic Reviews (PRISMA), supporting the meta-review with a structured, rigorous and transparent strategy to find concepts and new approaches. It also includes PRISMA's 27 item checklist and a three phase flowchart enabling the extraction and synthesis of data from several peer-reviewed literature databases (Liberati et al., 2009b).

A primary search for meta-reviews in Web of Science (WoS) database was conducted on the 13rd of February 2025, with no results found, using "Industry5.0" OR "I5.0" AND "manufacturing industry" AND "Europe" OR "European Union" AND "competitiveness"

AND “meta-review” only on topics (subject area, keywords and abstract). The search yielded 9 documents, but none of them was a meta-review. Considering this research was conducted in one of the most significant international databases and taking into consideration the importance and exponential growth in I5.0 research, this study may be considered innovative and original. Accordingly, on the 1st of March of 2025 research was conducted in WoS Core Collection database using the terms “Industry 5.0” AND “Manufacturing Industry” AND “competitiveness” AND “systematic Review” in the title, abstract and indexing (Topic) to find subject related documents (identification phase). Secondly, pre filters were applied to strict and condensate the most relevant documents such as, language, document type, year of publication, and Countries/Regions (screening phase). The third and last phase comprises all included articles for review after a thorough analysis on each of the selected articles to exclude any not related to topic or out of scope, identified as inclusion phase. With the sole purpose of broaden, justifying and reinforce some arguments in the following sections, additional articles were included in the study, such as, highly cited articles and regulatory/policy articles. Although the search was conducted only o WoS, WoS and Scopus, are considered to be the largest and multidisciplinary international databases of peer-reviewed manuscripts (Pranckutė, 2021), therefore, a significant coverage of peer-reviewed literature is analysed in present study corroborating it´s relevancy.

As mentioned before, the search was conducted in March of 2025 using the key words “Industry 5.0” AND “Manufacturing Industry” AND “competitiveness” AND “systematic Review” in topic and 108 documents were identified. During screening phase, filters were applied, only English documents were accepted to reduce bias and misinterpretation, time frame was set between 2021 and 2025, since this thematic is rapidly evolving due to technology advancements and lastly, only documents from within EU countries were selected to maintain the same regulatory and policy restrictions, reducing data misleads and bias due to different regulations or policies in manufacturing industry sectors. From these filtering restrictions, 12 documents were not EU related and therefore eliminated and 6 documents were not fully accessible. Finally, all remaining documents were examined by reading the title, abstract and introduction to assess their relevancy to this study. From this analysis 61 documents were considered as not relevant or out of scope and consequently excluded. In addition, 4 grey literature documents including reports and policy documents selected from international organizations were also included, resulting in 33 included articles. To maintain scientific relevancy, PRISMA protocol was followed and the process of identifying, screening and including articles followed the PRISMA guidelines, presented in figure 1.

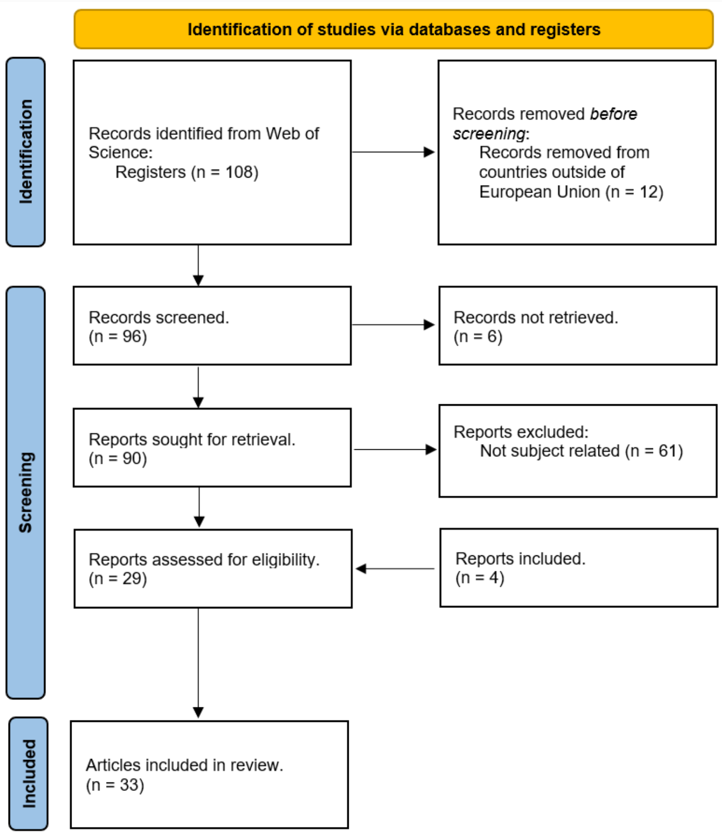

Fig. 7. *Prisma 2020 flow diagram for new systematic reviews(adapted from PRISMA 2020, Page et al. (2021)).*

Although Meta-review methodology offers many advantages, it has also limitations such as, filter application, researchers interpretation subjectivity and database search and selection may lead to exclusion of relevant studies. To minimize these limitations, PRISMA guidelines offers a unique possibility over traditional systematic reviews, it allows the inclusion of relevant articles not considered in primary research, mitigating some limitations previously considered. Present study is compared to a “snapshot” of the present reality regarding it´s relevancy ad longevity due to constant database update, led by new research and technology innovations. The next chapter will present and systematize the content from included documents to provide an insightful and pragmatic view of the literature.

II.4. Results and discussion

This section's objective is to address the key areas for the meta-review and provide a comprehensive and insightful analysis of how Industry 5.0 contributes to a competitive EU manufacturing sector through clear identification of the most relevant thematic areas, supported by WoS database analysis tools. Moreover, WoS provides a curated citation index, enhancing a reliable measure for scholar impact (Visser et al., 2021).

As shown in figure 2, from all 29 articles included for analysis from WoS, the number of citations has been increasing. The observed decrease in publications for the current year should have a cautious interpretation, as research in this field is dynamic, and the year's data at the time this research was conducted was incomplete (March 2025). A significant time frame must be considered for manuscript preparation, peer review, and publication, moreover, considering the topic relevancy at the present time, a significant proportion of research conducted within the current year has yet to be formally published.

In figure 2 it is possible to observe citations increase, specially from 2023 with 186 citations to 2024 with 553 citations, indicating I5.0 is an impactful and relevant key research subject.

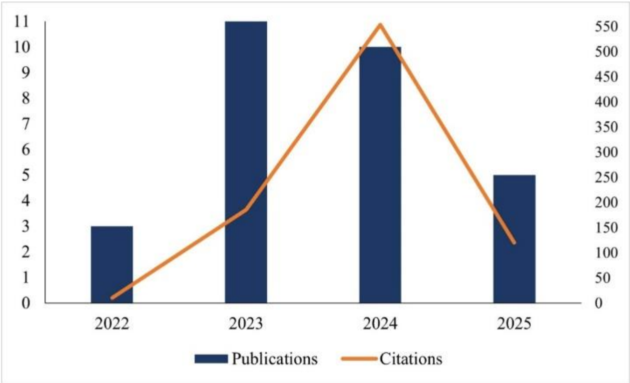

Fig. 8. *Graphical representation of Citations/Publications produced by WoS included articles*

The selected sources yielded 29,59 citations per document on average and if all 2025 documents were excluded for average citations analysis purposes, that number rises to 35,91 citations per document on average according to WoS analysis tools, excluding self-citations. Analysing data through WoS Analysis report, the top five categories are presented in figure 3. They are respectively Engineering Industrial, Engineering Manufacturing, Operations Research Management Science, Engineering Electrical Electronic and Chemistry Analytical, these results demonstrate how relevant research is in industrial and manufacturing categories regarding I5.0. At the same time these categories are connected over the industrial and manufacturing sectors of activity throughout EU, widening the study reach.

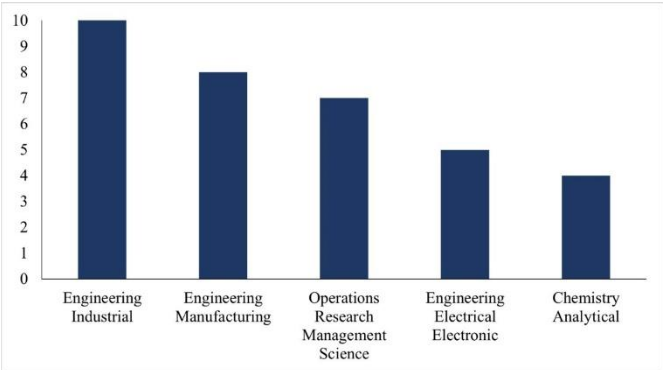

Fig. 9. *Top five WoS Categories*

Utilizing this quantitative analysis, with a data-driven point-of-view is possible to understand the importance and relevancy of the study and how it might contribute to future research and investigation. Therefore, and to accomplish predetermined goals, a thematic analysis was created to synthetise knowledge, simplify and present pragmatic results to ease the readers understanding. By organizing the results in themes, several areas were created to organize data within each theme, although, filtering the content of selected documents may indicate the separation of each theme, they generally interconnect and complement, making it very hard to define the reach of every document.

II.4.1. Theme 1 – Driving competitiveness in Industry 5.0 through a Human-Centric approach:

A Human-Centric approach is defined by several principles leading to innovative interfaces, opportunities and challenges directly impacting European Union Manufacturing and industrial competitiveness (Castagnoli et al., 2024).

To achieve this new I5.0 paradigm, a profound shift in focus is required, contrarily to I4.0, I5.0 focus fundamentally on human needs and interests as the forefront of production processes. It changes from technology driven progress to what can technology do for humans (Zizic et al., 2022). This new principle enhances human capabilities, rather than replacing workers for new technologies. These new technologies are being developed to enhance human skills and promote quality of life in industrial settings (Bucci et al., 2025), resulting in a human-automation symbiosis witch starts the transition from Operator 4.0 to Operator 5.0 (Krupas et al., 2024).

Prioritizing health, safety and worker well-being by creating a safer, sustainable and more fulfilling work environment is a core belief (Alves et al., 2023), addressing psychosocial and mental aspects while reducing ergonomic risks and physical strain is also considered crucial as a way forward into I5.0. Interactive innovative technology leverages the empowerment humans and industrial operators and it is deemed crucial to optimize and enhance creativity, individual skills, competencies and innovation (Alves et al., 2023). To achieve it, workers must understand and develop abilities using assisted digital systems (Ciccarelli et al., 2023). Human intelligence, talent and subjectivity must be recognized by joining together human cognitive and emotional capabilities with AI, precision and effectiveness using creativity, empathy and ethical judgment (Nazarejova et al., 2024). Although technology is gaining relevance, the ultimate and final decision will be taken by a human and so, the operator remains at the core of manufacturing process/system, hence, industries must address human-centred and human-sustainable production approach (Ciccarelli et al., 2023).

Human-Centred approach is directly related to technology and the interface between humans and machines, it allows seamless cooperation between humans and machines, considering that humans and robotics characteristics equally (Ciccarelli et al., 2023). DT are considered a pivotal technology to I5.0 transition, it empowers humans through intuitive interfaces that lead to process optimization and informed decision-making (Bucci et al., 2025). Complementing, wearable sensors and CPS are also seen as key enablers, providing intelligent personal digital assistants capable of responding to operators physiological or cognitive states (Nazarejova et al., 2024). CPS are being developed to enhance reciprocal relations between humans and AI (Valette et al., 2023), while AR and Virtual Reality (VR) are cornerstone technologies with the potential to dynamically integrate humans in production systems in real-time to enhance human and robotics cognitive capabilities (Gladysz et al., 2023). VR is of special significance when in use for training in simulated environments due to its significant cost reduction and resources utilization (Zeb et al., 2022).

With new and innovative technologies employed in I5.0, several challenges arise and have been identified by the researchers, among them the lack of investigation in management through a human-centred approach, it is only addressed ergonomically by engineering. Workers privacy protection and the difficulties in workers accepting cognitive-value of technology is also reported by Castagnoli et al. (Castagnoli et al., 2024). New technology implies reskilling and/or upskilling of the workforce to effectively collaborate with new technologies (Zafar et al., 2024) and virtual training (Zeb et al., 2022), to achieve it, redesigning workspaces and processes ensuring safety, aligning it to human capabilities are in great need (Krupas et al., 2024). Alongside with human-centric development metrics based on human needs, performance, efficiency, health, ergonomics, security and satisfaction (Castagnoli et al., 2024). Authors also highlighted technology specific challenges, such as, low consideration of human factor in the design and implementation of CPS (Ciccarelli et al., 2023), the absence of standardized methods assessing human factors in VR experiences within I5.0 applications (Escallada et al., 2025) and the existence of human DT frameworks are still deficient regarding the operationalization of their practical methodologies (Bucci et al., 2025)**.**

The above mentioned authors also emphasise new opportunities created by I5.0 approach, for example, improving workers well-being and satisfaction leading to a more fulfilling, safer and less stressful work environment (Ahmed Murtaza et al., 2024), or enhanced human performance and productivity leading to an increased performance and overall productivity (Nazarejova et al., 2024). When human-centric aspects are implemented, companies are equipped to respond to global challenges and sudden or abrupt changes such as pandemics, economic crises or changes in internal business models (Castagnoli et al., 2024). Alves et al. (Alves et al., 2023) underlines that, in order to increase production processes efficiency, it is necessary to empower workers and involve them in innovation and process design to stimulate and harvest their creativity and knowledge. Furthermore, I5.0 could generate more employment opportunities, including workers with disabilities, by developing smart and adaptative workstations (Bonello et al., 2024), or new role development to address new technology challenges. New roles and positions may also be created, caused by the increase in HMC, Chief Robotic Officer is a newly created role to cope with increased robotic use and relevancy (Zeb et al., 2022).

Lastly, to complete a proper and complete human-centred approach according to the literature, it is necessary to respect fundamental human rights, ensuring human dignity, workers' rights, such as, privacy or autonomy in a way that new technologies cannot interfere with (Pranckutė, 2021; Zafar et al., 2024).

In general, the above authors stress that human-centric principles of I5.0 must be fulfilled by prioritizing the needs, well-being and capabilities of human workforce in collaboration with innovative technologies available in manufacturing and other industries to enhance performance, innovation, sustainability, resiliency, and intrinsically, competitiveness.

II.4.2. Theme 2: Sustainability as a Competitive Imperative in Industry 5.0 Manufacturing

Sustainability marks a paradigm shift of I5.0, compared to the technology and productivity driven I4.0, is considered to be a pivotal imperative in I5.0 manufacturing (Madsen et al., 2023). Multiple sources refer to I5.0 as the way to integrate human-centricity, resiliency and sustainability (Mourtzis et al., 2022), EU emphasizes this transition as a sustainable, human-centric and resilient European Industry (Castagnoli et al., 2024) suggesting that sustainability is a fundamental pillar of a new industrial era (Madsen et al., 2023). Sustainability is also tied to human-centric aspect of I5.0, establishing it as a key pillar for competitiveness, ensuring that worker well-being and ethical practices contributes to social sustainability (Bonello et al., 2024).

Sustainability is mentioned as the driver of competitiveness that leads to competitive advantage implicitly or explicitly. Using resources efficiently and reduce waste focussing on 6R principles (Recognize, Reconsider, Realize, Reduce, Reuse, Recycle), I5.0 aims for waste prevention and logistics efficiency. The companies are focusing on resource optimization and operational efficiency as a way to reduce environmental effects, resulting in lower costs and improved efficiency, boosting competitiveness (Mourtzis et al., 2022). Also, directing efforts towards sustainability, aligned with environmental awareness and growing societal expectations, can potentially increase company's reputation and brand image, attracting new customers and investment, which will, eventually enhance stakeholder's value (Madsen et al., 2023).

Attracting and retaining talent is of paramount importance to maintain competitiveness, I5.0 helps companies to become more attractive to new high skilled workers drown by ethical values and environmentally responsible practices. With high skilled and motivated workers, companies can innovate and create new business models resulting in disruptive products, processes and sustainable business models, leveraging competitive opportunities (Antonaci et al., 2024). Gladysz et al. (Gladysz et al., 2023) also refers the importance of EU policy alignment and funding programmes in sustainable manufacture competitiveness by actively promoting I5.0 through Horizon Europe Calls Programme. Which, in turn, reorients previous I4.0 focus to include human-centrism, resilience, and a holistic sustainability approach towards I5.0.

Technology also plays a fundamental role in sustainable manufacturing and competitiveness, including AI, IoT, DT, blockchain, and 3D printing. They contribute to waste reduction, resource optimization, supply chain transparency and can also contribute to circular economy. Companies effectively using these technologies, may thrive in a sustainable and efficiently manner, leading to competitive advantages (Varriale et al., 2023). Alves et al. (Alves et al., 2023) mentions that I5.0 has been evolvingly linked to the Triple Bottom Line (TBL) approach, that focus on economic, social and environmental sustainability in Supply Chain Management (SCM). Placing digital technologies as the key to solve open issues in SCM they can improve SCM sustainable development and sustainable performance (Varriale et al., 2023).

Literature refers to sustainability as a foundational and essential aspect of Industry 5.0, and a crucial driver of competitive advantage through resource efficiency, talent attraction and spurring innovation aligned with societal values. Manufacturers can prosper both economically and environmentally, being at the same time socially responsible making sustainability a non-negotiable element to provide future competitiveness.

II.4.3. Theme 3: Building Resilience for Manufacturing Competitiveness in the Era of Industry 5.0

Resiliency is crucial to ensure manufacturing competitiveness in this new digital era emphasized through different fields of manufacturing industries, alongside sustainability, resiliency focus marks a significant evolutionary change from I4.0 and is pointed as essential to overcome future challenges and maintain competitive advantages (Hunkova & Haviernikova, 2024; Konstantinidis et al., 2023; Madsen et al., 2023; Mourtzis et al., 2022).

Several sources identify resiliency as one of the three pillars of I5.0 alongside Human-centricity and sustainability, indicating that, mastering the ability to withstand, recover and endure from disturbances/disruptions is a core principle of I5.0 and not just a desirable outcome (Alves et al., 2023; Gladysz et al., 2023; Konstantinidis et al., 2023; Madsen et al., 2023; Mourtzis et al., 2022; Zeb et al., 2022).

Resiliency as a key factor for manufacturing competitiveness can be built in several ways. By mitigating disruptions, minimizing crises downtime and maintaining operations continuity, manufacturers can create a robust and resilient manufacturing and industrial systems capable of withstanding unforeseen events like pandemics, supply shortage or economic crises (Castagnoli et al., 2024; Zeb et al., 2022). Also, through production stability, resiliency can actively contribute to a stable industrial production and recovery of manufacturing processes when disrupted by disturbances. When I5.0 key enabler technologies are used, manufacturers are equipped to cope with customer demands, maintaining market shares and competitiveness (Zeb et al., 2022). Attracting investment helps companies to become strongly resilient and tend to be more stable for reliable partners and investments, leveraging their competitive position while building trust (Varriale et al., 2023).

Technology is directly associated with resiliency to create the factories of the future and contribute to digital societies. Some technologies are fundamental to I5.0 manufacturing competitiveness, intelligent and wireless network software architectures are ready to contribute to resilient systems and objectives in an ever growing and complex communicational and computational manufacturing paradigm. (Zeb et al., 2022) Decentralized autonomous manufacturing paradigms are seen as a way to improve resiliency, because they can create distributed and adaptable manufacturing systems (Leng et al., 2025). DT are fundamental to aid on resilience, they empower manufacturers to simulate and predict potential disruptions, miss conceptions through digital prototyping and it is also possible to digitally test recovery strategies (Ahmed Murtaza et al., 2024). Blockchain networks are suggested for data protection and modelling security of manufacturers and industries sensible data, this contributes to stable and secure industrial operations, despite the need for bespoke solutions to prevent data security issues such as, the creation of all new private AI-based frameworks (Zeb et al., 2022).

Despite the significant centrality role played by technology in I5.0, humans also play a fundamental role in building resilient manufacturing systems (Panagou et al., 2024). Humans are often the ones who detect anomalies or deviations in production lines and processes, corroborating how important their training, education, awareness and skills are to an effective response (Zizic et al., 2022). The evolution from I4.0's approach to resiliency can contribute actively, since I5.0 leans to a more holistic and explicit integration into a human-centred and sustainable focus. This way the focus shifts to a more comprehensive approach capable of recovering and withstanding to a larger range of potential disruptions. (Marinelli, 2023)

Manufacturing competitiveness is directly connected to resiliency, a foundational I5.0 principle. I5.0 provides technology and tools to build robust and competitive manufacturing operations in the future to better recover and withstand disruptions. This can be achieved by leveraging technological advancements and recognizing how crucial human's expertise is.

II.4.4. Theme 4: The Strategic Role of Technology in Enhancing Manufacturing Competitiveness under Industry 5.0

Technology in I5.0 strategically builds upon I4.0 existing technological foundations, among them the most relevant ones are AI, the IoT, DT, VR and CPS. However, in I5.0 technology, applications are intentionally focused on the three core principles of I5.0 as fundamental aspects to stay competitive (Ahmed Murtaza et al., 2024; Madsen et al., 2023; Mourtzis et al., 2022; Zafar et al., 2024).

HMC technologies play a central strategic role to facilitate seamless collaboration between humans and machines, including Cobots or collaborative robots design to work alongside humans, augmenting physical and cognitive capabilities rather than replacing them (Mourtzis et al., 2022). This synergy can result in increased productivity, enhanced flexibility, improved quality in manufacturing and industry competitiveness (Zafar et al., 2024).

Augmentation technologies comprised by AR, VR and Mixed Reality, enhance operators' skills and decision-making abilities due to real-time information, guidance and training they can provide (Madsen et al., 2023). Extended reality can even extend the operators' sensorial attributes, boosting competitiveness by reducing errors, improving overall efficiency and empowering operators (Zafar et al., 2024).

The Human Machine Interface (HMI) technologies are user-friendly and intuitive interfaces, (Mourtzis et al., 2022), (Ahmed Murtaza et al., 2024), these technologies contribute to a higher standard of competitiveness, leading to greater efficiency and reduced cognitive load enabling operators to easily control and interact with complex systems (Ciccarelli et al., 2023; Zafar et al., 2024).

DT is a cornerstone technology included in I5.0, allowing performance optimization, prediction and prevention of failures and enables customization through virtual replicas of physical assets, processes or systems (Zafar et al., 2024). DT virtualization of scenarios and environments lead to maintenance cost and downtime reduction (Ahmed Murtaza et al., 2024), improved system performance and efficiency (Mourtzis et al., 2022), enhancement of product customization as required by the user (Zizic et al., 2022) and improved decision making (Zafar et al., 2024). Previously mentioned benefits have a significant impact on operational efficiency and responsiveness to ever changing market demands, thus improving competitiveness (Mourtzis et al., 2022).

AI and Big Data Analysis (BDA) play a strategic role driving intelligent automation, predicting maintenance, quality control, and personalized products/services. AI can identify patterns, optimize processes and predict anomalies (Mourtzis et al., 2022), in maintenance it can reduce unexpected downtime and optimize maintenance schedules (Ahmed Murtaza et al., 2024). AI can also be used to assist in product manufacturing personalization and design, respecting individual customer needs (Alves et al., 2023). BDA can be used by manufacturers to get value insights from huge amounts of data resulting in better decision-making and improved efficiency (Zafar et al., 2024).

IoT and CPS are employed in I4.0 but remain crucial to I5.0 assuring the connection and data exchange for the necessary interconnected industrial systems. Through real-time monitoring and control of manufacturing processes (Ahmed Murtaza et al., 2024), seamless physical and virtual worlds integration (Alves et al., 2023) and informed decision-making by data collection analysis (Ahmed Murtaza et al., 2024), IoT and CPS provide a boost in efficiency, responsiveness and flexibility through its interconnectivity and data-driven approach (Zafar et al., 2024).

Smart and Softwarized Wireless Networks, such as, 5G, Private 5G or O-RAN are part of the underlaying network infrastructure offering enhanced connectivity, low latency and reliability, essential for control and real-time data exchange (Mourtzis et al., 2022). They also offer scalability and flexibility, capable of coping with changing manufacturing needs and provide the support for advanced applications like real-time DT or collaborative robotics (Zeb et al., 2022).

Bio-Inspired Technologies and Intelligent Materials directly contribute to a more sustainable I5.0 through environmentally responsible practices (Marinelli, 2023), the use of recycled materials with embedded sensors and improved features reduces waste and improves product lifecycle management, as a consequence, cost reduction in the long run is leveraged and sustainability improved (Mourtzis et al., 2022).

However, with newer innovative technologies, ethical dilemmas arise and according to literature, five major dilemmas are highlighted, (1) data privacy, (2) AI associated risks, (3) sustainable environments development, (4) health implications due to technology use, and (5) infodemic and data weaponization issues (Dhirani et al., 2023).

I5.0 technology strategic contribution lies on human empowerment, creation of resilient operations and gathering sustainable practices while leveraging the potential of advanced digital tools to attain better efficiency, innovation and responsiveness. Manufacturers can differentiate themselves, attract talent and customers who value these principles achieving a sustainable competitive edge (Alves et al., 2023; Madsen et al., 2023; Zafar et al., 2024).

II.4.5. Theme 5: Organizational Adaptation and Strategic Planning for Industry 5.0 Competitiveness

The use of new technologies for I5.0 alone is not sufficient to ensure a successful transition, it requires a significant organizational adaptation, a shift in traditional hierarchical structures towards human-centric approach (Gladysz et al., 2023), more flexible and collaborative approach to meet customer’s needs (Alves et al., 2023).

EU recognizes that companies need to implement a culture of sustainable, resilient and human-centric principles, I5.0 manufacturing system must be adaptable and flexible through technology, enabling organizations to respond quickly and resiliently, respecting planetary limits while gathering talent and diversity (Castagnoli et al., 2024). Supporting workers is crucial to adapt and implement human-centric assistive planning, they promote innovative work behaviour, employability and digital literacy (Escallada et al., 2025), including, upgrading skills and capabilities of leaders and managers (Mourtzis et al., 2022). Organizations must also adapt to a strategic human resource management paradigm to create a flexible and resilient workforce, especially in critical areas like, human resources BDA, digital transformation impact, cost, technology management and organizational resilience (Hunkova & Haviernikova, 2024). To achieve an I5.0 business model, organizations must go through a transformation where sustainability becomes the core component and driver of competitiveness(Commission, 2022), creating value not only for shareholders but for all stakeholders promoting employment prosperity and resilient economic growth (Castagnoli et al., 2024).

Commercial and manufacturing system design are also affected due to technological innovations, strategic planning should concern about effective technology integration and knowledge change, considering design thinking, modelling methods, design processes and enablers (Leng et al., 2025; Leng, Guo, et al., 2024). Organizations must still adapt to new technology adoption and integration, not only adapt but also, strategically plan how enabling technologies will be implemented focusing in I5.0 principles (Ahmed Murtaza et al., 2024) and witch technologies will be more impactful to enhance sustainable practices and human capabilities (Nazarejova et al., 2024).

Authors also stress that challenges and future directions for strategic planning can be daunting. Standardized frameworks for strategic implementation are still lacking, more development and maturity in the models is still needed to fully address I5.0 human-centric approach (Hein-Pensel et al., 2023). It is necessary to move beyond a purely engineering-focused approach and adopt a wider and interdisciplinary perspective that involves management, society and economics to a successfully human integration in technological aspects (Castagnoli et al., 2024). Addressing specific needs of SMEs since, due to their size, are facing different challenges and strategic needs adopting I5.0 transformation (Nazarejova et al., 2024).

Summarizing, organizations should strategically learn on how to adapt to I5.0 core principles. Focusing on workforce development, transforming business models, thoughtfully integrate technology, prioritizing human factors and building resilience, organizations are more equipped to achieve competitive advantages as I5.0 continues to evolve.

II.4.6. Theme 6: Policy and Regulatory Framework for a Sustainable, Resilient, and Circular Industry 5.0 in Europe

Europe's transition towards I5.0 needs a robust and innovative thinking policy and regulatory landscape, actively promoting human-centric, sustainable, resilient and circular economy principles. EU pretends a complete transformation to achieve Europe's 2030 goals, addressing technological innovation, climate change, biodiversity and societal paradigm evolution (Directorate-General for Research and Innovation (European Commission) et al., 2021). To achieve this proposed transformative vision, EU must call for new economic orientations, innovative business model designs, new policymaking approaches in partnership with businesses and industry, repurposing digital transformation (Commission, 2022). By reenforcing these aspects EU should be able to fulfil 2030 goals, creating self-sustaining industries, responsible ecosystems and value chain, regenerative circular economy design, while respecting planetary boundaries (Zeb et al., 2022).

G5.0 is introduced as the new EU transformative vision, emphasizing the need for a new government role as a regulator and enabler, capable of setting frameworks and political directions for this transformation with new policies and efficient linking along different process levels. I5.0 transition will require innovative policy actions in several areas, such as, social, educational, energy, taxation and industrial policies, coordinated by different government bodies (Directorate-General for Research and Innovation (European Commission) et al., 2021).

EU is actively pursuing its objectives not only by setting policy and regulatory standards but also by actively creating funding programs like "Horizon Europe" (Gladysz et al., 2023), or "Industry of the Future Award", or even by promoting conferences such as "The European Research and Innovation Days" (*European Research and Innovation Days | Research and Innovation*, n.d.). The "European Institute of Innovation and Technology" is an EU body that has been strengthening Europe's innovation since 2008, leveraging the creation of highly skilled jobs and sustainable growth as part of "Horizon Programme" (*EIT at a Glance | EIT*, n.d.).

These set of actions and initiatives provide a structured framework to explore and enhance I5.0 manufacturing competitiveness, focusing on the crucial role of policy and regulatory standards to shape a human-centric, sustainable and resilient EU industry. Leadership and international cooperation are also vital to set the standards of sustainability, ethics, and digital economy in Europe's I5.0 (Commission, 2022).

II.5. Conclusions

This paper contribution is focused on thematic exploration as it enabled to synthesize sources 6 emerging themes. For instance, we focused on topics, such as human-centricity, sustainability and resiliency. As I5.0 is transcending the automation focus of its predecessor I4.0. the latest research highlights recent pivotal contributions that advanced technologies have to offer, specifically, Cobots and DT, as foundational for production processes optimization and innovation providers. Moreover, literature highlights the capability of the manufacturing sector to achieve both economic and environmental sustainability and underlines the synergy between I5.0 principles and the European Green Deal.

Although EU is actively working to address European Green Deal challenges, there has been limited progress made in the ethical domain in comparison to manufacturing innovative technological advancements. Statutory and regulatory standards lack empirical validation, raising concerns about sustainable and ethical innovation. It is crucial to clarify these standards in manufacturing, especially regarding AI, worker data privacy and machine autonomy.

To ensure responsible technological development, EU must prioritize the creation of robust ethical guidelines, informed interdisciplinary studies and inputs from stakeholders. Through these actions, EU can provide a framework with regulatory standards, in a comprehensive and equitable manner, involving social, economic and ethical impacts to ensure a responsible technological development.

Leadership and strategic vision must pursue business models aligned with I5.0 triple bottom down concept and a stricter collaboration between industry, academia and governments to reduce the gap in fostering ecosystems, supporting knowledge sharing and innovation. Doing so impacts positively in companies' investments and funding, reducing the difficulties to access financial incentives and funding, in particular SMEs. I5.0 is foreseen as a transformative model that reflects the evolution of post COVID-19 pandemic, taking into consideration the need to re-design a competitive industrial system that prevails in the future, capable to resist shocks and truly integrates social and environmental principles. Summarizing, there are some establishments made linking I5.0 themes to their respective manufacturing output. Technology should be used as an augmentation and not as a replacement of humans, sustainable practices are seen as a competitive advantage and not as an ethical imperative, resiliency is mainly achieved through digitalization, strategic planning must represent a necessity for I5.0 implementation and ethical frameworks must be robust and recognized as a guide.

Despite all previously mentioned conclusions, significant gaps persist, regarding the EU I5.0 manufacturing sector competitiveness. The absence of standard metrics to assess and measure I5.0 implementation impact results in a defective analysis leading to ineffective policy formulation. Furthermore, human-centricity quantifiable metrics are lacking to measure and evaluate practices in manufacturing regarding worker's well-being, productivity and innovation. Due to its complex systems and spread applications, manufacturing empirical studies and case analysis for each manufacturing sector are scarce, requiring further investigation in real-world applications and outcomes to a real and tangible assessment of I5.0 impact.

As for future research and development propositions, human-centred technologies should be prioritized to potentiate seamless integration in existing manufacturing systems and processes. Future research should focus on circular economy model development and sustainable materials innovation, aligning manufacturing sectors with EU's environmental goals. Empirical studies should also be addressed, making use of the robust technologies to assess and evaluate long-term I5.0 impact in EU manufacturing sector's competitiveness. Moreover, interdisciplinary research will be crucial to evaluate the development of I5.0 policy framework to facilitate and equitable implementation across EU, encompassing social, technological and economical dimensions.

CONCLUSIONS

Present research was conducted with the main purpose of filling the gaps that were identified regarding the DTs in EU manufacturing sector and how I5.0 can be a key driver for Europe to become the competitive industrial powerhouse that once was. This research, based on thematic analysis, gathered information in an organized and pragmatic manner, leading to a simple and more understandable state of knowledge display. As a result, two articles were created to study two main subjects, DTs and I5.0 in EU.

The primary aim of this master thesis was to search the existing gaps in literature regarding I5.0 adoption and implementation towards a competitive EU manufacturing sector. A conceptual framework, theme oriented, was deemed necessary, given the shear amount of data available, spread through the many manufacturing sectors across European countries. In addition, every industry has its own specific technologies, regulations and standards that must be respected, hence, the creation of a framework capable of presenting it in a pragmatic and systematic format.

The adoption and implementation of DTs in European manufacturing industry is essential to leverage productivity, efficiency and competitiveness, involving both theoretical and practical approaches resulting in a more resilient EU, bringing policy makers and manufacturers closer together. Although DTs adoption in manufacturing is already underway, several challenges must be addressed, data-related challenges, technological barriers, collaboration issues, economic factors and market development early stage. Unlocking DTs full potential must be done through secure data practices, standardization, collaboration, reskilling, additional study and innovative development. A successful DT implementation can enhance efficiency and productivity, save costs, enhance decision-making and improve product development in a secure, cost effective and digitalized framework, fully integrated in the manufacturing process, leveraging competitiveness.

I5.0 represents an industrial shift reaching beyond the automation focused I4.0, and cannot be dissociated from its advanced technologies, particularly, DTs and Cobots. They form the fifth industrial revolution, focused on a human-centred, sustainable and resilient approach. Industries, specially manufacturing, must understand how pivotal the adoption of I5.0 technologies can be to achieve competitive advantages and create innovative manufacturing ecosystems. The manufacturing sector has now the ability to achieve economic growth and environmental sustainability aligned with the European Green Deal, establishing I5.0 as the new human, economic and environmental paradigm. Moreover, business owners must realize that humans are at the core of the manufacturing industry and that machines are just an enhancement to these skilled workers. Robotics are seen as a helping hand and not as a human workforce killer.

Challenges and Limitations:

Despite all the advancements in technology, I5.0 has its own limitations and challenges in several areas, substantially in ethics, where progress has been limited. Ethical concerns regarding AI, worker data privacy, and machine autonomy, must be prioritized through the creation of robust ethical guidelines and clarifying statutory and regulatory standards to ensure a responsible technological development. Agile ethical, political and regulatory standards can reduce adoption and implementation times, leveraging financial resiliency and sustainable business models.

A stricter collaboration between academia, industry and governments is fundamental to promote knowledge share, innovation support and improve access to funding, particularly for SMEs. SMEs are the backbone of EU manufacturing sector and, besides the previous mentioned, they face other constraints, such as, technological barriers, workforce adaptation and the need to upskill/reskill their work force, or even investment requirements. These constraints can dictate the future of these organizations since DTs initial cost for adoption and implementation is particularly high. Moreover, Industry 5.0 is established on the concept of digital factories, supported by a strategic and informed decision-making framework that relies on key enabling technologies such as DTs. Without a fully digitalised manufacturing ecosystem, the capabilities and core principles of Industry 5.0 cannot be effectively implemented, and the European Union won't be able to elevate its industrial base to a new level of global competitiveness.

The entire organizational ecosystem must be reskilled to a new paradigm, including leaders, and a change in strategic vision must be made to align business models with the Triple Bottom Line concept, focused on societal, economic and environmental tenets. I5.0 is pointed as a transformative model, highlighting the need for a competitive industrial system with the resiliency to thrive through disruptive events, integrating societal and environmental principles.

Summarizing, technology should augment human capabilities, not replace them, sustainable practices offer a competitive advantage, resiliency is largely achieved through digitalization, strategic planning is essential for I5.0 implementation and ethical frameworks must be robust.

Gaps and future research:

Significant gaps persist in understanding on how DTs and I5.0's impact the EU manufacturing sector. Empirical studies and case analyses in different manufacturing sectors remain scarce and require further real-world investigation to provide a tangible assessment of I5.0's actual impact.

Existing human DT frameworks are still deficient concerning the practical operationalization of their methodologies, highlighting the absence of standardized methods to assess human factors in technologies like DT and VR within I5.0 applications.

Statutory and regulatory standards are lacking empirical validation, raising concerns regarding sustainable and ethical innovation, particularly in work data privacy and machine autonomy. Furthermore, the absence of standard metrics to assess and measure the impact of I5.0 implementation can lead to inefficiencies in policy formulation and strategic implementation. Current models require further development and maturity to fully address I5.0 central tenet, the human-centric approach.

In manufacturing, management investigation through a human-centred approach is lacking, making it difficult to measure practices related to workers' well-being, productivity and innovation to provide quantifiable metrics for human-centricity. Further investigation is needed to address the specific needs and challenges of Small and Medium Enterprises (SMEs) in adopting the I5.0 transformation and DTs implementation, as they face different challenges and strategic requirements due to their size.

Concluding that, future research should prioritize human-centred technologies, the development of circular economy models and sustainable materials, conducting empirical studies and pursuing interdisciplinary research for policy development.

Since the present study was a compilation of various types of articles, it would be of great importance to validate the conclusions. The systematic literature review focussed on a single database and only in EU industry and manufacturing, therefore, it is relevant to investigate how other countries and economic areas are dealing with this industrial and societal transition, such as the EUA, China or Japan. Different countries have different political and regulatory frameworks that may impact legally, socially and ethically the adoption and implementation of I5.0, and their related technologies, especially DTs.

Further investigation must also be conducted to assess how these I5.0 core tenets can impact industry, to create high value products, produced in a responsible and ethical way, respecting the human condition, planetary boundaries and future generations.

Digitalization is becoming the main focus of companies and organizations, consequently, academics, professionals and policy makers should also prepare to control and monitor future technologies and strategic alignments to cope and contribute to this new industrial era with a human-centric, sustainable and resilient approach.

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APPENDIX A1

Rethinking Business Models: Pathways to Efficiency and Sustainability

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Abstract. This study explores the integration of Circular Economy (CE) and Lean Management (LM) to improve operational efficiency and promote environmental sustainability. CE focuses on keeping materials in closed cycles through practices such as recycling, remanufacturing, and reuse, while LM seeks to eliminate waste and optimize processes. These approaches create synergy, giving companies a competitive advantage. This advantage is achieved by aligning sustainability with cost reduction and innovation. Case studies from companies such as Toyota, Renault, and Patagonia highlight practical benefits such as cost savings and resource optimization. For example, Toyota integrates remanufacturing with lean principles, while Renault achieves significant waste reduction through circular strategies. However, challenges such as cultural resistance and the need for reverse logistics infrastructure persist. This study proposes a six-step framework to guide the integration of CE and LM, focusing on process mapping, circularity opportunities, lean principles, reverse logistics, employee engagement, and continuous improvement. The conclusions point to how companies can balance economic growth and environmental responsibility, offering applicable insights for sustainable and efficient business models.

Keywords: *Circular Economy, Lean Management, Sustainability.*

1 Introduction

The Circular Economy (CE) emerges as an alternative to the linear economic model, proposing the maintenance of materials and products in continuous cycles, with a focus on reuse, recycling, and remanufacturing, thus reducing dependence on new resources and minimizing environmental impacts (Geissdoerfer et. al., 2017). On the other hand, Lean Management (LM) focuses on eliminating waste within production processes, promoting operational efficiency and value creation (Womack, 2007). The integration of these approaches offers a promising path for companies wishing to align economic efficiency with sustainable practices, responding to regulatory pressures and growing demands from conscious consumers.

Integrating CE and LM allows companies to improve their internal processes and extend the useful life of materials. This helps reduce the extraction of natural resources and waste generation. This alignment is facilitated by the advance of Industry 4.0 technologies, such as the Internet of Things (IoT), Big Data, and Artificial Intelligence (AI), which enable real-time monitoring and dynamic adjustments to production flows (Ciliberto et. al., 2021). These technologies allow a more agile transition to circular and lean practices, increasing the overall efficiency of operations.

This study explores how integrating CE and LM can promote sustainable business models. Firstly, the fundamentals of these approaches and their relevance to the current context are analyzed. Next, successful examples in sectors such as automotive and consumer goods are presented to illustrate the practical benefits of this combination. Finally, the cultural and structural barriers that companies face when adopting these practices are discussed, as well as proposed strategies for overcoming these challenges. The relevance of the topic is evident in a scenario where sustainability is not only an environmental responsibility, but also a competitive advantage and a global market requirement (Kirchherr et. al., 2023; Kirchherr et. al., 2017).

Based on the examples presented and the analysis of the barriers faced, this study also proposes a theoretical framework that can guide companies from different sectors in the efficient implementation of these practices. This work therefore seeks to contribute to the construction of business models that reconcile economic growth and environmental responsibility, providing practical insights and strategies for facing new challenges.

2 Literature Review

The literature on CE and LM points to a natural alignment between the two concepts, although their origins and approaches are different. CE emphasizes keeping resources in continuous cycles, while LM focuses on eliminating waste in production processes. When integrated, these approaches offer a powerful framework for creating more sustainable and efficient business models (Geissdoerfer et. al., 2017; Womack & Jones, 1997).

2.1 Circular Economy

The CE emerged as a response to the limitations of the linear economic model, characterized by the 'extract, produce, dispose' cycle (Kirchherr et. al., 2023). The CE proposes strategies such as recycling, reusing and redesigning products to extend the useful life of materials while reducing the extraction of natural resources. This model is supported by two main cycles: the biological cycle, which returns biodegradable materials to nature, and the technical cycle, which reuses and recycles non-biodegradable materials such as plastics and metals. Moreover, Rosa et al. (2024) have made a description of the CE most important principles (see **Fig. 1Error! Reference source not found.**) (Rosa et. al., 2019):

1. Design for Longevity: Emphasizes creating durable products that can withstand prolonged use, reducing the need for frequent replacements.

2. Reuse and Sharing Models: Highlights systems that enable the sharing and reuse of resources to extend product life cycles.

3. Repair and Maintenance: Encourages practices that allow for regular maintenance and repair to keep products functional and valuable.

4. Recycling: Focuses on the recovery of materials to be reprocessed into new products, ensuring minimal waste.

5. Industrial Symbiosis: Illustrates how waste or by-products from one industry can serve as inputs for another, creating a closed-loop system.

6. Energy Efficiency and Renewable Energy: Advocates for using renewable energy sources and optimizing energy use throughout product life cycles.

7. Circular Supply Chains: Supports the use of renewable, recyclable, or biodegradable materials in supply chains to minimize environmental impact.

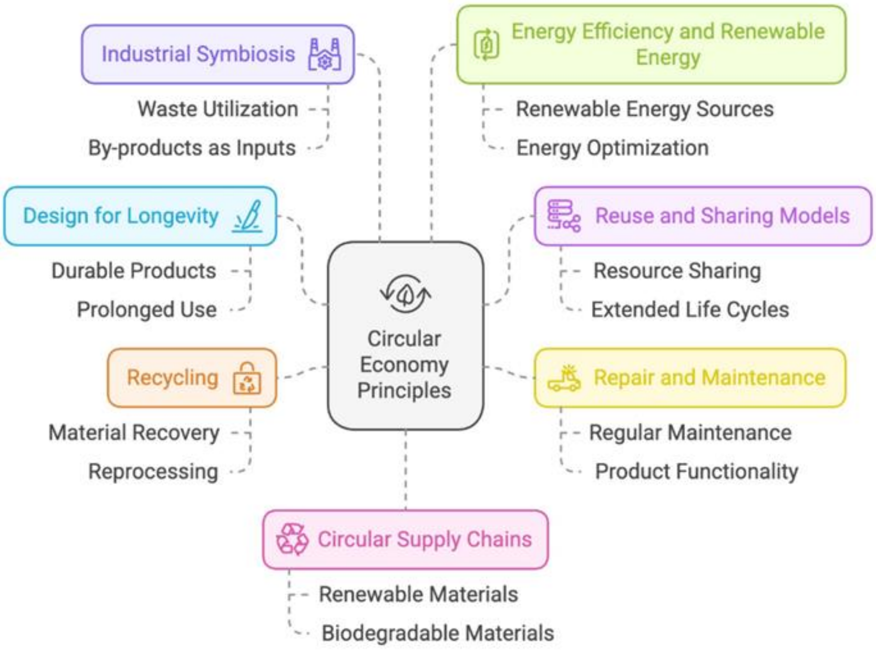

Fig. 1. *Circular Economy Principles.*

Some practical examples of CE include Renault's remanufacturing program for automotive parts, which reuses engines and other components, reducing costs and carbon emissions (Schroeder et. al., 2019). Similarly, companies like Interface adopt recycling strategies in their products, promoting closed cycles of materials in the coatings sector (Adenle et. al., 2024).

2.2 Lean Management

LM, in turn, was born within the context of the Toyota Production System, which pursued efficiency along with the scarcity of resources in post-war Japan (Womack & Jones, 1997). The approach is based on principles such as kaizen (continuous improvement) and just-in-time (production according to demand), with the aim of eliminating waste and optimizing processes.

The seven types of waste identified by LM include 1) overproduction, 2) waiting, 3) unnecessary transport, 4) excessive processing and 5) inventories, 6) unnecessary movements and 7) defects (see **Fig. 2**) (Ōno et. al., 2008). Companies like Toyota and

General Electric have used these principles to increase their competitiveness and reduce operating costs (Shah & Ward, 2007).

Fig. 2. *Lean Management Seven Wastes.*

2.3 Synergies between CE and LM

Although different in their origins, CE and LM share the goal of maximizing value and minimizing waste. CE focuses on the circularity of external resources, while LM optimizes internal processes. When combined, these practices allow an integrated approach that benefits both operational efficiency and environmental sustainability (Bocken et. al., 2016).

Companies like Unilever illustrate this integration by adopting lean practices in their factories and developing recyclable packaging, aligning productive efficiency with environmental responsibility (Unilever, 2023a). On the other hand, Toyota exemplifies how the integration of lean principles with remanufacturing can generate significant financial and environmental benefits (Pagoropoulos et. al., 2017).

Despite these opportunities, the combined implementation of CE and LM faces challenges. Cultural barriers, such as resistance to change, and structural ones, such as the lack of infrastructure for reverse logistics, delay the adoption of these practices on a large scale (Jabbour t. al., 2019). Overcoming these barriers requires an organizational transformation that includes training, employee engagement and the development of robust logistics chains (Kirchherr et. al., 2023).

2.4 Conclusion of the Literature Review

The integration between CE and LM offers a promising solution for companies that seek to increase their efficiency and reduce their environmental impacts. However, the successful adoption of these practices requires not only technological changes but also cultural and organizational. The existing literature highlights the need for clear frameworks to guide companies in the practical application of this integration, emphasizing the importance of a continuous commitment to innovation and sustainability (Bocken et. al., 2016; Ciliberto et. al., 2021; Kirchherr et. al., 2023).

3 Methodology

This study used a qualitative approach based on case analyses and data collection from public documents such as corporate reports and academic publications. Documents such as Toyota's Sustainability Data Book 2024 (Toyota, 2024) and Renault's Integrated Report 2023-2024 (Renault, 2024) were key to identifying successful CE and LM practices, as well as the challenges faced by the companies.

Ten companies from different sectors were analysed, including automotive, consumer goods, technology, clothing and medical. The selection was based on the following criteria: commitment to sustainability, previous experience in adopting lean practices and documented evidence of circular practices in their operations. To provide a comprehensive overview of the companies and reports analysed, Table 1 presents the sectors and key insights derived from the sustainability and operational documents.

Table 1. *Comprehensive summary of companies and insights on sustainability and operational strategies.*

Company	Document	Industry	Key Focus	Main Insights
Toyota	Sustainability Data Book 2024 (Toyota, 2024)	Automotive	Sustainable Mobility	Reverse logistics and remanufacturing reduce costs and emissions.

Renault	Integrated Report 2023-2024 (Renault, 2024)	Automotive	Carbon-Neutral Manufacturing	Success in remanufacturing parts and reducing material waste.
Unilever	Annual Report and Accounts 2023 (Unilever, 2023b)	Consumer Goods	Recyclable Packaging	Challenges in global logistics for circular practices.
Patagonia	B Corp Report 2021 (Patagonia, 2021)	Apparel	Circularity in Fashion	Dependence on consumer engagement for reuse and repair programs.
HP	Sustainable Impact Report 2022 (HP Inc., 2022)	Technology	Ink Cartridge Recycling	Difficulty scaling reverse logistics globally.
Interface	Impact Report 2023 (Interface, 2023)	Carpets	Circular Production Processes	High costs of logistics and infrastructure for closed-loop production.
IKEA	Sustainability Report FY2023 (IKEA, 2023)	Furniture	Recycling and Reuse of Furniture	Complex supply chains for recycling and reuse.
Philips	Annual Report 2023 (Philips, 2023)	Medical Technology	Medical Equipment Remanufacturing	Technical challenges in recovering and remanufacturing products.
General Electric	Annual Report 2023 (General Electric, 2023)	Heavy Industry	Industrial Sustainability	High capital investment required for implementing circular practices.

Thermo Fisher	Sustainability Report 2023 (Thermo Fisher, 2023)	Medical Technology	Laboratory Equipment Recycling	Challenges in scaling global programs for circular lab equipment practices.

3.1 Methodological Approach

The choice for a qualitative approach is justified by the exploratory nature of the research, which seeks to understand the complexity of the interaction between CE and LM. According to Creswell and Creswell (2013), qualitative approaches are particularly effective in investigating multifaceted phenomena in their real context. For this, the analysis of multiple case studies was selected, allowing an in-depth view on the practical application of these strategies (Yin, 2007).

3.2 Selection of Companies

Ten companies from various sectors were analysed, including automotive, consumer goods, technology clothing, and medical technology. The selection was based on the following criteria:

1. Commitment to sustainability, evidenced by initiatives recognized in indices such as the Dow Jones Sustainability Index.
2. Previous experience in adopting lean practices.
3. Documented evidence of circular practices in their operations.

Among the companies selected are:

- Toyota: pioneer in adopting lean practices and remanufacturing initiatives.
- Renault: highlighted for its program of reusing automotive parts.
- Patagonia: promoter of circularity in clothing through the Worn Wear program.
- HP: known for its ink cartridge recycling system.
- Unilever: Recognized for its recyclable packaging initiatives, despite facing logistical complexities in scaling circular practices.
- Interface: A leader in circular production processes within the carpet industry, overcoming infrastructure-related challenges.

- IKEA: Focused on recycling and reusing furniture, tackling complex supply chains to achieve circularity.
- Philips: Committed to remanufacturing medical equipment, addressing technical recovery challenges.
- General Electric: Concentrated on industrial sustainability, requiring high capital investment for implementing circular initiatives.
- Thermo Fisher: Dedicated to laboratory equipment recycling, overcoming challenges in scaling global programs for circular laboratory practices.

3.3 **Data Collection**

Data collection used secondary sources, including corporate sustainability reports and relevant academic literature. To support the framework development, key references from academic journals were analysed. Table 2 highlights the most relevant works. These documents provided detailed information on CE and LM practices and results achieved. The analysis was performed manually, identifying patterns and recurring themes that could reveal practical and theoretical insights.

Table 2: *Key References on CE and LM.*

Author(s)	**Year**	**Title**	**Source/Journal**	**Key Focus**
Geissdoerfer et al.	2017	"The Circular Economy – A new sustainability paradigm?"	Journal of Cleaner Production	Introduction of the Circular Economy and its implications for sustainability.
Womack & Jones	1997	"Lean Thinking: Banish Waste and Create Wealth"	Book/Journal of the Operational Research Society	Foundational concepts of Lean Management

				and waste elimination.
Kirchherr et al.	2017	"Conceptualizing the Circular Economy"	Resources, Conservation and Recycling	Barriers and enablers for the Circular Economy.
Bocken et al.	2016	"Product design and business model strategies for a circular economy"	Journal of Industrial and Production Engineering	Practical strategies for integrating circular economy in product design.
Stahel	2016	"The Circular Economy"	Nature	Overview of economic and environmental benefits of circular systems.
Ciliberto et al.	2021	"Digitalization and sustainability: Industry 4.0 tools"	Sustainability Journal	Role of IoT and AI in implementing Circular Economy and Lean practices.

3.4 Analysis of the Data

The analysis followed the thematic analysis method described by Braun and Clarke (2006), which allows the identification of significant patterns in the data. The steps included:

- Familiarization with the data through in-depth reading.

- Coding relevant information in categories such as "operational efficiency", "reverse logistics" and "organizational challenges".
- Grouping of codes into broader themes, such as "operational benefits" and "barriers to implementation".
- Interpretation of the themes to build a narrative that connects the findings to research questions.

3.5 Validation

The data was validated by cross-referencing the information obtained in these reports with academic sources. For example, Unilever's Annual Report and Accounts 2023 provided details on recycling initiatives, while Interface's Impact Report 2023 provided insights into logistical and environmental challenges (Unilever, 2023b; Interface, 2023). In addition, the selection of successful companies in the integration of CE and LM allowed us to identify lessons applicable to different sectors.

3.6 Methodological Limitations

Although qualitative analysis provides detailed insights, there are limitations related to the subjectivity of the interpretation process and the dependence on secondary data. Internal information, such as managers' perceptions of cultural challenges, was not included, representing an opportunity for future studies. The approach adopted allowed us to explore how leading companies integrate CE and LM, highlighting good practices and corresponding results. This methodological basis provides a comprehensive view to guide the implementation of these practices in different organizational contexts.

4 Results and Discussion

The analysis of the cases studied revealed that the integration between CE and LM provides significant improvements in operational efficiency, environmental sustainability, business resilience and competitiveness. However, this integration faces practical challenges, including cultural barriers and structural limitations, which must be overcome to maximize benefits.

4.1 Benefits of CE-LM Integration

One of the main benefits observed was the improvement in operational efficiency. Companies like Toyota and Renault have demonstrated how combining lean processes with circular practices can reduce costs and minimize waste. Toyota, for example, applied LM principles to optimize its internal operations while promoting the remanufacturing of automotive parts, aligning productive efficiency with sustainability (Ōno et. al., 2008; Pagoropoulos et. al., 2017). Renault, with its plant in Choisy-le-Roi, has managed to significantly reduce carbon emissions and material costs by integrating remanufacturing with lean practices (Schroeder et. al., 2019).

Another clear benefit was the strengthening of corporate responsibility. Companies like Patagonia and IKEA have been using the CE-LM integration to respond to the growing demand for sustainable practices. Patagonia, through the Worn Wear program, encourages the reuse and repair of clothing while applying lean principles to reduce waste in its supply chain (Chouinard, 2006). Similarly, IKEA has developed systems for recycling and reusing furniture, combining circular design with operational efficiency (Hofmann, 2019).

The application of Industry 4.0 technologies, such as IoT and Artificial Intelligence, was also crucial to increase efficiency. These tools allow real-time monitoring of resources and processes, facilitating dynamic adjustments that reduce waste and promote circularity (Ciliberto et. al., 2021). Digital integration further strengthens the synergy between CE and LM, allowing a more agile and informed approach.

4.2 Identified Challenges

Despite the benefits, companies face several challenges in the combined implementation of CE and LM. A common obstacle is organizational resistance. Employees are often reluctant to adopt new practices, especially in companies with already established processes (Kirchherr et. al., 2017). This problem has been reported by companies such as Unilever, which faced difficulties in implementing circular practices in their global operations (Unilever, 2023b).

The lack of infrastructure for reverse logistics was also identified as a significant barrier. The collection, classification and processing of materials for reuse or recycling require substantial investments that not all companies are willing or able to undertake. HP, for example, encountered challenges in scaling its cartridge recycling program due to logistical complexity (Bocken et. al., 2016).

4.3 Implications for Companies

The results suggest that CE-LM integration is not only a strategy to improve operational efficiency, but also a competitive differential in increasingly sustainability-oriented markets. Companies that overcome cultural and structural barriers can reduce operating costs and strengthen their image with consumers. In addition, the combination of circular practices with lean principles offers a viable path for the transition to more resilient and environmentally responsible business models.

5 Proposal of Framework for the Integration of CE and LM

Based on the results and literature review, this study proposes a practical framework to guide companies in the efficient integration of CE and LM. This model highlights six essential steps for the implementation of these practices, considering the challenges identified and the success examples analysed:

1. Mapping of Internal Processes. The first step is to map in detail the internal processes of the organization to identify waste points and circularity opportunities. Tools such as value stream mapping (VFM) can be used to visualize bottlenecks and material flows (Womack & Jones, 1997). This initial diagnosis is fundamental to align the strategies of LM and CE with existing operations.
2. Identification of Circularity Opportunities. After mapping, it is necessary to identify specific opportunities for implementing circular practices such as remanufacturing, recycling and reuse. Companies like Renault and HP have demonstrated that well-planned strategies can not only reduce the need for new resources, but also create new sources of revenue through the sale of remanufactured products (Bocken et. al., 2016; Schroeder et. al., 2019).
3. Application of Lean Principles. Integrating LM principles such as kaizen and just-in-time helps eliminate waste and optimize resource use at every step of the process. The combination of these principles with circular practices increases operational efficiency and reduces costs (Ōno et. al., 2008). In addition, the focus on continuous improvement ensures that sustainable initiatives are adaptable to future changes.

4. Development of Reverse Logistics Infrastructure. To support circular practices, it is essential to create a robust reverse logistics infrastructure. This includes systems for collecting, sorting and remanufacturing discarded materials. Companies like HP and Interface have faced challenges in this regard, but they have also demonstrated that vendor partnerships and the adoption of technologies such as blockchain can facilitate implementation (Pagoropoulos et. al., 2017).

5. Employee Engagement and Training. The success of CE-LM integration depends on employee engagement. Continuous training is necessary to promote an organizational culture focused on innovation and sustainability. Incentives and recognition for good practices can motivate employees to adopt these initiatives (Kirchherr et. al., 2023).

6. Monitoring and Continuous Improvement. Finally, it is crucial to establish performance indicators to measure the environmental and economic impacts of integrated practices. Tools such as life cycle analysis (LCA) can be employed to evaluate results and identify areas for continuous improvement (Stahel, 2016). The use of real-time data, made possible by Industry 4.0, facilitates dynamic adjustments in operations (Ciliberto et. al., 2021).

5.1 Summary of the Framework

The framework combines LM's operational benefits with CE's long-term vision (see **Fig. 3**). Following these steps, companies can align sustainability and efficiency, creating resilient and competitive business models. The proposal also serves as a basis for future research and for the development of more specific sector guides.

Fig. 3. *Proposed Framework for Integrating the Circular Economy and Lean Management.*

6 Conclusions

This study explored how the integration of Circular Economy (CE) and Lean Management (LM) can transform business models, promoting operational efficiency and environmental sustainability. Through the analysis of real cases, it was evidenced that the synergy between these approaches offers practical solutions to the contemporary challenges faced by companies, as the reduction of environmental impact and the increase of competitiveness in markets increasingly oriented towards sustainability.

Leading companies such as Toyota, Renault and Patagonia have demonstrated that combining circular practices with lean principles generates substantial benefits including reduced operating costs, new revenue streams and a stronger corporate image. On the other hand, cultural barriers such as organizational resistance and structural ones, such as the lack of reverse logistics infrastructure, were identified as the main obstacles to implementation.

The framework proposed in this study provides a practical guide for companies that wish to integrate CE and LM efficiently. The steps, which include process mapping, identifying circularity opportunities, infrastructure development and employee engagement, highlight the need for a systematic and continuous approach to overcome challenges and maximize benefits.

6.1 Recommendations and Future Research

This study reinforces the importance of investing in technological innovation, as tools of Industry 4.0, to facilitate the integration of CE and LM. In addition, the development of public policies that encourage the adoption of these practices, such as subsidies for reverse logistics infrastructure, can accelerate its implementation in companies of different sizes.

For future studies, it is recommended to explore the applicability of this framework in small and medium-sized enterprises (SMEs), which face specific challenges to adopt sustainable practices. In addition, regional analyses could reveal how cultural and regulatory differences impact the effectiveness of CE and LM integration.

6.2 Final Considerations

The integration of CE and LM offers companies a unique opportunity to align economic growth with environmental responsibility. Organizations that adopt these practices not only excel in efficiency and innovation, but also contribute significantly to a more sustainable future. This study provides a theoretical and practical basis for companies to face the challenges of the 21st century with resilient business models aligned to global sustainability demands.

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