



Corso di Laurea in Ingegneria Gestionale

Understanding Smart Warehouses: A Systematic Literature Review

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Introduction

Industry advances through technological progress (European Court of Auditors, 2020). With the advent of the Fourth Industrial Revolution, companies have increasingly undertaken the modernization of their infrastructures to strengthen control over their operational processes. At the core of this transformation lies the objective of obtaining real-time access to all production-related information (European Court of Auditors, 2020), made possible through a digital transformation process that views products as *smart products* and manufacturing facilities as *smart factories*. In this context, the concept of integration refers to active communication among the various actors involved in the production chain, ensuring consistency and synchronization of shared information. Achieving this objective requires seamless interconnection between devices and information systems.

Consequently, the paradigm of interconnection and integration that characterizes this new industrial model has permeated every aspect of the supply chain, including warehouse operations. Warehouses represent a critical component of modern supply chains, both because of their substantial impact on operational costs and because the activities performed within them directly influence the quality of customer service. The adoption of new technologies and organizational principles, together with changes in companies' physical and digital infrastructures, has led to the emergence of the concept of the *smart warehouse*, for which this thesis explores possible definitions.

More broadly, this new paradigm has stimulated growing academic interest in intelligent warehouses, resulting in studies that address both cross-cutting supply chain issues (Perotti et al., 2025; van Geest et al., 2022) and more narrowly focused, single-dimensional topics (Nicoletti et Appolloni, 2024). Within this still evolving and fragmented research landscape, there is a need to consolidate these contributions into a broader, comprehensive, and multidimensional perspective. Specifically, it is important to examine how the smart warehouse concept has evolved into distinct research dimensions, explore the relationships among these dimensions based on the evidence available in the existing literature, and identify the main directions for future research.

Through a Systematic Literature Review, this thesis seeks to address the need for a comprehensive and integrated understanding of the current body of knowledge on smart warehouses. This is achieved by adopting an interpretative framework that conceptualizes the smart warehouse as the outcome of integrating digital technologies, business processes, and operational performance. From this perspective, the literature review aims not only to synthesize existing research but also to contribute to a deeper understanding of the smart warehouse concept and the mechanisms underlying its development. Furthermore, the findings can be useful to support managers in making more informed strategic decisions by increasing awareness of the potential implications associated with warehouse digitalization initiatives. The second chapter presents the methodology adopted for conducting the Systematic Literature Review, describing the selection and review processes, detailing the analytical dimensions used to classify and examine the selected studies. The third chapter reports the findings of the review, followed by the fourth chapter in which the results are

discussed, underlying emerging trends and research gaps, and a research agenda is proposed. Finally, the fifth chapter summarizes the main conclusions of the study giving highlights for future research.

The results of this study highlight a significant research gap concerning warehouse data, showing that, although data are central to smart warehouse functioning, they are still rarely treated as a structured research dimension. The findings also suggest new directions for investigating human resource data, particularly in relation to workers' physical and psychological conditions, in line with the increasingly human-centric vision promoted by Industry 5.0. More broadly, the study identifies the key themes that continue to shape academic research on smart warehousing, including the central role of IoT and data-driven technologies, the strategic relevance of inventory management and operational efficiency, and the strong concentration of research on information-intensive processes such as picking and storage.

1. Research motivation and research questions

To provide appropriate context for this research on smart warehousing, it is necessary to examine its fundamental concepts. In this regard, this chapter discusses the role of the warehouse within the supply chain, the Industry 4.0 paradigm that has driven its digital transition, and the subsequent evolution toward Industry 5.0 and its underlying principles. Building on these foundations, a definition of the smart warehouse is proposed, in order to contextualize the topics covered in this thesis.

1.1. Research scope

1.1.1. The role of warehouses

A warehouse is a facility dedicated to the storage of goods that plays a fundamental role within the supply chain, as its operational efficiency directly affects the efficiency of the entire logistics system (Sun, 2009; van Geest et al., 2021), helping to ensure the continuity of production and distribution flows. Typical warehouse activities are mainly structured into three main phases: inbound goods management, storage management, and outbound distribution management (Yongsheng and Wenling, 2004). Beyond its storage function, the warehouse now plays a broader role in integrating supply chain processes, improving service visibility, and helping to prevent overstock situations across the entire chain (Tubis and Rohman, 2023). Over time, it has also begun to incorporate value-added services such as labeling, repackaging, and kitting, in line with the growing need for flexibility in the value chain.

Traditional warehouses, however, present numerous structural inefficiencies, including inefficient space management, damaged material, inefficient operations, over-handling material, and inefficient material handling equipment (Kamali, 2019; van Geest et al., 2021). These inefficiencies are even more impactful when considering the structural changes in demand that have occurred over time: consumer expectations have become increasingly personalized, requiring additional operations and greater organizational flexibility. The growth of e-commerce has led to an increase in the variety of stored goods, a reduction in the predictability of picking activities, and growing pressure for increasingly fast deliveries, up to same-day delivery (Hofmann et Rüscher, 2017; Kagermann et al., 2013; Winkelhaus et Grosse, 2022). At the same time, shorter product life cycles and the increasing number of new product introductions have heightened uncertainty in inventory planning (Hofmann et Rüscher, 2017). Inventory inaccuracies can trigger the “bullwhip effect,” causing a distortion of information and an amplification of costs across all segments of the supply chain (Hui et al., 2025); similarly, operational errors in the warehouse directly affect the quality of service perceived by the final customer.

Warehouses are gradually evolving in line with technological progress and the transition toward increasingly digitalized and autonomous logistics. The implementation of advanced technologies and automation systems is transforming warehouse operational and strategic

management. These new, more *intelligent*, warehouses are known as Smart Warehouses and represent one of the emerging frontiers in supply chain management (Winkelhaus and Grosse, 2022).

Consequently, the transition from traditional warehouses to Smart Warehouses cannot be considered in isolation, but rather as part of the wider digital transformation promoted by the Industry 4.0 paradigm.

1.1.2. Industry 4.0 and Industry 5.0

The expression *Industry 4.0* was introduced in Germany in 2011 during the Hannover Fair in reference to the Fourth Industrial Revolution (da Silva et al., 2023; Oztemel and Gursev, 2020). In 2015, the Platform Steering Committee stated:

"The term Industrie 4.0 stands for the fourth industrial revolution, a new level of organizing and controlling the entire value chain across product lifecycles. This cycle focuses on increasingly personalized customer wishes and extends from the concept to the order, development, production, and shipping of a product to the end customer and ultimately to its recycling, including all associated services. The foundation is the real-time availability of all relevant information through the integration of all objects in the value chain and the capacity to determine the optimal value flow at any time from the data. The interconnection of people, objects, and systems produces dynamic, real-time-optimized, self-organizing, cross-enterprise value-adding networks that can be optimized according to various criteria such as cost, availability, and resource consumption."

The Fourth Industrial Revolution emerged at a historical moment marked by significant changes both in Europe and globally, in which technological improvements, the shift away from standardized production and the emergence of new major players in the global market created the need to operate at new levels of competitiveness. It is within this context that the need to increase the technological level of firms became evident, as they had already begun implementing robotic solutions to balance operators' workloads and improve operational efficiency, as well as using the Internet for data management. Industry 4.0, however, aims to act on a more infrastructural level in order to create an integrated system involving the company as a whole; indeed, it should not be interpreted merely as a technological evolution, but rather a systemic transformation of production processes. Oztemel and Gursev (2020) define it as methodology to generate a transformation from machine dominant manufacturing to digital manufacturing, with the objective of decentralizing decision-making processes through the development of autonomous decision-making capabilities (Borghetti et al., 2020; Ghosh et al., 2020; Oztemel and Gursev, 2020) and achieving high levels of operational autonomy, up to systems characterized by self-regulated behavior (Oztemel and Gursev, 2020). The aim is not to replace humans, but rather to minimize inaccuracies and enable faster processes through the seamless sharing of information in real-time (Markov and Vitliemov, 2020). This new perspective therefore seeks to increase efficiency and productivity within firms through

improved communication among machines, operators, and processes, which acquire, interpret, and exchange data in a continuous flow, resulting in a higher degree of integration throughout the entire value chain.

Industry 4.0 is based on seven fundamental principles, including real-time data management, interoperability, virtualization, decentralization, agility, service orientation and the integration of business processes (Wang and Wang, 2016). Oztemel and Gursev (2020) added to these principles characteristics such as intelligence, flexibility, adaptability, autonomy and the use of sensors. The combined implementation of these principles enables the creation of intelligent and communicative systems including machine-to-machine communication and human-machine interaction (Ustundag and Cevikcan, 2018). Such communication, together with value creation from data exchanged, is made possible by the introduction of disruptive technologies such as adaptive robotics, data analytics and artificial intelligence (big data analytics), simulation, embedded systems, communication and networking such as Industrial Internet, cloud systems, additive manufacturing and virtualization technologies (Ustundag and Cevikcan, 2018). These technologies enable significant improvements in productivity, flexibility and efficiency, while also fostering the development of data-driven business models and innovative services (Lichtblau et al., 2015).

Lichtblau et al. (2015) identify Industry 4.0 as the fusion of the physical and virtual worlds and recognize four fundamental dimensions within it: *smart factory*, *smart products*, *smart operations* and *data-driven services*, as represented in Figure 1. The first two concern the physical world, including intelligent production environments and products equipped with digital capabilities, respectively, while the latter represent the virtual dimension, based on data processing and the digital integration of processes. This configuration enables both vertical integration, involving people, resources, and machinery, and horizontal integration across the entire value chain, including suppliers and customers (Lichtblau et al., 2015).

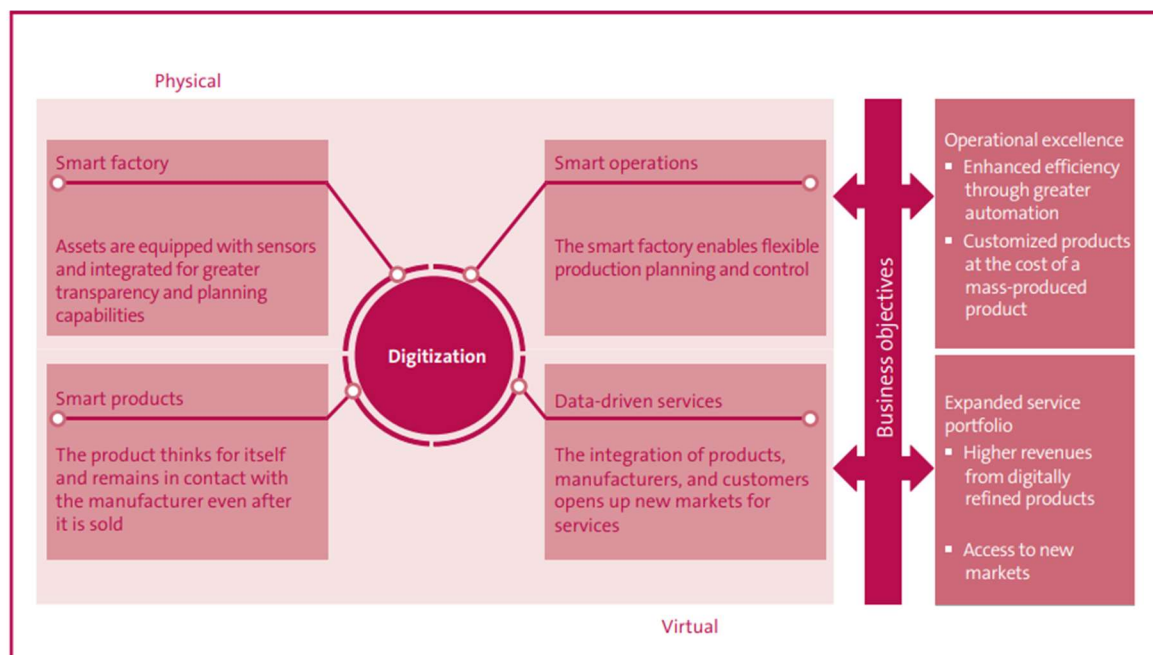


Figure 1. Industry 4.0 as the fusion of the physical and virtual worlds (source: Lichtblau et al., 2015)

Although the topic of Industry 4.0 has been widely discussed and increasingly reflected in companies' strategic choices, in recent years academic debate has focused on the concept of Industry 5.0, closer to social and environmental matters. This has been a rather natural transition: recent studies highlight a growing interest in sustainability already within the context of Industry 4.0, confirming that reflection on the environmental and social implications of digital transformation was already underway before a new paradigm emerged. Digital technologies can in fact support the monitoring of environmental parameters, improve worker safety, and enable more resource-efficient production processes (Shabur, 2024; Amjad et al., 2020). In particular, the combination of artificial intelligence, the Industrial Internet of Things (IIoT) and cloud computing promotes data-driven process management and intelligent automation, reducing waste, energy consumption and inefficiencies (Qu et al., 2020; Harikannan et al., 2020).

Industry 5.0 should not be conceived as an autonomous industrial revolution equivalent to Industry 4.0, but rather as a shift in perspective and an inevitable response to new social and environmental demands, which companies cannot ignore if they intend to remain sustainable in the long term (Ghobakhloo et al., 2023a). In this sense, Industry 5.0 is rooted in the progress and outcomes of the digital transition initiated by Industry 4.0 (Ghobakhloo et al., 2023a), but, as Breque, De Nul, and Petridis (2021) state, it provides a different focus and highlights the importance of research and innovation to support industry in its long-term service to humanity within planetary boundaries.

At the core of this new paradigm are three fundamental principles: human-centricity, sustainability, and resilience. These dimensions stem from the growing awareness that industrial change cannot be interpreted exclusively in terms of the technologies that enable it, but must also consider the factors that ensure its continuity and long-term sustainability. From this perspective, the importance of promoting synergy between technology and human operators has emerged, as such integration can increase the value and effectiveness of the solutions adopted, amplifying their benefits. Moreover, placing the individual and their well-being at the center of the transformation process helps reduce distrust toward technological innovation and the risk that it may be perceived as a threat instead of an opportunity. At the same time, sustainability, which has become increasingly central in scientific and managerial debate, represents an essential element for achieving a durable industrial transition compatible with the planet's environmental and energy resource limits. Analyzing the contribution that enabling technologies can make in this direction, by mitigating the environmental impact of production processes, is therefore essential to fully exploit their innovative potential. These considerations are ultimately linked to the concept of resilience, which has become increasingly relevant due to growing external instability. Events such as geopolitical tensions, economic crises, and natural disasters create new cross-sector challenges, including within the industrial sector. As a result, companies need to develop greater flexibility and adaptability in order to manage change effectively, prevent operational disruptions, and limit the economic and social consequences arising from potential crisis situations (Breque et al., 2021).

1.1.3. Defining a smart warehouse

One of the aims of this research is to clarify the relationship between the concepts of Industry 4.0 and Smart Warehousing, which in the literature appear to be affected by ambiguity (Winkelhaus and Grosse, 2022) and are often used as synonyms (Tubis and Rohman, 2023).

Through an in-depth analysis of 16 articles, we identified the main characteristics associated with the concept of a Smart Warehouse. This concept originates from the Industry 4.0 framework (Tubis and Rohman, 2023). Evidence from the literature suggests that the concepts of Industry 4.0 and Smart Warehouses are closely connected, with the latter representing an implementation of Industry 4.0 technologies and Industry 5.0 concepts.

In particular, smart warehouses place greater emphasis on the emerging needs to adapt to the dynamic business environment of today's economy (Winkelhaus and Grosse, 2020) and on new ways of conceptualizing the relationship between customers and enterprises.

Based on the results of this analysis, it is possible to define a smart warehouse as a facility characterized by highly integrated infrastructures (Winkelhaus and Grosse, 2022; Zhen and Li, 2022) and highly digitalized processes (Leng et al., 2021; Kandarkar and Ravi, 2024; Lin and Low, 2023), scalable and flexible (Plakantara, 2024) and interconnected through real-time information flows (Plakantara, 2024; Oliveira, 2022; Winkelhaus and Grosse, 2022; Abdirad and Krishnan, 2021). The adoption of technologies such as Cyber-Physical Systems (CPS), which enable seamless interactions between physical components and their digital counterparts (Ho et al., 2025), and Internet of Things (IoT) technologies, which enable real-time communication between sensors, machines, and equipment (Azwan et al., 2025), has enabled the development of a network of coordinated and interconnected facilities that use data to exchange information, achieve automatic identification, tracking, positioning and intelligent control and management (Heng L., Kaiyou, Y., 2022).

This configuration enables the combination of process automation (Liu et al., 2018; van Geest et al., 2021; Zhen and Li, 2022) with rapidly changing market demand (Liu et al., 2018) for increasingly customized services (Culot et al., 2020; Winkelhaus and Grosse, 2020), thereby allowing continuous adaptation to today's dynamic business environment (Winkelhaus and Grosse, 2020). In addition, several advanced technologies, such as Cloud Computing (CC), robotics, Artificial Intelligence (AI), Augmented Reality (AR), Big Data, Machine Learning (ML), 3D printing and others (Krstić, M. et al., 2021) have further contributed to this shift of the warehouse management toward *smartness*. Modern warehouse automation uses machine vision, deep learning, drone-based solutions, multi-robot systems, Automated Guided Vehicles (AGVs), and AI-powered smart devices to optimize inventory, enhance efficiency, and reduce human intervention (Antoniou et al., 2026). These smart warehouses, in this way, became an important component of Industry 4.0 (Tubis and Rohman, 2023; Guo et al., 2024). Moving toward Industry 5.0, smart warehouses are going to be focused on a human-centered perspective in which technology supports human operators rather than human operators supporting the technology (Winkelhaus and Grosse, 2022). This perspective addresses contemporary challenges, with particular emphasis on environmental sustainability (Breque et al., 2021) and the enhancement of resilience in dynamic and highly uncertain environments (Breque et al., 2021). This change reflects the new logistics paradigm, focusing on the

interaction between humans and robots in the manufacturing context, looking into ways how to benefit from the respective strengths and how to valorize human capital (Breque et al., 2021).

1.2. Literature background

The existing literature already includes several Systematic Literature Reviews (SLRs) focused on smart warehousing, consistent with the definition adopted in Section 1.1.3. In order to identify and contextualize the existing literature on smart warehousing, this section presents the main contributions that characterize the topic, either in a generic way or more focused on single aspects. A total of eleven reviews is examined and discussed in relation to the systematic literature review carried out in this work. In the first part, the contributions that most closely align with the intent of this SLR are presented; in the second part, works that are nonetheless relevant to the main topics of this review are illustrated, but which differ in terms of research approach or object of investigation. These contributions examine, for instance, the benefits and challenges associated with the adoption of Industry 4.0 technologies, their impact on warehouse processes, and the enabling factors driving the transition towards a more efficient and advanced management paradigm. In addition, a growing number of studies explore how these technologies can support sustainability objectives; more recently, several reviews have also addressed the relationship between workers and new technological solutions, as well as workforce perceptions of these technologies. Despite this, a comprehensive and structured discussion that interprets warehouse smartness as the integrated outcome of specific objectives, enabling technologies, managed data types, and their application to specific warehouse processes, capturing their interconnections and synergies, is still missing. In particular, the topic of data managed within a smart warehouse has not yet been addressed in a structured way: existing studies do not provide systematic analyses on this dimension, treating it as a secondary issue relative to their main technological and operational research objectives, even though data management is itself a key element for understanding how to implement a smart warehouse.

All these contributions are then synthesized in Table 1.

van Geest, Tekinerdogan and Catal (2022) focus on the design and transition towards smart warehousing, examining the technologies employed and the related challenges, the main application domains of such technologies, the motivations behind adoption - such as namely external threats, strategic advantages, increased quantity of data, warehouse complexity, operational agility, and customer demand - and the characteristic features of smart warehouses - such as automation, real-time data management, connectivity, and operational flexibility. Their work identifies increasing warehouse complexity and growing demand as the main drivers of this shift towards more advanced solutions, both informational and automation-oriented. One of the emerging challenges is the difficulty of integrating information systems across different supply chain actors, especially considering the transition from materials-tracking systems to decision-making systems. The former corresponds to traditional

warehouse management systems in which data are entered and managed by operators; the latter pursue greater decisional autonomy, enabled by the integration of data analytics tools and the availability of real-time information. However, while the contribution is valuable for researchers and practitioners interested in the transition towards a smart warehouse, it does not systematically clarify how technologies concretely contribute to achieving the main key motivations identified.

Tikwayo and Mathaba (2023) analyze the benefits and barriers of selected Industry 4.0 technologies and decision support systems (DSS) applied to warehouse operations, classifying technologies into seven categories: DSS tools, RFID, IoT, Autonomous Mobile Robots (AMRs), blockchain, cloud computing, and Augmented Reality (AR). The most recurrent benefits highlighted in their work concern process efficiency improvements, real-time data availability enabled by IoT sensors providing constant visibility, competitive advantage derived from increased efficiency and interconnectivity, and digital integration of activities that eliminate information-flow inefficiencies. The main barriers include high life-cycle costs - encompassing both initial device acquisition costs and maintenance expenses - complexity of physical environments, because warehouse structures often lack adequate space for the deployment of certain robotic technologies, insufficient supporting resources such as IT networks and management systems, security risks, and high energy consumption, for which possible solutions are proposed. However, the analysis only covers a subset of Industry 4.0 technologies, limiting the completeness of the overview of benefits and challenges applicable to the full range of technological solutions available in warehouse contexts.

Perotti, Cannava, Ries and Grosse (2025) propose a conceptual framework that maps Industry 4.0 technologies, warehouse processes, and Sustainable Development Goals (SDGs), categorized along the three dimensions of sustainability: economic, environmental and social. Their work highlights the interrelations among these elements and underscores that assessing the sustainability impact of these technologies requires explicit consideration of existing trade-offs. The authors also note that the existing literature often presents overly generic analyses or studies focused on individual technologies, without adequately clarifying the mechanisms through which they concretely contribute to sustainability. In this sense, the proposed framework offers a more integrated and process-oriented perspective. Nevertheless, the model is confined to the sustainability dimension and does not account for other relevant factors, such as the data managed within smart warehouses, that could represent an additional, meaningful dimension for more completely understanding how Industry 4.0 technologies are integrated in these contexts.

El Kadmiri, Benghabrit, Nait Sidi Moh and Moufaddal (2024) acknowledge that many studies on warehouse management primarily present theoretical models, with only a few providing technical explanatory models or real-world implementations in warehouse settings; this frequently results in a lack of standardization of findings, making it difficult to compare results or replicate successes across different contexts. The authors, through their systematic review using the PRISMA method, focus on the advancements of Industry X.0, defined as a holistic approach to create more flexible, efficient, responsive, and personalized industrial systems. Their aim is to identify specific issues and inefficiencies within each core warehouse

management activity. These warehouse activities are mapped to their corresponding objectives and technologies; however, the role and the type of data managed is not explicitly addressed, leaving an important dimension of warehouse operations largely unexplored.

The works described have, in different ways, provided a general overview of how certain technologies can support warehouse activities and contribute to achieving valuable purposes. The following studies address themes related to smart warehousing adopting a broader focus or examining specific aspects of the topic.

Tubis and Rohman (2023) conduct a study on the digitalization of warehouse processes through Industry 4.0 technologies. Based on their analysis, the authors propose a two-level framework consisting of 10 main categories and 24 subcategories, useful for organizing the existing literature. The primary categories are Literature Review, Assessment/Evaluation, Design/Model, Framework, Implementation, Improving Knowledge, Method, Network, Safety, and Undercategorized (for papers in which the warehouse is a secondary topic). Several categories are further developed into subcategories: under Literature Review, these include AI, AR, Emerging Technologies, IoT, Manufacturing related with Warehousing, Storage Systems, Supply Chain Management, and Other Topics; under Assessment/Evaluation, Case Study and Maturity Model; under Design/Model, Algorithm, Layout, Method, Tool/System, and Other; under Method, Algorithm, Data Analysis, and Other; and under Implementation, Augmented Reality, IoT, RFID, Visual Technology, and Other. The study aims to characterize and classify the reviewed literature, but it takes on a very general connotation and maintains a broad focus, addressing highly heterogeneous aspects.

Mohammed, Rahman, Demir, Shah and Alaya (2025) propose a framework for smart warehouses intended to support management in defining KPIs aligned with the principles of Industry 5.0: resilience, sustainability, and human-centricity. The authors draw on the literature review, direct observation of four real warehouse settings in India and Oman and feedback from 14 professionals from both public and private sectors regarding the validity of the indicators identified in the literature. Based on this, KPIs are defined across four interrelated dimensions: traditional, sustainability, resilience, and Industry 5.0. These KPIs measures, for example, resource utilization and operational performance, environmental impact, flexibility and risk management, as well as the synergy between humans and technology. The authors identify continuous improvement, safety, and mutual cognitive human-robot collaboration as particularly relevant dimensions. The study remains primarily focused on definition and validation on indicators, without extending the analysis to the integration of warehouse processes, enabling technologies, and data managed.

Winkelhaus and Grosse (2022) identify enabling technologies for the transition from traditional to smart warehouses, distinguishing between digital technologies, which support operators, and automation technologies, which replace human labor in repetitive tasks. Building on these technologies and on how they interact with workers for the order-picking process, the authors propose an operational guide to support companies in implementing sustainable change in smart warehousing, while keeping close attention on the human factors involved, including perception, cognition, motor action, and psychosocial aspects. In this respect, the contribution moves beyond a purely technical treatment towards a social perspective, in line

with the emerging horizon of Industry 5.0. Therefore, the aim of the study is to frame enabling technologies within a broader sociotechnical context, where human dimensions play a central role alongside technological ones.

Nicoletti and Appolloni (2024) analyze the role of Artificial Intelligence in developing green warehouses 5.0. While acknowledging the growing attention to sustainability in industry, the authors highlight a shortage of warehouse-specific studies on this topic. In this context, AI-based predictive maintenance emerges as a central element among others, thanks to its capacity to monitor key parameters, such as equipment efficiency, environmental parameters or storage levels, all framed within a broader plan to achieve net-zero buildings. The focus on Artificial Intelligence enables a comprehensive overview of its contribution across distinct warehousing dimensions. However, the analysis focuses almost exclusively on AI, without considering other enabling technologies.

Mahroof (2018) examines the benefits and barriers associated with implementing artificial intelligence in warehouses, drawing on the case of a large retail distribution center and employing the Technology–Organization–Environment (TOE) framework to identify the main technological (T), organizational (O), and environmental (E) factors. The analysis reveals different levels of trust towards AI between implementation managers, who are considerably more confident in its potential, and operational managers, with the exception of a subset of the latter who had prior experience with AI. This highlights how the background and prior exposure to artificial intelligence concretely affect its perception among adopters. However, this study remains limited to the specific application area of AI, overlooking many other technologies that can be implemented in a smart warehouse context. Nevertheless, the study provides a comprehensive view of the context in which AI is applied, the data it processes, and its contribution to warehouse operational management.

Aravindaraj and Rajan Chinna (2022) conduct an SLR on the benefits and challenges of Industry 4.0 technologies with respect to the achievement of the Sustainable Development Goals (SDGs). Among the goals most significantly influenced are zero hunger, which means a global mission aimed at eliminating fame and all forms of deprivation, quality education, clean energy, industry and innovation, sustainable consumption and production, and climate action. Technologies such as IoT, AI, AR, blockchain, and AGVs play a decisive role in enabling conscious and more efficient inventory management, overcoming the limitations of traditional warehouse configurations. However, the authors acknowledge that certain themes such as human health, the movement of employees, and fatigue still receive little attention in several countries, and that the lack of a long-term vision represents a significant obstacle to achieving meaningful and lasting outcomes. Indeed, a truly smart warehouse is not simply one that implements technologies, but rather one that builds a more structured ecosystem that also involves human resources. The sustainability-oriented analysis provides a broad overview of the benefits and challenges associated with the adoption of selected technologies; however, its scope remains limited to the relationship between Industry 4.0 technologies and the Sustainable Development Goals.

Cupido and Jokonya (2024) explore the factors influencing companies' decisions to adopt Industry 4.0 technologies in their warehouses, employing the TOE framework to identify the

main technological (T), organizational (O), and environmental (E) factors. The analysis highlights the centrality of relative advantage, that refers to the perceived benefit related to technology adoption, followed by security of information systems and technologies among technological factors; management, cost, and support among organizational factors; and market structure, support, and customer demand among environmental factors. However, the study lacks an in-depth discussion of how these factors can be managed and how they condition one another.

In summary, the existing literature already offers a range of contributions on smart warehousing, including analyses focused on specific Industry 4.0 technologies, such as those by Nicoletti and Appolloni (2024) and Mahroof (2018) on AI, as well as broader overviews examining multiple technologies and their application to warehouse contexts (van Geest et al., 2022; Tikwayo and Mathaba, 2023; El Kadmiri et al., 2024; Tubis and Rohman, 2023). However, a literature review that considers the smart warehouse as the result of the joint integration of specific objectives, technologies, generated and managed data types, and individual warehouse processes is still absent. The objective of this research is therefore to map the state of the art of the smart warehouse literature, that allows the systematic identification of the interactions and synergies among these key elements: specifically, the objectives addressed by a smart warehouse, the enabling Industry 4.0 technologies involved, the types of data generated and managed, and the individual warehouse processes concerned.

Authors	Title	Year	Objectives	Technologies	Data	Processes
van Geest, Tekinerdogan and Catal	<i>Smart warehouses: Rationale, challenges and solution directions</i>	2022	✓	✓		
Tikwayo and Mathaba	<i>Applications of Industry 4.0 Technologies in Warehouse Management: A Systematic Literature Review</i>	2023	✓	✓		
Perotti, Cannava, Ries and Grosse	<i>Reviewing and conceptualising the role of 4.0 technologies for sustainable warehousing</i>	2025	✓	✓		
El Kadmiri, Benghabrit, Nait Sidi Moh and Moufaddal	<i>Survey of Industry X.0 paradigm for sustainable and smart warehouse management</i>	2024		✓		✓
Tubis and Rohman	<i>Intelligent Warehouse in Industry 4.0—Systematic Literature Review</i>	2023		✓		
Mohammed, Rahman, Demir, Shah and Alaya	<i>When warehouses dream: a systems-informed exploration of Industry 5.0 principles in warehousing performance management</i>	2025	✓			
Winkelhaus and Grosse	<i>Smart warehouses a sociotechnical perspective</i>	2022		✓		
Nicoletti and Appolloni	<i>Green Warehouse 5.0</i>	2024		✓		
Mahroof	<i>A human-centric perspective exploring the readiness towards smart warehousing: The case of a large retail distribution warehouse</i>	2018		✓		
Aravindaraj and Rajan Chinna	<i>A systematic literature review of integration of industry 4.0 and warehouse management to achieve Sustainable Development Goals (SDGs)</i>	2022	✓	✓		
Cupido and Jokonya	<i>Exploring the factors affecting the adoption of emerging technologies in warehouse management</i>	2024		✓		

Table 1. Summary of the main contributions in the literature on smart warehousing

1.3. Theoretical framing and research questions

1.3.1. Theoretical lens

This SLR is framed into a two-level theoretical lens.

The *primary lens* is the warehouse design and control perspective developed by Rouwenhorst et al. (2000), operationally reinforced by Gu et al. (2007; 2010). This primary lens provides the warehouse-specific backbone of the review, because it conceptualizes the warehouse as a system that can be analyzed through *processes, resources, organization/information and control, and design/performance decisions*. Rouwenhorst et al. (2000) explicitly propose a reference framework for warehouse design and control, while Gu et al. (2007; 2010) extend this logic through a unifying view of warehouse operations and performance evaluation. More specifically, Rouwenhorst et al. (2000) provide a conceptual backbone for understanding warehouse design and control problems, while Gu et al. refine the operational perspective by classifying warehouse planning around the core functions of receiving, storage, order picking, and shipping.

The *complementary lens* is the *digital technologies–business processes–performance framework* proposed by Perano et al. (2023). This second lens is used to interpret the findings

of the SLR from the perspective of digital transformation. It is especially useful because it aligns well with the objective of the SLR: to study technologies together with processes, and objectives of a smart warehouse that, in turn, affect its performance.

Role of the primary lens

The primary lens constitutes the starting point of this analysis and provides the guiding framework for structuring the research questions.

On the one hand, Gu et al. (2007) relate performance evaluation to decisions made at both the warehouse design and warehouse operations levels. According to the contribution, these two dimensions both contribute to the overall operational performance of the warehouse, so they should be discussed together. On this basis, RQ1 is formulated to investigate the objectives pursued by smart warehouses through their design, as the factors influencing warehouse performance. Then, building on this framework proposed by Gu et al. (2007), the classification of warehouse operation planning according to the different warehouse functions leads to the formulation of RQ4, which explores the warehouse processes. In this way, the existing literature can be analyzed and organized according to the various operational functions.

On the other hand, Rouwenhorst et al. (2000), recognizing that decisions made during the warehouse design phase have a significant impact on warehouse costs, developed a framework for warehouse design and control based on two complementary dimensions: three decision-making levels (strategic, tactical, and operational) and three perspectives from which a warehouse can be examined (processes, resources, and organization). Adopting this perspective, the present study introduces two additional research questions, RQ2 and RQ3. The first focuses on the resource dimension, investigating the digital technologies implemented within the context of a smart warehouse. The second addresses the organizational dimension, examining the data flows generated and exchanged within an integrated warehouse environment such as a smart warehouse.

So, in a nutshell, the primary lens helps to answer the question:

How can smart warehousing be understood as an evolution of warehouse design, operations, control, and performance management?

Role of the complementary lens

In their contribution, Perano et al. (2023) propose a three-dimensional perspective to understand supply chain digitalization, choosing performance impacts, digital technologies and business processes as interpretative framework. Building on this interrelationship, the functional link that emerges considers which technology is implemented, within which specific process it is applied, and which positive outcomes are expected to be achieved.

Based on this work, the complementary lens has an interpretive function: it helps explain how digitalization manifests itself in the reviewed literature on smart warehouses. Thus, the complementary lens allows the findings to be interpreted at a higher level through three categories:

- *performance impacts*
- *digital technologies*
- *business processes*

The two levels will be applied in sequence.

The primary lens explains the warehouse system, providing the warehouse-specific analytical structure, whereas the complementary lens provides digitalization-oriented interpretive layer for analyzing the digital transformation process of the warehouse system.

1.3.2. Research questions

Building on the two-level theoretical lens presented in Section 1.3.1, this SLR investigates how smart warehousing can be understood as an evolution of warehouse design, operations, control, and performance management, through four distinct research questions.

Each RQ addresses one of these dimensions:

- RQ1: *What are the objectives of smart warehousing?*
- RQ2: *What technologies are used in a smart warehouse, including both hardware and software?*
- RQ3: *What data are generated and managed in a smart warehouse?*
- RQ4: *Which warehouse operational processes do smart warehouse technologies apply to?*

The relationships of these research questions with the theoretical lens presented in Section 1.3.1 are illustrated in Tables 2 and 3, respectively. Addressing these questions enables the development of a comprehensive and structured overview of smart warehousing, valuable not only from an academic perspective, but also for providing strategic and managerial insights for decision-makers.

Primary-lens dimension	Main focus	Research Question
<i>Warehouse design /performance evaluation</i>	Objectives of smart warehousing	RQ1
<i>Resources / enabling systems</i>	Technologies present in a smart warehouse	RQ2
<i>Organization / information and control</i>	Data generated and managed in a smart warehouse	RQ3
<i>Warehouse processes / warehouse operations</i>	Warehouse processes addressed by a smart warehouse	RQ4

Table 2. Primary-lens dimension and related research questions

Main complementary-lens category	Research Question
<i>Performance</i>	RQ1
<i>Digital technologies</i>	RQ2
<i>Digital technologies (with a data/information emphasis)</i>	RQ3
<i>Business processes</i>	RQ4

Table 3. Complementary-lens dimension and related research questions

This thesis is structured as follows. Chapter 2 describes the methodological approach adopted to conduct the SLR, presenting the PRISMA protocol and the variables included in the analysis. Chapter 3 reports the findings, covering both the bibliometric and the content analysis and highlighting the key relationships among the investigated variables. Chapter 4 critically discusses the results, identifies gaps in existing literature, outlines directions for future research, and presents the corresponding managerial implications.

2. Methodology

The Systematic Literature Review presented in this work was conducted following specific methodological guidelines. This chapter describes the adopted approach, the main stages of the review process, and the study selection procedure, which is documented according to the PRISMA guidelines.

2.1. Systematic Literature Review

The work presented in this thesis was conducted using the methodological approach of the Systematic Literature Review (SLR), an established approach in the management domain (Kraus et al., 2020) based on the rigorous application of rules and procedures in order to collect and present knowledge on a specific topic. Systematic Literature Reviews can be used for various purposes, from describing the state of the art of a selected topic, to testing hypotheses in order to support a given argument based on existing literature, or to extend or critically evaluate literature (Xiao and Watson, 2019). In this case, the SLR aims to address the topic of Smart Warehousing, summarizing the related academic literature and identifying future research directions.

The development of this Systematic Literature Review was based on the guidelines provided by Sauer and Seuring (2023). Structurally, the SLR is presented as a qualitative review consisting of six distinct steps: 1) defining the research question; 2) determining the required characteristics of primary studies; 3) retrieving a sample of potentially relevant literature; 4) selecting the pertinent literature; 5) synthesizing the literature; 6) reporting the results. These six steps help both to guide the development of the research and to reduce the high stylistic variability of published contributions.

Once the literature review has been conducted, it is necessary to address how to present the work. This SLR follows the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) presented by Moher et al. (2010), which are structured around a 27-item checklist organized into four distinct phases: identification, screening, eligibility, and inclusion.

2.1.1. Database and search strategy

The literature analyzed for the development of this SLR was retrieved from the Scopus database, one of the largest databases of peer-reviewed literature. The search was structured according to the four distinct research questions guiding this literature review. For this reason, four corresponding search queries were developed, as presented in Table 4.

Research Question	Search Query
RQ1	TITLE-ABS-KEY(("smart warehous*" OR "warehouse 4.0" OR "warehouse 5.0" OR "intelligent warehous*") AND (objective* OR goal* OR aim* OR <u>target</u> * OR purpose* OR motivation*))
RQ2	TITLE-ABS-KEY(("smart warehous*" OR "warehouse 4.0" OR "warehouse 5.0" OR "intelligent warehous*") AND (technolog* AND hardware OR software OR automat*))
RQ3	TITLE-ABS-KEY(("smart warehous*" OR "warehouse 4.0" OR "warehouse 5.0" OR "intelligent warehous*") AND (data OR information))
RQ4	TITLE-ABS-KEY (("smart warehous*" OR "warehouse 4.0*" OR "warehouse 5.0" OR "intelligent warehous*") AND (build* OR structur* OR implement* OR test* OR design))

Table 4. Research Queries

2.1.2. Inclusion and exclusion criteria

In order to ensure a relevant selection aligned with the research topic, inclusion criteria were applied to the publication's selection process. These criteria are presented in Table 5 and allowed the exclusion of contributions that were less aligned with the scope of the study. It should be noted that no other filters were applied in this search, such as a temporal one, as the topic is still relatively underdeveloped in literature. Therefore, it was considered necessary to include the entire body of existing research, while remaining consistent with the scope of the investigation.

Criteria	Condition	Why
C1. Subject Area	Only papers related to Computer Science; Engineering; Business, Management and Accounting; Decision Sciences; Energy; Economics, Econometrics and Finance; and Multidisciplinary fields	As smart warehousing is strongly linked to technology evolution and operational dynamics, the subject areas selected have to reflect its technological, operational and managerial nature.
C2. Language	Only papers written in English	To avoid intermediary translations that might distort the original meaning of the paper

Table 5. Inclusion Criteria

2.1.3. Selection of pertinent literature

Based on the guidelines proposed by Sauer and Seuring (2023), this Systematic Literature Review involved a series of distinct stages for selecting contributions from literature. Following

the definition of the search queries and the retrieval of an initial set of potentially relevant publications, the study selection phase was carried out. This process was structured into three successive stages, described below, which ultimately led to the identification of a final corpus consisting of 217 publications.

First Phase: title and abstract screening

In the first round of selection, the title and abstract of each result retrieved from Scopus for the different search queries were examined, allowing for an initial screening of publications considered consistent with the objectives of the research. To ensure the traceability of the entire process, an Excel file was created to record all retrieved results and document the decisions made for each contribution. In this preliminary stage, the selection was primarily based on the overall relevance of the contribution to the topic addressed by the SLR.

Second Phase: full-text screening

Subsequently, a second, more in-depth level of analysis was conducted based on the full-text reading of the papers selected in the previous stage. This activity was carried out separately for each research question in order to keep the publications clearly organized, as potential duplicates had not yet been removed at this stage. This approach made it possible to understand how the literature addressed the topic of smart warehousing for each dimension of analysis, to determine how many papers were actually relevant to each macro-theme, and to identify those that were out of scope.

At this stage, the exclusion criteria concerned the unavailability of the full text in Scopus or the focus of the publications, which could be more clearly assessed through full-text screening. Only those contributions in which smart warehousing represented the central topic and from which useful information could be extracted for the purposes of the investigation were retained. Conversely, studies primarily aimed at presenting optimization models were excluded. Although these papers had been retrieved by Scopus due to the presence of keywords consistent with the search, such as specific technologies or the smart warehouse context, they merely described algorithms and experimental results without providing a thematic contribution relevant to the present review. Papers exclusively focused on the prototyping of a technology, adopting a purely engineering approach without offering any theoretical contribution, were also excluded, as were studies dealing in detail with network communication protocols from a highly technical perspective.

Once the eligible publications had been selected, duplicate papers were removed, resulting in an initial corpus for analysis.

Third Phase: snowballing selection

The final stage of the process involved the snowballing activity. This phase aimed to identify relevant contributions that had not yet been included in the corpus in line with the guidelines provided by Wohlin, Mendes, Felizardo and Kalinowski (2016). The snowballing procedure consists of two parallel activities: backward snowballing, which refers to the identification of

relevant studies through the reference lists of the selected articles, and forward snowballing, which concerns the identification of studies that cite each of the papers included in the review. The snowballing process was carried out starting from the publications obtained from the previous selection. Therefore, it involved the identification of a high number of bibliographic references that might be interesting. However, many of these referred to publications already analyzed during the previous stages. After removing duplicates and excluding non-relevant papers through title and abstract screening, only 128 additional potentially relevant papers not included in the predefined list were identified. Of these, 70 were found not to be indexed in Scopus and were consequently excluded. Subsequently, the studies considered potentially relevant were subjected to full-text analysis, leading to the exclusion of an additional 37 articles for being out of scope. Overall, the snowballing process contributed 21 additional studies to the final corpus.

Therefore, considering the additional papers obtained, the final structure of the overall SLR corpus was completed, comprising a total of 217 analyzed contributions, as shown in Table 6.

	RQ1	RQ2	RQ3	RQ4
Scopus Results	260	170	383	342
Out Of Scope	83	27	108	93
Selected (1st phase)	177	143	275	249
No Full Text	92	61	136	124
Out Of Scope	9	11	7	22
Selected (2nd phase)	76	71	132	103
Duplicated	186			
Initial Corpus	196			
Snowballing	21			
Total Corpus	217			

Table 6. Corpus selection phases for each RQ

These same stages are also illustrated in Figure 2, which depicts the sequential steps applied, in line with the PRISMA methodology guidelines.

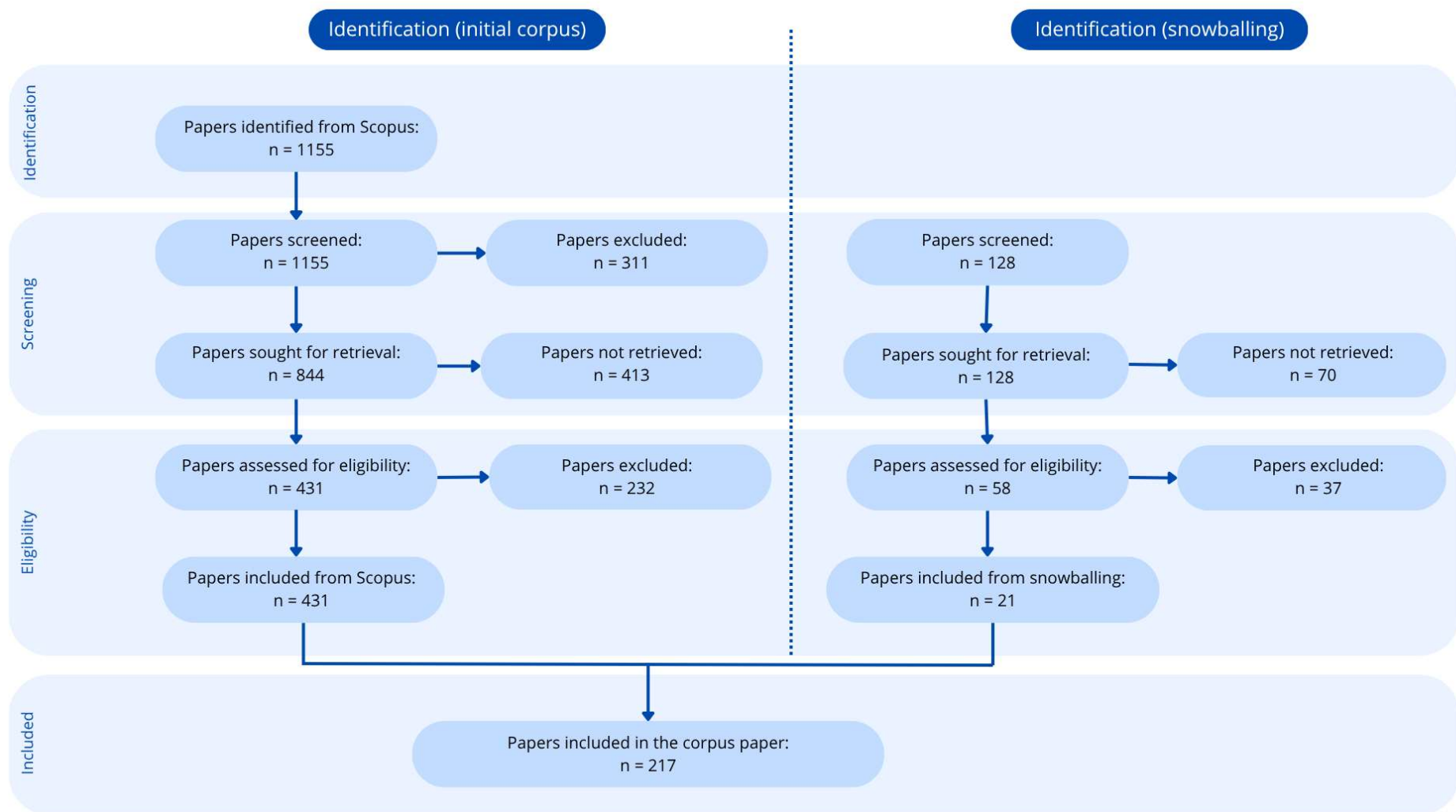


Figure 2. PRISMA Scheme

2.2. Descriptive variables of the papers

A first step toward understanding the state of the art in the literature consists of analyzing the descriptive variables of publications. These variables are related to the information that help contextualize each contribution, such as author information, publication year, and publication source, along with details regarding the type of publication and the research methodology adopted. Examining this information allows for the identification of potential trends, research gaps, and possible geographical influences on the development of the subject under investigation.

2.3. Thematic variables

The analysis then focuses on content-related variables, which are closely linked to the dimensions investigated in this SLR through the four defined research questions. These variables aim to describe the smart warehouse as an evolution of warehouse design, operations, control, and performance management. Accordingly, the dimensions examined are the objectives, technologies, data and processes of a smart warehouse. A detailed discussion of the thematic variables for each of these dimensions follows.

Smart warehouse objectives

The identification of the objectives pursued by a smart warehouse was carried out using an inductive approach. Starting from the analysis of the abstracts of the papers included in the corpus, a comprehensive classification was developed to encompass all the potential goals associated with the adoption of intelligent warehouse solutions. Seven categories emerged from this process: improvement of efficiency and cost reduction, increase in productivity, improvement of inventory management, innovation of logistics and supply chain processes, improved market positioning and competitiveness, increase in safety, and enhancement of environmental sustainability.

The following section provides a description of each objective defined in the context of smart warehousing.

Improvement of efficiency and cost reduction

The first objective, improvement of efficiency and cost reduction, is a broad category encompassing the various aspects of enhanced operational efficiency and improved coordination within the logistics infrastructure. It includes performance improvements in individual warehouse activities, reductions in error rates and positive impacts on business performance indicators. Measures contributing to this objective include those aimed at reducing task completion times (Khan et al., 2022; Tian and Cao, 2023) minimizing resource-related inefficiencies (Ho et al., 2025; Reman et al., 2022) and increasing the ability to manage uncertainty (Tang et al., 2022; Xie and Xie, 2025). Within the context of a smart warehouse, this

objective is supported by route optimization models, the use of data analytics and artificial intelligence for task allocation (Zhou et al., 2025; Asai et al., 2024), and the adoption of IoT technologies to enable real-time communication among systems and devices (Zhu et al., 2023; Srilatha et al., 2023). In addition, several technologies that provide operational support to workers contribute to streamlining warehouse activities (Zhao et al., 2024; Arvind et al., 2025). This category also includes initiatives aimed at reducing operating costs, such as lowering labor requirements, optimizing the use of physical space, and decreasing corrective maintenance expenses through the implementation of predictive maintenance strategies.

Increase in productivity

The second objective, increase in productivity, has a more operational focus and refers to the benefits that smart warehouses bring to logistics performance indicators. This category includes improvements in material handling accuracy and reduction of cycle time, enabled by robotic and automated systems such as cobots, AGVs, AS/RS, and AMRs; increases in overall throughput (Ho et al., 2025); higher sorting speeds (Epe et al., 2024; Pwc, 2021); and the achievement of 24/7 operational continuity through automation (Strøm et al., 2025). For example, the use of smart devices by warehouse operators can significantly reduce task completion times (Epe et al., 2024). Similarly, AI-powered robots are capable of substantially lowering error rates, thereby enhancing operational productivity (PwC, 2021). In addition, simulation techniques can identify delays in workforce procedures and support the development of optimized solutions for workstation layouts and placements (Kosmidis et al., 2024).

Improvement of inventory management

The third objective, improvement of inventory management, concerns the management of stored goods, a central element in warehouse operations and across the entire logistics chain. More effective inventory management generates economic, organizational and logistics benefits. A higher level of real-time control over stock levels, enabled by the integration of IoT sensors and management systems, makes it possible to reduce waste caused by product deterioration, prevent stockout or overstock situations, and improve knowledge of the specific location and status of each item on the shelf (Zhou, 2024; Ellithy et al., 2025; Zhao et al., 2020).

Innovation of logistics and supply chain processes

The fourth objective, innovation of logistics and supply chain processes, has a less operational nature and encompasses outcomes related to technological and organizational advancement within the firm. The adoption of smart solutions, ranging from CPS to Digital Twins (Tang et al., 2022), and from the integration of WMS and ERP systems to cloud platforms (Oyon et al., 2024), transforms traditional warehouses into intelligent cyber-physical systems (Khan et al., 2022; Strøm et al., 2025) capable of supporting real-time decision-making and enabling full horizontal and vertical integration along the value chain (Strøm et al., 2025).

This objective reflects the evolutionary trajectory toward the Industry 4.0 paradigm and, although it may not always represent the main objective of a firm transitioning from a traditional warehouse to a smart warehouse, it is certainly one of the most evident outcomes associated with digital transformation.

Improved market positioning & competitiveness

The fifth objective, improved market positioning and competitiveness, is linked to competitive strength in the market and the value perceived by customers in relation to the firm and its logistics processes. In a highly competitive environment, where even slight differences in response speed or service reliability can lead to significant shifts in market share, the adoption of smart solutions represents a highly relevant strategic lever. Improvements like increased operational flexibility, reduced inefficiencies, and the resulting decrease in order fulfillment times, translate into an improved customer experience, strengthening the firm's reputation and its long-term competitive capability (Pethe et al., 2024).

Increase in safety

The sixth objective concerns safety, namely the protection of human operators who, within a smart warehouse, may work in synergy with automated and robotic systems. The introduction of pieces of equipment, such as AGVs, AMRs, cobots and drones, into warehouse operating spaces creates new forms of human-machine interaction that require specific preventive measures. Smart solutions address this challenge through the integration of computer vision (Sang-Ngenchai et Nakazawa, 2025), object recognition (Tadjine et al., 2025), proximity sensors, and alarm systems (Liu et al., 2010; Zhou, 2024; Heng and Kaiyou, 2022) enabling the real-time detection of hazardous situations (Sang-Ngenchai and Nakazawa, 2025; Ellithy et al., 2024). Continuous monitoring of environmental parameters, such as temperature, humidity, and smoke, also helps safeguard working conditions and reduces the occurrence of accidents (Heng and Kaiyou, 2022; Liu et al., 2010).

Increase in environmental sustainability

The final objective, increase in environmental sustainability, is closely linked to contemporary challenges and the constraints associated with the planet's limited resources. An increasing number of firms pursue this objective both in response to regulatory requirements and to reduce energy-related costs. In the context of smart warehousing, environmental sustainability is reflected in the optimization of energy consumption through intelligent management systems, the reduction of CO₂ emissions associated with logistics operations through route optimization and the adoption of energy-efficient technologies, and the minimization of waste through more accurate management of inventory and resources (Umamaheswari et al., 2024; Lei, 2024; Nicoletti and Appolloni, 2024).

Smart warehouse technologies

The second research question concerns the enabling technologies of a smart warehouse. This topic has been widely addressed in the literature (Khan et al., 2023; van Geest et al., 2021; Tikwayo and Mathaba, 2023; Strøm et al., 2025), and some of these studies have proposed taxonomies and classifications to categorize these technologies into representative groups. Among these, a relevant reference is the framework proposed by Strøm et al. in “Conceptualizing Warehouse 4.0 Technologies in the Third-Party Logistics Industry: An Empirical Study” (2025), which serves as the main source for the categorization adopted in this review. However, several modifications to the original framework were introduced in order to define categories capable of comprehensively encompassing all relevant Industry 4.0 technologies. In particular, compared with the categories identified in the aforementioned study, an eleventh category, Communication Technologies, was added to include technologies aimed at enabling data transmission among devices, machinery, and systems. Furthermore, the category Big Data and Data Analytics was expanded to incorporate Artificial Intelligence, as AI is based on these first elements and constitutes a further enhancement of analysis resulting in the new category Data Analytics and Artificial Intelligence. This expansion allows to capture the growing relevance and increasing adoption of AI-based technologies in the smart warehouse environment which would not have been adequately captured under the initial category configuration. Finally, the category Horizontal and Vertical System Integration was generalized into Information Systems Integration, because, when referring to technologies, the intention was to emphasize that the actual contribution in terms of integration is provided by information systems

Considering these adaptations, the final categories adopted in this study are Internet of Things (IoT), Automation and Robotics, Augmented & Virtual Reality, Information Systems Integration, Additive Manufacturing, Data Analytics and Artificial Intelligence, Simulation, Cloud Computing, Cybersecurity, Blockchain, and Communication Technologies.

The following section provides a description of each technology defined in the context of smart warehousing.

Internet of Things

IoT represents the foundational enabling technology for data collection from the physical environment. It is defined as a dynamic global network infrastructure with self-configuring capabilities, in which physical and virtual objects are endowed with identities, physical attributes, and intelligent interfaces (Vermesan et al., 2011). In its industrial application, it is referred to as Industrial Internet of Things (IIoT). The system relies on heterogeneous sensors: RFID for contactless automatic identification of pallets, goods, and equipment (Yang et al., 2022); LiDAR sensors for spatial detection; and environmental sensors for monitoring temperature, humidity, and weight. The availability of real-time data produces benefits at multiple levels by improving warehouse management through time savings and enhanced visibility, with continuously updated information providing the basis for operational

optimization strategies by supporting timely, data-driven adjustments to warehouse operations. Globally, by contributing to supply chain efficiency, through a fluent material flow, product lifecycle optimization and digitalization of SMEs (Vukićević et al., 2021). Furthermore, continuous product tracking represents one of the key enablers for the development of smart products, defined as products equipped with ICT components capable of collecting and communicating data to higher-level systems (Lichtblau et al., 2015).

Automation and Robotics

Automation represents one of the primary drivers of transformation in modern logistics systems. The integration with AI, Machine Learning, and Reinforcement Learning has progressively shifted these systems from being automatic to autonomous, a trajectory described in the literature as Intelligent Automation (Acker et al., 2023). The robotic ecosystem of the warehouse encompasses solutions for different operational functions: traditional AGVs navigate along predefined paths via magnetic-based or optical guides (Lynch et al., 2018), whereas AMRs move dynamically through sensors, LiDAR, and AI-based navigation algorithms, making them particularly suited to frequently changing warehouse configurations (Arvind et al., 2025). A further layer of warehouse automation concerns storage management: AS/RS systems in their different variants, automate storage and retrieval operations (Hur and Nam, 2006). Collaborative robots work alongside human operators to increase productivity and reduce physical and cognitive workload (Arvind et al., 2025), while Unmanned Aerial Vehicles (UAVs) are used for inventory counting, stock inspection, and surveillance through the integration of cameras, RFID, and computer vision. The coordination of the entire automated ecosystem is entrusted to the Programmable Logic Controller (PLC), which acts as an integration layer between physical devices and digital systems (Vijayachitra et al., 2025).

Augmented & Virtual Reality

Augmented Reality (AR) is part of the broader Extended Reality (XR) concept, which encompasses Mixed Reality (MR) and Virtual Reality (VR). Unlike VR, which fully immerses the user in a digital environment, AR overlays digital information onto the real world without removing the operator from their physical context. MR, on the other hand, involves the fusion of virtual elements with the real world allowing real-time interaction between the two worlds. Although considered one of the most promising technologies of Industry 4.0, its adoption in real warehouse scenarios remains limited (Piardi et al., 2019). From an operational standpoint, it contributes to reducing errors in handling and placing activities and supports pick-by-voice and pick-by-light operations by providing dynamic, context-sensitive instructions in real time. Commonly used hardware includes smart glasses, smartphones, and tablets; smart glasses in particular enable the integration of intelligent recommendation systems (Zhang et al., 2025) and machinery anomaly detection (Tayal et al., 2022), while also supporting an emerging trend in gamification aimed at increasing operator engagement and motivation (Epe et al., 2024).

Information Systems Integration

Horizontal integration across the value chain and vertical integration across the hierarchical levels of an organization are considered structural pillars of Industry 4.0 (Ustundag and Cevikcan, 2018; Kagermann et al., 2013). This integration is made operational by an ecosystem of IT systems: which effectively implement integration in practice by exchanging both the data collected through IoT sensors and information produced through human activities. For example, the Warehouse Control System (WCS) coordinates physical equipment in accordance with Warehouse Management System (WMS) directives; the Manufacturing Execution System (MES) operates at the level of production planning and control and the Enterprise Resource Planning (ERP) integrates administrative, logistics, and commercial functions into a single platform. Also included in this category are the Inventory Management System (IMS), the Advanced Planning and Scheduling system (APS), and the Transport Management System (TMS) (Reaidy et al., 2014), whose interoperability constitutes one of the technological pillars of Industry 4.0. Cyber-Physical Systems (CPS) represent the underlying infrastructure connecting the physical and virtual dimensions of production processes, enabling real-time monitoring through IoT devices (Mashayekhy et al., 2022).

Additive Manufacturing

Additive manufacturing consists of reproducing objects from 3D models through an additive process. This technology offers significant advantages in terms of production flexibility and scalability: it enables, for example, the creation of prototypes for testing and the on-demand production of spare parts, reducing the need to hold replacement part inventories and shortening response times in the event of failure or operational need. Another possible advantage is that modules, components, and even finished products can be manufactured in a single location or distributed anywhere along the supply chain (Kandarkar and Ravi, 2024). AM processes are mainly distinguished by the use of polymers, typically adopted for prototyping and low-load applications, and metals, used for functional, high-performance, and load-bearing components in industrial sectors (Duda and Raghavan, 2016).

Data Analytics and Artificial Intelligence

The volume, variety, and velocity of data generated by connected devices give rise to the Big Data phenomenon (Khan et al., 2023). The transformation of raw data acquired from sensors and intelligent devices into structured information suitable for in-depth analysis requires analytical processing (Pethe et al., 2024). Recognizing patterns and trends in collected data is valuable for multiple operational functions, enabling predictive maintenance, anomaly detection, and production and inventory forecasting. Artificial Intelligence (AI), defined as the simulation of human intelligence by machines capable of learning, reasoning, and decision-making (Russell and Norvig, 2021), plays a transformative role in this context, with applications ranging from routing to forecasting and inventory management (Antoniou et al., 2026). Machine Learning extracts patterns from data, enabling for example path planning and self-localization

for autonomous vehicles (Jagadeesan et al., 2023); Deep Learning, through Convolutional Neural Networks (CNNs), supports visual classification, while Artificial Neural Networks (ANNs) are applied in process control and fault detection (Sarathkumar et al., 2025). Computer Vision, in its industrial declination of Machine Vision, is used for automated monitoring and quality control (Vukićević et al., 2021). Finally, Reinforcement Learning enables an agent to make optimal decisions through iterative interaction with the environment (Zhang et al., 2012), with applications in routing and dynamic scheduling. In its Deep Reinforcement Learning variant, it is used for dynamic storage location assignment (Francuz et al., 2025).

Simulation

Simulation is defined as the process of designing a model of a real or hypothetical system in order to describe and analyze its behavior (Scheidegger et al., 2018). It constitutes a decision-making support tool that allows optimization strategies to be evaluated without requiring a physical model in advance. Among the various approaches detailed by de Paula Ferreira, Armellini and De Santa-Eulalia (2020) are included, for example, Discrete Event Simulation, System Dynamics, and Agent-Based Simulation. Both these simulation types represent an approach widely applied in logistics: by modeling all involved entities, from AGVs to inventory items and operators, as agents, it allows complex dynamics to be analyzed in a flexible and scalable manner (Kodadi et al., 2025). Moving steps from simulation, the Digital Twin emerges as one of the most promising technologies in the Industry 4.0 context. It consists of a highly faithful simulation capable of mirroring the physical system in real time (de Paula Ferreira et al., 2020). It goes beyond the realization of a virtual prototype by establishing continuous two-way communication between the physical system and its digital counterpart, simulating its behavior in real time (Acker et al., 2023) and replicating processes, systems, and devices through 3D models (Tang et al., 2023). Its operation depends closely on IoT, which constitutes its foundational data infrastructure (Lv et al., 2022), since IoT enables the real-time transmission of information.

Cloud Computing

Cloud computing provides on-demand computational resources as data, software, platforms, and infrastructure delivered via the Internet, increasing computational capacity, reducing operational costs, and making intelligent warehouse technologies, such as management systems, the Internet of Things or automated systems, more accessible and scalable (Min, 2022). Data can be stored in online databases that enable their management, processing, and sharing, with characteristics of flexibility and on-demand availability (Xingqi et al., 2017). This centralized paradigm is complemented by Edge Computing, which moves data processing to local nodes close to the data source, significantly reducing latency, a critical factor in applications where automated systems and robots must operate in a coordinated and real-time manner (Zhang and Abellera, 2025). The integration of Cloud and Edge Computing,

combined with intelligent algorithms, enables a balance between scalability and responsiveness (Sarathkumar et al., 2025).

Cybersecurity

The growing hyperconnectivity of industrial systems makes cybersecurity a structural component of Industry 4.0: in such hyperconnected industrial environments, new challenges emerge related to information security, which represents one of the most pertinent concerns to be addressed (Al Mawali et al., 2021). Its function is both preventive and detective, safeguarding the integrity of data and the overall system (Strøm et al., 2025). The proliferation of cloud technologies, data centralization, and the extensive information flows managed in modern production environments make the development of an adequate defense infrastructure increasingly urgent.

Blockchain

Blockchain ensures end-to-end traceability across the value chain, significantly reducing the risks of counterfeiting and data tampering (Arvind et al., 2025). Its potential lies in the ability to make products "digital" by providing traceable and verifiable information at every stage of their lifecycle (Wang et al., 2019; Verma et al., 2025), in line with the smart product concept enabled by IoT. A smart product, in fact, is a physical object equipped with ICT components (sensors, RFID, communications interface, etc.) that make it uniquely identifiable, so it can interact with its environment, record its environment and status through sensors, and offer various add-on functionalities in operation (Deindl, 2013). By making every transaction recoverable and verifiable, it strengthens trust among all supply chain participants (Akram and Bross, 2018; Morgan et al., 2018) and facilitates the identification of errors, anomalies, and inefficiencies, fostering a more proactive management of logistics processes. This type of technology is frequently applied in the food sector for food traceability, in the healthcare sector for medical logistics traceability, and also in the manufacturing and agricultural sectors (Rahman et al., 2024).

Communication Technologies

Effective data transmission is enabled by an articulated ecosystem of communication technologies. 5G networks provide high bandwidth, low latency, and near-real-time connectivity (Kanellos et al., 2022); the combination of 5G and edge computing creates a high-performance platform for advanced automation and real-time analytics (Arvind et al., 2025). Looking ahead, 6G aims to extend this perimeter toward native AI and blockchain platforms that are ultra-fast and highly adaptive (Stavroulaki et al., 2021). At the protocol level, Message Queuing Telemetry Transport (MQTT), a lightweight messaging protocol for data exchange between IoT devices, offers an efficient publish/subscribe architecture for communication between heterogeneous devices (Bukhamseen et al., 2023). For short-range communication, Zigbee, a short-range, low-power communication standard, provides secure transmission and

a flexible network topology (Liu et al., 2010), Bluetooth Low Energy (BLE) offers a low-energy solution for tracking and monitoring, while Ultra-Wideband (UWB) stands out for its exceptional precision in indoor positioning (Aouani et al., 2023). For long-range, low-power transmissions, the LoRa (Long Range) protocol is particularly well-suited to large warehouse environments, as its extended communication range allows it to cover wide distances with minimal energy consumption (Lee et al., 2017). Furthermore, there are Wireless Sensor and Actuator Networks (WSAN), which enable bidirectional communication between machines and devices.

Smart warehouse data generated and managed

Within the scope of this Systematic Literature Review, one of the analytical dimensions concerns the types of data generated, monitored and managed in a smart warehouse. To structure this dimension on a theoretically grounded basis, reference was made to the contribution of Ashraf, Yalci, and Hos (2024), which highlights the tendency in the current literature to classify warehouse flows into material flow, information flow and financial flow. The authors further extend this framework, based on interviews with industry practitioners, by adding two emerging categories: human flow and equipment flow.

For the purposes of this research, which is operational in nature, the financial flow was excluded, and the analysis was structured around the remaining four categories.

Data on physical flows and warehouse infrastructure

The category data on physical flows and warehouse infrastructure includes the data most directly related to the physical movement of goods and to warehouse infrastructure. It encompasses identification and tracking data, such as product IDs, current material location, and movement history (Li et al., 2011; Rizqi et al., 2024), which are essential to ensure visibility and control across the entire logistics chain.

These are complemented by internal environmental monitoring data, such as temperature and humidity levels (Liu et al., 2010; Gowrishankar et al., 2023), which are relevant for managing products subject to specific storage conditions or, more generally, for reducing product deterioration on the shelf, as well as data on product physical characteristics, including weight, dimensions, and packaging type (Daïos et al., 2024; Khan et al., 2023), which are necessary for space optimization and handling operations.

The category also includes inventory data, such as quantities per SKU, number of stored pallets, and warehouse locations (Arvind et al., 2025; Reman et al., 2022) along with structural data related to the physical infrastructure of the warehouse itself (van Geest et al., 2021), such as spatial organization, distances between storage locations and layout. These are required to support path-planning strategies for both human and autonomous robots.

Data on information flows

The category data on information flows refers to the set of data that supports and complete information flows within the logistics chain. This category includes both the data that enriches the information associated with the products handled and the data required to enable the management of a smart warehouse. It includes security-related data, both in the digital domain, such as intrusion attempts or data protection issues, and in the physical domain, such as workplace accidents (Wu et al., 2025; van Geest et al., 2021). It also encompasses data on energy and environmental impact, such as CO₂ emissions and energy consumption (Strøm et al., 2025; Li et al., 2022), as well as order-related data, which constitute a central informational element (Zhang et al., 2021) for coordinating demand with warehouse operations.

Data on human flows

The third category, data on human flows, concerns the human resources employed in the warehouse and the information associated with them. It includes personnel identification and (Cheng and Tu, 2019), as well as data related to their movements within the warehouse.

In a smart warehousing context, such data are relevant not only for human resource management, but also for integration with operational support systems such as wearable devices (Epe et al., 2024), for managing access to corporate information systems, for task allocation, and for defining appropriate training and upskilling pathways (Kosmidis et al., 2024; Koreis and Klumpp, 2025).

Data on equipment flows

The final category, data on equipment flows, concerns industrial machinery, transport vehicles, and production support equipment (Halawa et al., 2020; Lyu, 2024). The data included in this category primarily relates to the status and performance of these assets: error logs, anomaly detection signals, operational performance data of machinery, and vehicle identifiers.

This type of data is central to predictive maintenance systems and to real-time monitoring of operational efficiency (Ho et al., 2025), as well as to performance analysis and the assessment of task completion times (Oyon et al., 2024).

Smart warehouse operational processes

One of the questions of this research is to identify how Industry 4.0 technologies are applied in warehouse logistics and, in particular, how they impact each specific process, from inbound to outbound operations. To define the typical warehouse management processes, this study refers to the framework proposed by Bartholdi and Hackman (2019).

According to Bartholdi and Hackman (2019), the main warehouse processes are receiving, put-away, order picking, checking, packing and shipping.

Based on this framework, the processes have been reorganized for this study, and a distinct storage process has been introduced to include all activities related to inventory monitoring

and management. Moreover, the packing process has been separated from shipping and was associated with the antecedent sorting process.

As a result, the final list of processes considered in this work is: receiving, put-away, storage, picking, sorting and packing, and shipping.

Receiving

The receiving process begins even before the physical arrival of stock in the warehouse. It includes an initial notification regarding the unloading, to help schedule receipts and coordinate subsequent operations within the warehouse. Upon arrival, the goods are identified by scanning their codes and the quantity of each SKU is registered in the Warehouse Management System. An inspection is carried out to detect any anomaly, such as damage, incorrect counts, wrong descriptions. If any issues are identified, they are promptly reported to the competent office. Damaged goods are then placed in a designated area of the warehouse, waiting for further handling, while compliant materials are correctly stored in their assigned locations.

In most cases, this process ensures the transfer of ownership and risk and enables the corresponding payment, depending on the applicable Incoterms.

Putting-away

The putting-away process, together with receiving, is part of the inbound operations in a warehouse. It concerns the assignment of a storage location to the incoming stock, with the aim of optimizing subsequent product retrieval during the picking phase, followed by the physical placement of the goods in the assigned storage location. The location assignment problem is widely discussed in academic literature (Bashatah and Elnaggar, 2025), due to its significant impact on operational efficiency: the choice of storage location largely determines the speed and cost of retrieving products. The goods are transported by the operators to the assigned storage location and registered in the Warehouse Management System. After having checked the correspondence of the stock details, the goods are positioned and, if necessary, the storage information is modified. Information is transmitted to the system to ensure real-time data updates (Yang et al., 2023).

Storage

The storage process includes monitoring and managing stock levels. Depending on the type of products stored, with increasing attention to preventing the deterioration of goods, several indoor parameters like temperature, humidity or light intensity are monitored to ensure proper maintenance. Real-time awareness of stock levels enables more efficient management of operational processes. Stock levels can be monitored either continuously or periodically. Different inventory management policies can be adopted, which define when and how much to order. For example, in some cases a fixed quantity is ordered when stock reaches a minimum level, the reorder point (Cao et al, 2025). Another common approach is to determine an optimal

order quantity based on costs, called Economic Order Quantity. In other cases, inventory is checked at regular intervals and replenished up to a target level, commonly known as the order-up-to-level.

Picking

The picking process is essential in the warehouse context and for the entire order management process, as it refers to the retrieval of goods from their storage locations. Order-picking represents almost 55% of warehouse operating costs (Tompkins et al., 2010), and the most time-consuming sub-activity is travelling, which consists in the movement of the operator eventually assisted by automated vehicles to retrieve goods from their storage locations on the shelves.

When the Warehouse Management System (WMS) generates a pick list, order pickers travel to the storage locations of the required items and retrieve the requested quantities, especially when the list includes multiple orders containing multiple SKUs. If an order involves a single type of product, the operator can easily reach the storage location and pick the desired quantity. However, if the order includes multiple SKUs, the operator must pick each product separately, often combining the picking and sorting activities to prepare the order efficiently. In some cases, for the batch order picking, the operator needs to reach different locations retrieving the items of all the listed orders.

Just like when items are located, every time an item is picked the operator scans the identification code and updates the inventory information.

Therefore, reducing warehouse operating costs largely depends on optimizing the routing of order pickers.

Several order-picking strategies can be adopted, differing in the number of orders processed on a single picking tour and in the logic used to group them. In some cases, a single-order picking strategy is more convenient, particularly when an order includes multiple pallets of the same SKU. In other cases, a batch picking strategy is preferred, where items belonging to different orders are picked in the same route. When multiple orders are handled within the same picking tour, different batching logics can be applied. One approach is proximity-based order batching, where orders are grouped according to the physical location of items in the warehouse. Another approach is time-window order batching, where orders received within a fixed time interval are grouped and processed together.

The introduction of several technologies, such as Automated Guided Vehicles (AGV), Autonomous Mobile Robots (AMR) and other automated systems, has increasingly supported the automation of these activities, enabling a more efficient organization of the picking process and generating benefits in terms of costs, time and productivity.

Sorting and packing

Except in the case of single-order picking, the items collected from storage locations usually must be grouped based on the composition of each order. This activity is known as sorting.

Sorting precedes the final preparation stage of the order, packaging, during which items are packed and prepared for shipment. Both sorting and packaging activities are fundamental to ensuring a satisfactory customer experience, as any error may significantly affect customer satisfaction, the efficiency of order management and overall cost of operations.

In addition to traditional warehouse operations, other value-added processes (VAP) are increasingly performed within warehouses. Typical value-added processes include labeling, repackaging or kitting, which consists in the assemble of multiple SKUs in a single unique unit. All these activities are time-consuming and generate additional operational costs, as they require dedicated labor and facilities.

Shipping

The final process of order management is shipping, which is part of the outbound process in a warehouse. Like the receiving process, the shipping process requires a significant amount of documentation to certify the delivery, the quantity of items shipped and their final destination. The most fundamental capability of a WMS is to record receipt of inventory into the warehouse and to register its shipment out. This is fundamental because it drives essential financial transactions. Once everything has been checked and confirmed to be correct, the material is loaded onto trucks and ready to be sent.

In addition to the core warehouse processes described above, when both finished products and intermediate components are handled, further activities like final assembly operations can be postponed and carried out in dedicated warehouse areas. This aims to postpone certain supply chain activities (e.g., assembly, packaging, labelling, distribution, design, purchasing) until more accurate information regarding customer order is realized (Pagh and Cooper, 1998; Yang et al., 2004a; Zinn, 2019).

3. Analysis and findings

Having defined the variables examined in this Systematic Literature Review, it is now possible to conduct a comprehensive analysis of the current state of the art in smart warehousing research. Accordingly, this chapter presents an analysis of the selected corpus of publications, considering both its descriptive characteristics and its thematic dimensions.

3.1. Descriptive analysis of the corpus

The analysis of the corpus represents an essential starting point for understanding the state of the art regarding the topic of smart warehousing. Through the examination of the main bibliometric variables of the existing literature, it is possible to identify the ways in which the topic has developed internationally, as well as the main trends that have characterized its evolution over time.

Publication over time

The corpus analyzed consists of 217 scientific articles published between 2010 and 2026. The analysis of the time distribution of publications (Figure 3) highlights an increase in academic interest in the topic. The first publications, still sporadic, appeared during the period 2010–2017; starting from 2018, a more substantial increase in the number of published papers can be observed, with an average of more than 30 articles published per year from 2023. This trend can be explained by the fact that, as discussed in Section 1.1.2, the concept of Industry 4.0 was introduced in 2011. Even earlier, in 2010, the European Union launched the initiative “An Integrated Industrial Policy for the Globalisation Era”, aimed at overcoming the sector-specific approach that had traditionally characterized industrial policies. Consequently, the emergence of this cross-sectoral process of digital transformation and globalization also affected warehouse operations, given their central role within companies' supply chains. In 2016, the European Commission launched the Digitising European Industry (DEI) initiative to strengthen the competitiveness of European firms and enable them to benefit from digital innovations (European Court of Auditors, 2020). This initiative may have contributed not only to the modernization of the physical and digital infrastructures of European companies, but also to the promotion of academic research in this field. It is important to emphasize that the apparent decline in publications in 2026 should not be interpreted as a reduction in scientific interest in the topic; rather, it is due to the timing of the present Systematic Literature Review. The selection of articles from Scopus was carried out up to January 2026, at which time only a limited number of contributions referring to the current year were available.

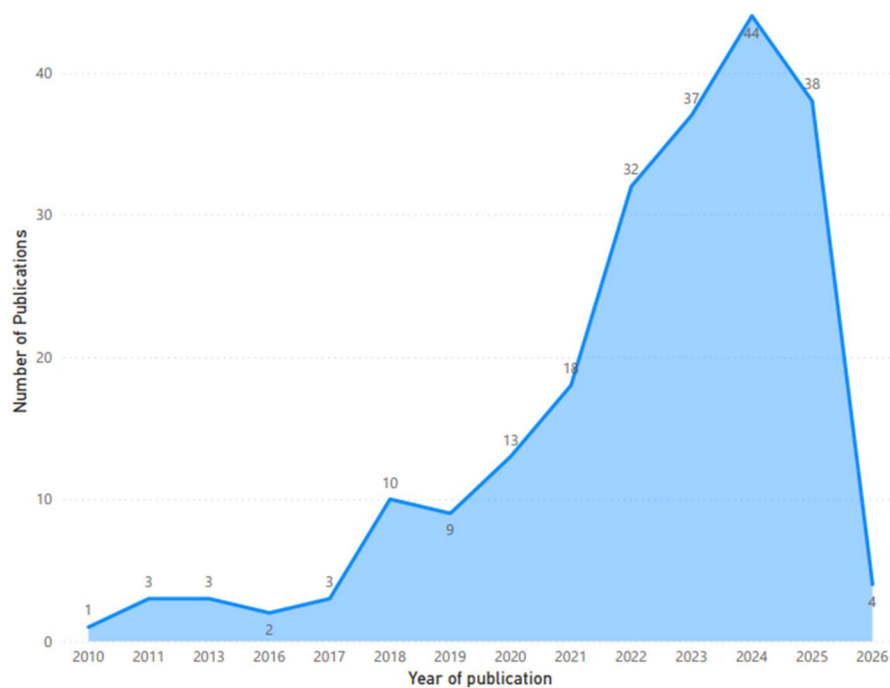


Figure 3. Publications over time

Publication Type

The analyzed publications mainly belong to two categories: conference papers, which account for 59.9% of the total, and journal articles, representing 34.6% (Figure 4). This distribution is consistent with the relatively recent nature of smart warehousing research. Conference papers often serve as the primary channel for disseminating preliminary findings, innovative ideas, and early theoretical developments within the scientific community (Faramarzi-Oghani et al., 2022; Ghasemi et al., 2022). In contrast, journal articles generally present more mature and comprehensive studies, characterized by established methodologies (Tikwayo et al., 2023). Less common are reviews, book chapters, surveys, and short surveys, which together account for slightly more than 5% of the analyzed corpus, probably due to the relatively limited maturity of the research field. In particular, reviews require a substantial and consolidated body of literature to enable critical analysis and systematic synthesis of existing knowledge. Similarly, book chapters are part of volumes addressing well-established topics supported by a solid theoretical foundation. Moreover, given the growing interest in smart warehousing, academics may prefer publishing their work in journals or conference proceedings, which provide broader visibility, especially for a topic experiencing increasing interest. As for surveys and short surveys, their limited presence can also be explained by the relative immaturity of the field.

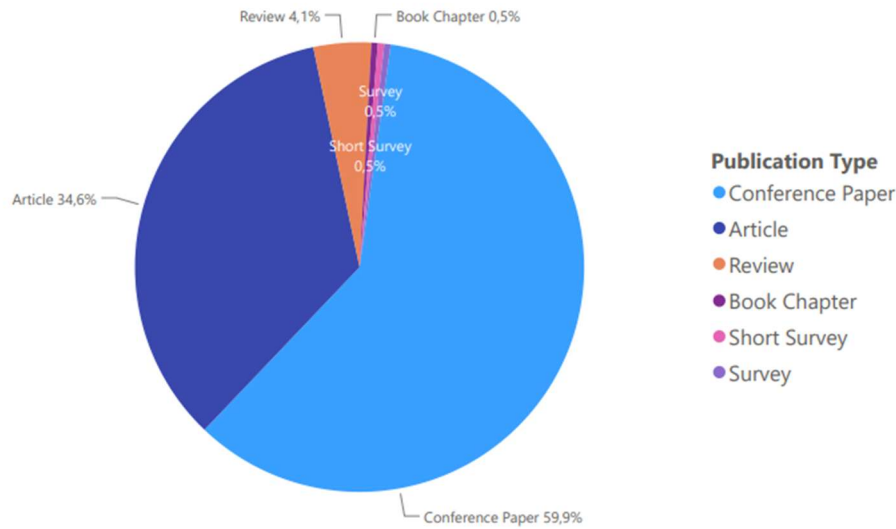


Figure 4. Publication Type

Methodology

A further point of interest emerges from the analysis of the methodologies adopted in the corpus papers, as it provides insights into the nature of the studies conducted on smart warehousing. The assignment of methodological categories was carried out in parallel with the review process. Methodology types were identified based on the characteristics of each publication, considering both the structure of the paper and the sequence of research activities undertaken. The methodologies identified include Design Science research-like, literature reviews, optimization models, case studies, conceptual frameworks, simulations, and survey and empirical studies (Figure 5). For many of these methodological categories, papers were classified through a deductive approach based on the reading of each study and the subsequent recognition of its methodological characteristics. In contrast, for Design Science Research-like studies a more inductive approach was followed. Specifically, this category was created to group papers exhibiting a recurring configuration that does not correspond to an officially recognized methodological category in academic literature. Indeed, this category was considered because these contributions exhibit a structure comparable to that of Design Science Research (DSR), while not fully satisfying all the methodological requirements necessary for a rigorous classification as DSR. In particular, although they do not completely follow the DSR standard phases, many of these studies incorporate some of its key phases, such as the design and development of a technological artefact, the demonstration of its applicability in real or simulated environments and the evaluation of its performance through quantitative analyses. Accordingly, this category includes studies that adopt some of the characteristic phases of DSR without following the entire methodological process that would justify their direct classification. Indeed, a DSR process is characterized by four distinct steps: solution incubation, in which the problem is framed and an initial solution is proposed; solution refinement; Explanation I – substantive theory, in which the relevance and applicability of the

proposed solution are assessed; and Explanation II – formal theory, in which the theoretical and statistical generalizability of the solution is strengthened, leading to the development of a formal theory (Holmström et al., 2009). More generally, the DSR aims to develop a solution to a practical problem, referred to as an artifact, whose findings are subsequently generalized to demonstrate the theoretical relevance of the proposed solution (Romme and Holmström, 2023). This methodology category accounts for approximately 46% of the corpus, and its predominance reflects the relatively recent stage of development of smart warehousing research. In a context characterized by rapid technological evolution, a large share of the literature focuses on the design and testing of new solutions (Sathya et al., 2023; Antoniou et al., 2026), the integration of multiple technologies (Liu et al., 2022; Tang et al., 2023), and the implementation of robotic and autonomous systems (Zhao et al., 2024; Marin-Segura et al., 2025). Consequently, research in this area remains largely exploratory, aiming to investigate the potential practical applications of technological innovations within logistics and warehouse operations. The next most frequent methodologies are literature reviews and optimization models. The next most frequent methodological categories are literature reviews and optimization models, although the number of publications adopting these approaches is considerably lower than that of DSR-like studies. Literature reviews provide syntheses of the state of the art on specific research topics and, as previously discussed, tend to be more common in research fields that have reached a higher degree of scientific maturity. Regarding optimization models, it is important to underline that the smart warehousing literature includes numerous contributions focused on optimizing specific processes, particularly in autonomous systems path planning. Consequently, many publications propose mathematical models aimed at addressing narrowly defined optimization problems. However, most of these studies were excluded from the present systematic literature review because of their highly specialized focus. Only a limited number of optimization-oriented papers were retained, namely those providing insights that were considered relevant to the broader objectives of this review. Finally, case studies, conceptual frameworks, simulations, survey and empirical studies are less frequently represented and together account for approximately 27.4% of the analyzed literature. The limited number of conceptual frameworks can be attributed to the fact that research on smart warehouses often concentrates on individual themes or single dimensions of analysis. In contrast, the development of a conceptual framework requires a broader and more integrative perspective. As discussed in Section 1.2, the main literature reviews and theoretical contributions on the topic highlight the relatively small number of conceptual frameworks currently available. The limited presence within the analyzed body of literature case studies, surveys, simulations, and empirical studies, can be attributed to the fact that these research approaches require the availability of real-world data collected over sufficiently long periods of time. As smart warehouse technologies are still relatively recent, their limited maturity and adoption have so far restricted the availability of such data, resulting in a lower number of studies employing these methodologies. It is important to emphasize that papers did not always conform to a single methodological approach, as authors frequently adopted

mixed methods in their investigations. In such cases, each paper was assigned to the predominant methodology, namely the approach that most strongly underpinned the overall research design and objectives.

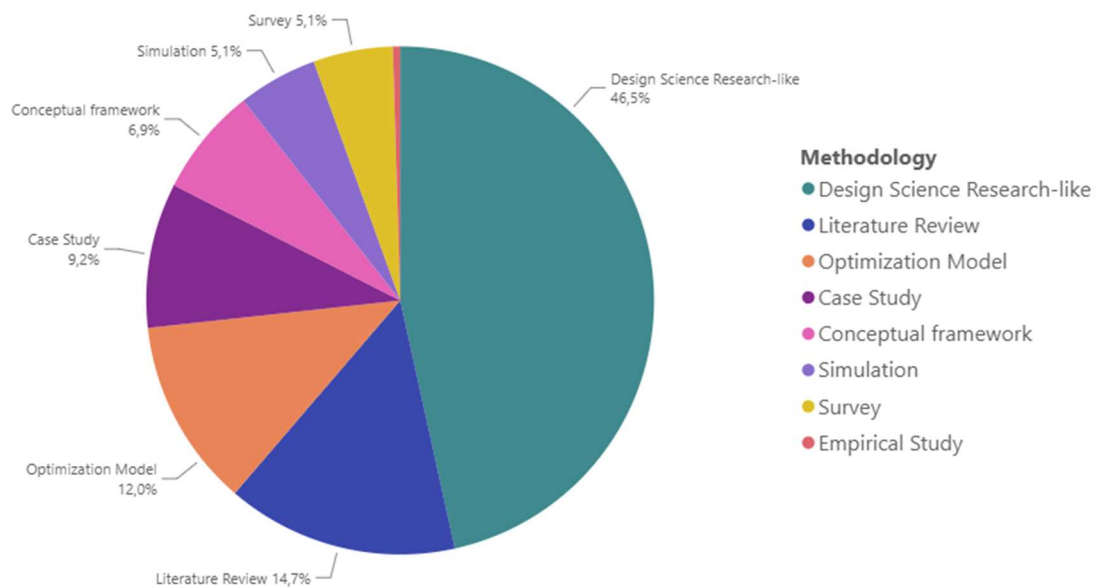


Figure 5. Methodology

To complement the methodological analysis, the methodology type adopted by the authors of the publications was also examined, which can be classified as qualitative, quantitative, or mixed. Similar to methodological categorization, the mixed approach refers to studies that combine descriptive and theoretical discussions with quantitative analyses, such as experimental tests, statistical analyses of collected data, or simulations. According to the results of the analysis, the proportions of quantitative and qualitative studies are almost perfectly balanced, representing 41.5% and 41.9% of the corpus of articles, respectively. Meanwhile, 16.6% of publications take a mixed approach. This information is represented in Figure 6.

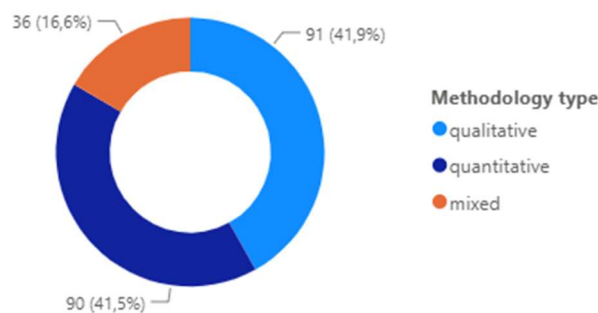


Figure 6. Methodology type

Nationality of the First Author

The analysis of the nationality of the first author allows for the observation of the geographical distribution of scientific interest on smart warehousing. This makes it possible to reflect on the propensity of specific geographical areas towards the topic, in relation to their industrial structure, long-term strategic objectives, and national technological development prospects. The results reported in Figure 7 highlight a clear dominance of China (35.0% of the corpus paper) in terms of the number of publications, consistent with its advanced technological position and with the substantial investments allocated to digital transformation and the modernization of the national manufacturing sector, aimed at revitalizing Chinese manufacturing industry (Breque et al., 2021). India also shows a significant number of scientific contributions (14.3%), attributable to the ongoing process of technological and industrial innovation that is affecting the country and its growing role as an active player in the global industrial landscape (Maiorano, 2024).

Figure 8 shows the geographical distribution of publications.

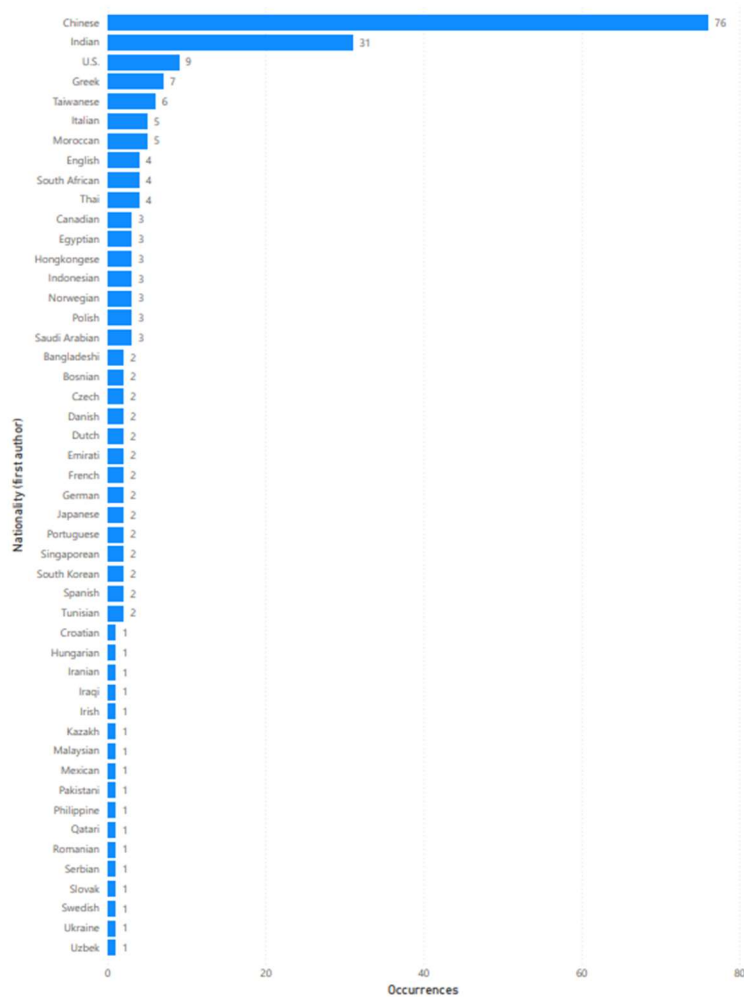


Figure 7. Publications by nationality of the first author



Figure 8. Geographical distribution of publications

A Cumulative Distribution Analysis based on the frequency of country occurrences within the corpus revealed that two countries account for nearly half of the total publications included in the dataset (49.3%). Approximately 42.4% of the publications are attributable to 30 countries, whereas the remaining 8.3% are associated with a further 18 countries. Figure 9 summarizes the Cumulative Distribution Analysis graphically, while the complete distribution is presented in Table 7.

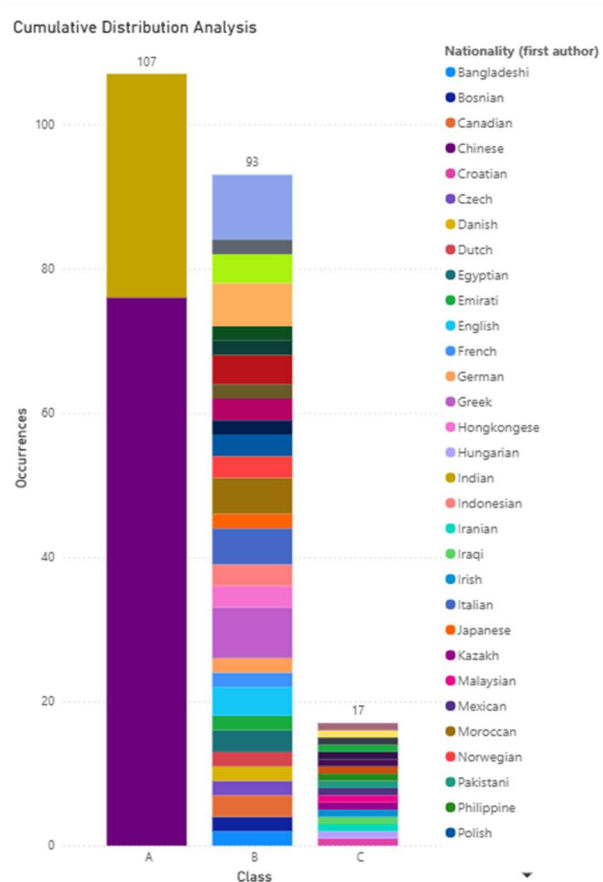


Figure 9. Cumulative Distribution Analysis

Nationality (first author)	Number of publications	Perc Cumulata	ABC Class
Chinese	76	35,02%	A
Indian	31	49,31%	A
U.S.	9	53,46%	B
Greek	7	56,68%	B
Taiwanese	6	59,45%	B
Italian	5	64,06%	B
Moroccan	5	64,06%	B
English	4	69,59%	B
South African	4	69,59%	B
Thai	4	69,59%	B
Canadian	3	79,26%	B
Egyptian	3	79,26%	B
Hongkongese	3	79,26%	B
Indonesian	3	79,26%	B
Norwegian	3	79,26%	B
Polish	3	79,26%	B
Saudi Arabian	3	79,26%	B
Bangladeshi	2	92,17%	B
Bosnian	2	92,17%	B
Czech	2	92,17%	B
Danish	2	92,17%	B
Dutch	2	92,17%	B
Emirati	2	92,17%	B
French	2	92,17%	B
German	2	92,17%	B
Japanese	2	92,17%	B
Portuguese	2	92,17%	B
Singaporean	2	92,17%	B
South Korean	2	92,17%	B
Spanish	2	92,17%	B
Tunisian	2	92,17%	B
Croatian	1	100,00%	C
Hungarian	1	100,00%	C
Iranian	1	100,00%	C
Iraqi	1	100,00%	C
Irish	1	100,00%	C
Kazakh	1	100,00%	C
Malaysian	1	100,00%	C
Mexican	1	100,00%	C
Pakistani	1	100,00%	C
Philippine	1	100,00%	C
Qatari	1	100,00%	C
Romanian	1	100,00%	C
Serbian	1	100,00%	C
Slovak	1	100,00%	C
Swedish	1	100,00%	C
Ukraine	1	100,00%	C
Uzbek	1	100,00%	C
Total	217		

Table 7. Number of publications per Nationality

Author keywords

To confirm the robustness of the article selection process, an analysis of the keywords present in the corpus was also conducted. Keywords represent an effective tool for identifying the main research directions and the semantic relationships among different thematic areas, based on their frequency of use and co-occurrence patterns (Li et al., 2016). To this end, the keyword dataset was first subjected to a cleaning process aimed at removing duplicates and textual variants of the same term. Subsequently, the data were analyzed using VOSviewer, a software developed for constructing and viewing bibliometric maps, especially useful for dataset containing at least a moderately large number of items (van Eck and Waltman, 2010), yielding the results shown in Figure 10. A threshold of at least three occurrences per keyword was applied to reduce the dataset size and focus the analysis on recurring and more representative expressions. This threshold was obtained through an iterative process in which several datasets, generated using different minimum occurrence values, were compared. This threshold value made it possible to retain frequently used keywords while avoiding both excessive dispersion and excessive filtering of the dataset.

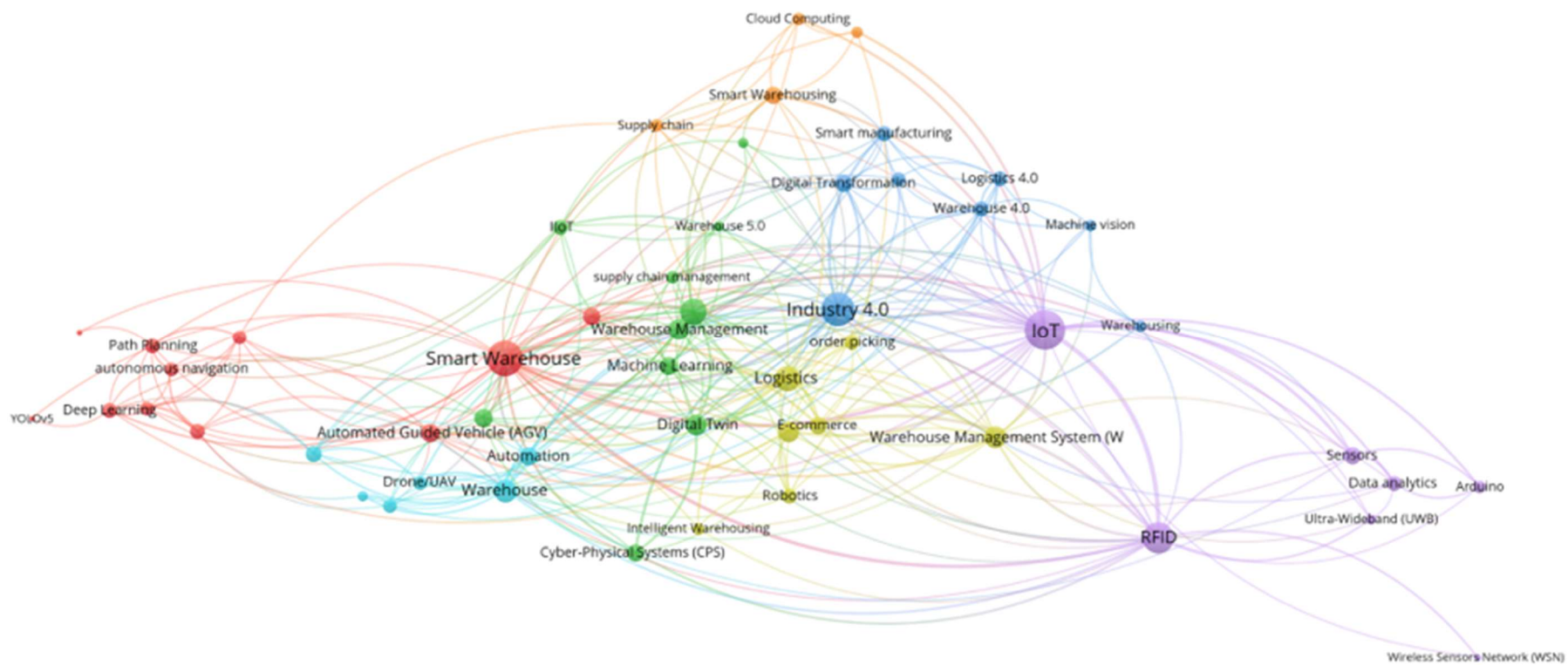


Figure 10. VOSviewer Map

Seven clusters can be identified in the graph, the details of which are reported in Table 8 below.

Cluster	Keywords	Emerging Theme
1	✓ Automated Guided Vehicle (AGV) ✓ autonomous navigation ✓ Deep Learning ✓ Object detection ✓ Path Planning ✓ Reinforcement learning ✓ Sensors fusion ✓ Smart Logistics ✓ Smart Warehouse ✓ Warehouse Automation ✓ YOLOv5	Cluster 1 includes themes related to navigation autonomy and autonomous vehicles for internal goods handling, including keywords such as Automated Guided Vehicle (AGV), autonomous navigation, path planning, and reinforcement learning.
2	✓ Artificial Intelligence (AI) ✓ Augmented Reality (AR) ✓ Cyber-Physical Systems (CPS) ✓ Digital Twin ✓ IIoT ✓ Inventory management ✓ Machine Learning ✓ Supply chain management ✓ Warehouse 5.0 ✓ Warehouse Management	Cluster 2 encompasses Industry 5.0 technologies, including Artificial Intelligence (AI), Digital Twin, IIoT, Machine Learning, and Warehouse Management.
3	✓ Digital Transformation ✓ Industry 4.0 ✓ Innovation ✓ Logistics 4.0 ✓ Machine vision ✓ Smart manufacturing ✓ Warehouse 4.0	Cluster 3 focuses on digital transformation and the Fourth Industrial Revolution, through keywords such as Industry 4.0, Logistics 4.0, and Smart Manufacturing.
4	✓ E-commerce ✓ Intelligent Warehouse ✓ Intelligent Warehousing ✓ Logistics ✓ Order picking ✓ Robotics ✓ Warehouse Management System (WMS)	Cluster 4 includes some of the most widely discussed topics in warehouse operations management, such as order picking, robotics, e-commerce, and Warehouse Management Systems (WMS).
5	✓ Arduino ✓ Data analytics ✓ IoT ✓ RFID ✓ Sensors ✓ Ultra-Wideband (UWB) ✓ Wireless Sensors Network (WSN)	Cluster 5 primarily concerns data collection, transmission, and analysis, including IoT, RFID, sensors, and data analytics.
6	✓ Automation ✓ Autonomous Mobile Robots (AMR) ✓ Computer vision ✓ Drone/UAV ✓ Optimization ✓ Warehouse	Cluster 6 is focused on automation and robotics technologies, with particular reference to AMRs, drones, computer vision, and optimization.
7	✓ Cloud Computing ✓ Management system ✓ Smart Warehousing ✓ Supply Chain	Cluster 7 gathers cross-cutting keywords that act as links between the different clusters, such as cloud computing, supply chain, and smart warehousing.

Table 8. Clusters VOSviewer

3.2. Thematic analysis of the corpus

The thematic analysis of the corpus aims to answer four research questions formulated based on the theoretical lens presented in Section 1.3.1. Indeed, the primary objective of this Systematic Literature review is to develop a comprehensive view of the warehouse as an integrated operational system encompassing design, operations, control, and performance management. From this perspective, an in-depth analysis of each dimension can provide valuable insights into the current directions of research and highlight the topics that are most extensively discussed within the academic literature.

Frequency analysis of each research question

Figures 11, 14, 15 and 16 present the percentage of papers in the corpus related to each research question.

Objectives of smart warehousing

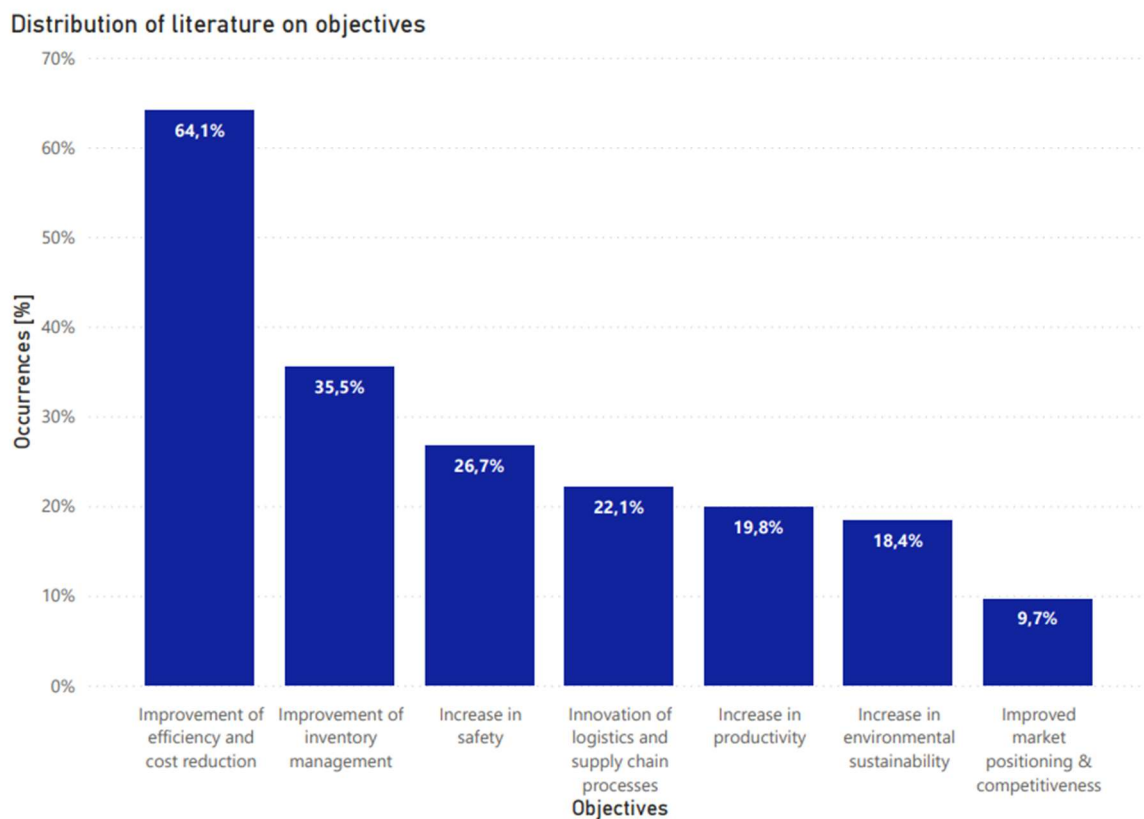


Figure 11. Distribution of literature on objectives

To analyze the dimensions of warehouse design and performance evaluation, the first research question investigates the objectives that firms may pursue through the implementation of smart warehouses. These objectives include improvements in efficiency and cost reduction, increased productivity, enhanced inventory management, innovation in logistics and supply

chain processes, improved market positioning and competitiveness, greater safety, and enhanced environmental sustainability. According to the results of the analysis (Figure 11), the improvement of efficiency and cost reduction emerges as the dominant theme (64.1% of the corpus paper), and therefore represents the main benefit linked to smart warehousing. The concept of efficiency extends beyond simple performance gains, encompassing reduced operational costs (Lyu, 2024; Malopolski and Skoczypiec, 2024), improved resource utilization (Zhou, 2024; Ding and Feng, 2018), data-driven decision-making (Nicoletti and Appolloni, 2024; Arvind et al., 2025), and enhanced system adaptability through automation and real-time information processing (Francuz and Bányai, 2025; Min, 2023). Its high coverage in literature can thus be attributed to this broad spectrum of associated benefits.

The improvement of inventory management also represents a frequently cited objective (35.5% of the corpus paper), as a smart warehouse can enable greater visibility over goods, their storage conditions, and related material flow dynamics.

This is followed, with lower frequency, by the increase in safety (26.7% of the corpus paper): the introduction of new automated and collaborative solutions requires renewed attention to worker protection, and the observed statistics confirm that this is an active topic in literature. In fact, although it is less frequently discussed compared to the previous ones, its relevance has increased in recent years, reflecting the evolution of the debate from Industry 4.0 towards Industry 5.0 principles. As autonomous and robotic systems become increasingly widespread, ensuring safe human-machine collaboration has become a fundamental challenge, bringing the human dimension back to the center of innovation processes.

These are followed by innovation of logistics and supply chain processes (22.1% of the corpus paper), increase in productivity (19.8% of the corpus paper), increase in environmental sustainability (18.4% of the corpus paper) and improved market positioning & competitiveness (9.7% of the corpus paper). The relatively lower frequency of these objectives across the analyzed papers may be explained by the fact that the adoption of smart warehousing technologies is primarily driven by operational and efficiency-oriented goals. In other words, it seems less common for organizations to adopt specific technologies - or to undertake a broader transformation of their warehousing systems - with the primary aim of improving environmental sustainability or strengthening market positioning. As a result, the main drivers behind the transition toward smart warehouses appear to be predominantly operational in nature. An interesting consideration concerns productivity, which would intuitively be expected to be one of the most frequently associated objectives in the context of smart warehousing. The relatively lower prominence of this aspect in the literature may be explained by its conceptual proximity to efficiency: since efficiency is a broader construct that already encompasses productivity-related improvements, it may be more frequently adopted by scholars as an overarching category, thereby partially absorbing more specific productivity-related contributions.

The discussion of objectives of a smart warehouse can also be meaningfully analyzed over time, to understand how priorities evolve and shift across different stages. Figures 12 and 13 illustrate the evolution over time of the discussion on the different objectives.

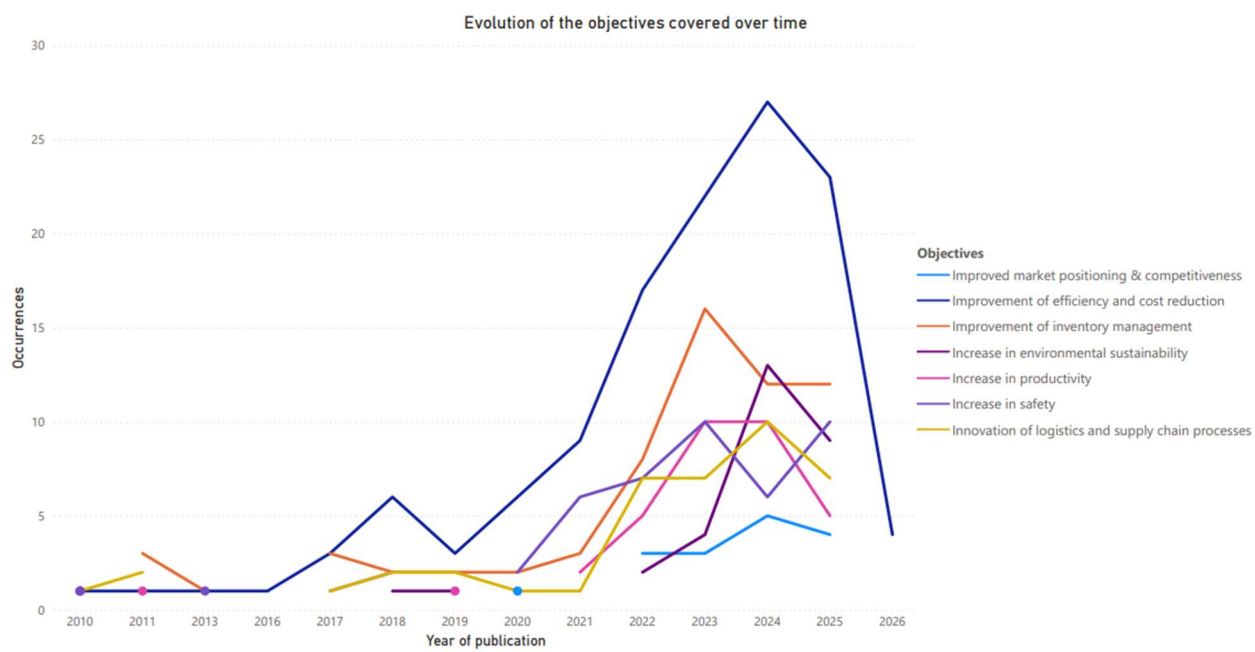


Figure 12. Evolution of the objectives of a smart warehouse over time

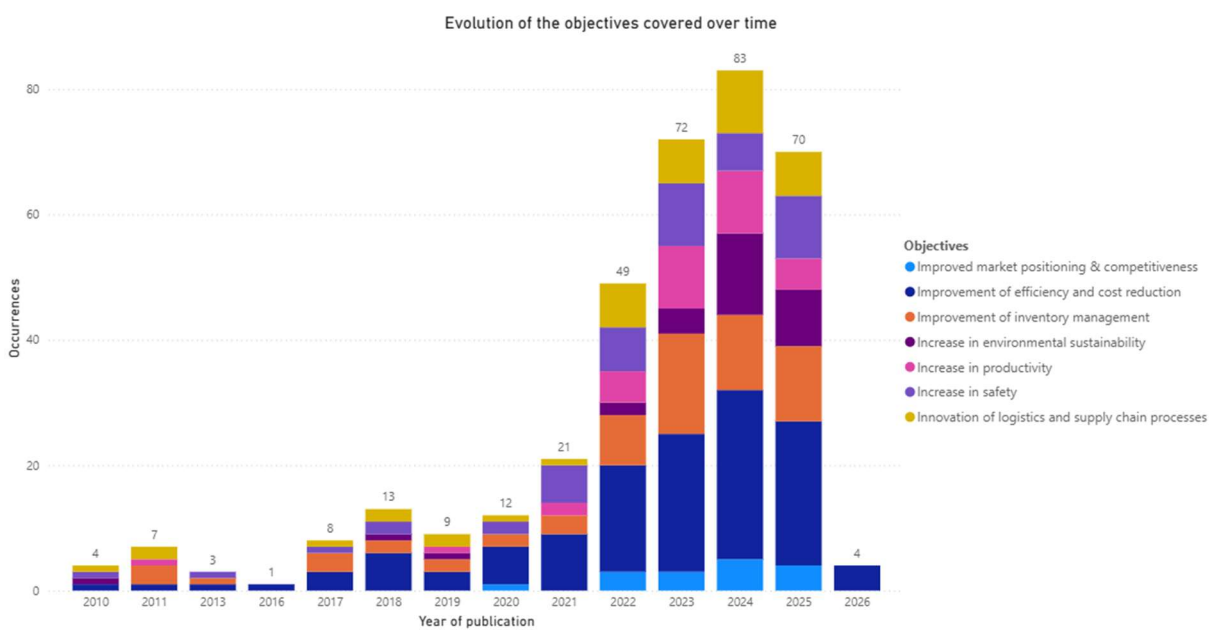


Figure 13. Evolution of the objectives of a smart warehouse over time (2)

This configuration also makes it possible to highlight the evolution of research trends over time. In particular, it can be observed that operational objectives, such as efficiency and warehouse management, are discussed more consistently over time, while safety and environmental topics appear more prominently in recent studies. In line with the growing emphasis on environmental sustainability driven by European and international regulations, discussion of environmental aspects of a smart warehouse has progressively increased. By contrast, although improved competitiveness is often associated with the adoption of smart warehouse technologies (Shabur, 2024; Cupido and Jokonya, 2024), it is less frequently addressed in literature. This may be explained by the fact that the adoption of smart warehouses can provide an initial competitive advantage during the early stages of diffusion, when such solutions are not yet widespread. However, this effect diminishes once these systems become a standard requirement for market participation. Another possible interpretation is that, due to their relatively recent emergence and still limited adoption, smart warehouses have not yet provided sufficient empirical evidence of their ability to generate a sustained competitive advantage. In this sense, market positioning and competitiveness are not generally considered long-term objectives in academic literature, which may explain why they are less extensively discussed.

Technologies present in a smart warehouse

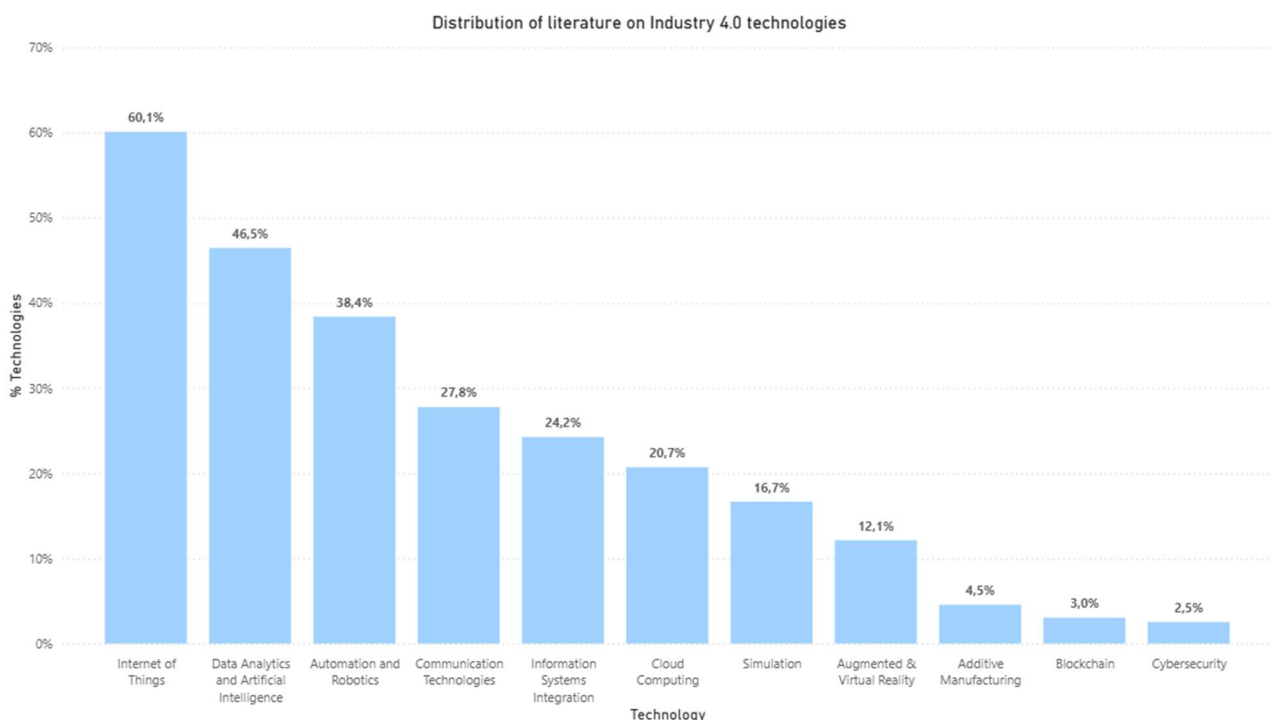


Figure 14. Distribution of literature on Industry 4.0 Technologies

The second research question focuses on the technologies employed within smart warehouses, as the analytical dimension under investigation concerns resources and enabling systems. The identified technologies in this context include Internet of Things, Automation and Robotics, Augmented & Virtual Reality, Information Systems Integration, Additive

Manufacturing, Data Analytics and Artificial Intelligence, Simulation, Cloud, Cybersecurity, Blockchain and Communication Technologies.

Based on results (Figure 14), the most frequent technology addressed in smart warehousing literature is the Internet of Things (IoT), which clearly emerges as the dominant theme, followed by Data Analytics and Artificial Intelligence and by Automation and Robotics. As discussed in Section 2.3, IoT represents a fundamental component of the digital transformation driven by the fourth industrial revolution, due to its ability to connect devices and systems within integrated digital ecosystems. The topic of Data Analytics and Artificial Intelligence, now widely relevant across multiple sectors, unfolds through several sub-areas, including Artificial Intelligence (20.5%), Machine Learning (16.7%), Convolutional Neural Networks (12.2%), Deep Learning (10.9%), and Reinforcement Learning (4.5%). The broader category of Automation and Robotics also encompasses a wide range of technologies, including Automated Guided Vehicles (AGVs), Autonomous Mobile Robots (AMRs), Automated Storage and Retrieval Systems (AS/RS), and Unmanned Aerial Vehicles (UAVs). These technologies are primarily used for material handling across different operational areas in a warehouse. The most frequently reported benefits include reduced physical workload for operators, fewer operational errors, increased process flexibility, and greater system scalability (Ellithy et al., 2024). In particular, AGVs enable highly precise automated transport, positively affecting both costs and operational cycle times (Ellithy et al., 2024)., while AMRs, thanks to advanced sensor systems, can support picking activities and human-machine interaction (Ammar et al., 2022). Finally, AS/RS systems are widely used to optimize storage, sequencing, and sorting operations, efficiently exploiting vertical storage space (Liu et al., 2021). Among these, AGVs alone account for 25.5% of the citations within the category. Communication Technologies include solutions and protocols such as 5G, 6G, Bluetooth, and Wi-Fi, which are used to enhance communication efficiency and reduce latency in real-time decision-making processes. Within Information System Integration, a clear predominance of Warehouse Management Systems (WMS) emerges, followed by Cyber-Physical Systems (CPS) and Enterprise Resource Planning (ERP) systems. Regarding Cloud Computing, Edge Computing, although representing an evolutionary development of cloud architectures, remains less frequently discussed in the literature compared to traditional cloud solutions. Simulation technologies, mainly associated with Digital Twin applications, are more widely addressed than Augmented & Virtual Reality systems, while Blockchain, Cybersecurity, and Additive Manufacturing remain relatively underexplored within the analyzed corpus. This may be explained by the more limited range of application perspectives associated with these technologies in the warehouse context. For instance, blockchain is more frequently associated with supply chain-level processes, such as the certification and traceability of goods transfers, rather than with intra-warehouse activities.

Data generated and managed in a smart warehouse

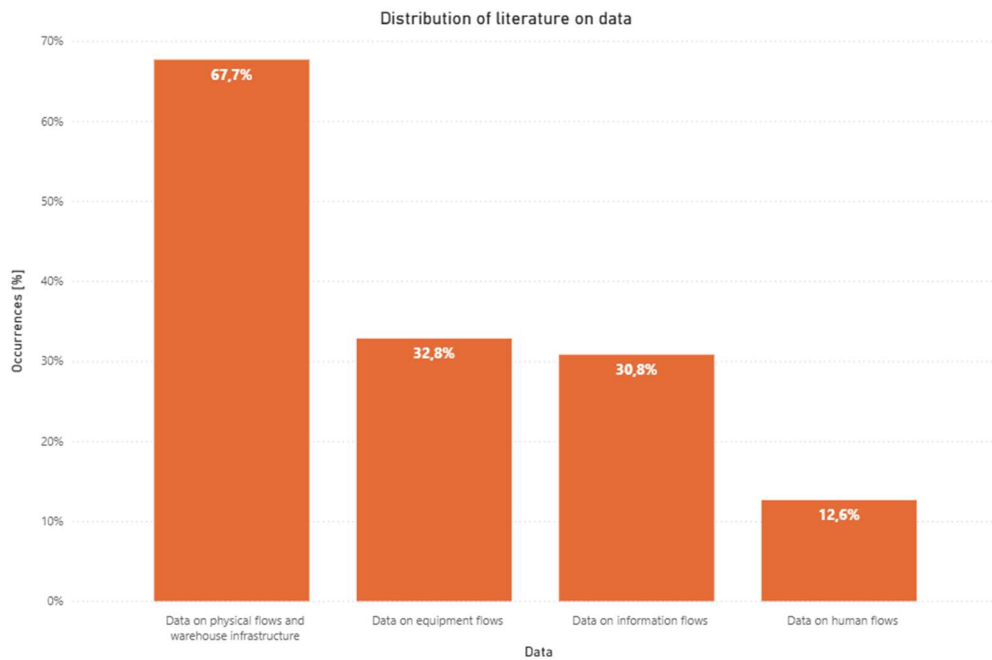


Figure 15. Distribution of literature on data

The third dimension under investigation is information and control, which concerns the information layer responsible for maintaining control over the smart warehouse. In this context, the third research question examines the types of data collected, managed and monitored by this infrastructure, distinguishing four categories: data on physical flows and warehouse infrastructure, data on equipment flows, data on information flows and data on human flows. While the other dimensions have been extensively investigated in literature, the role of data has received considerably less attention in academic research. This asymmetry is itself a significant interpretative finding: although data constitute the raw material of digitalization, literature tends to treat them as supporting elements for other themes rather than as central objects of analysis. The results of the analysis presented in Figure 15 shows a clear predominance of data on physical flows and warehouse infrastructure can be observed. This category includes heterogeneous information such as environmental parameters, data on the characteristics of stored products, as dimensions, weight, batch number, manufacture date, expiration date; information related to internal goods movement, as real-time location and trajectory of goods or shelf pickup time; and data concerning the physical structure of the warehouse, as map and layout dimensions which are essential, for example, for the development of optimization models. In contrast, data on human flows, as information related to operators and users of warehouse systems, appear to be significantly less frequent. A possible explanation for this lower occurrence, for example, may be that information related to operators and users is often considered a standard component of warehouse information systems, so it tends to remain implicit rather than being explicitly addressed in literature. This lack of discussion is particularly critical at a time when the transition to Industry 5.0 requires rethinking the relationship between technology and human labor, together with a broader set

of factors related to employees' psychological and physical well-being, in line with an increasingly human-centric paradigm.

Warehouse processes addressed by a smart warehouse

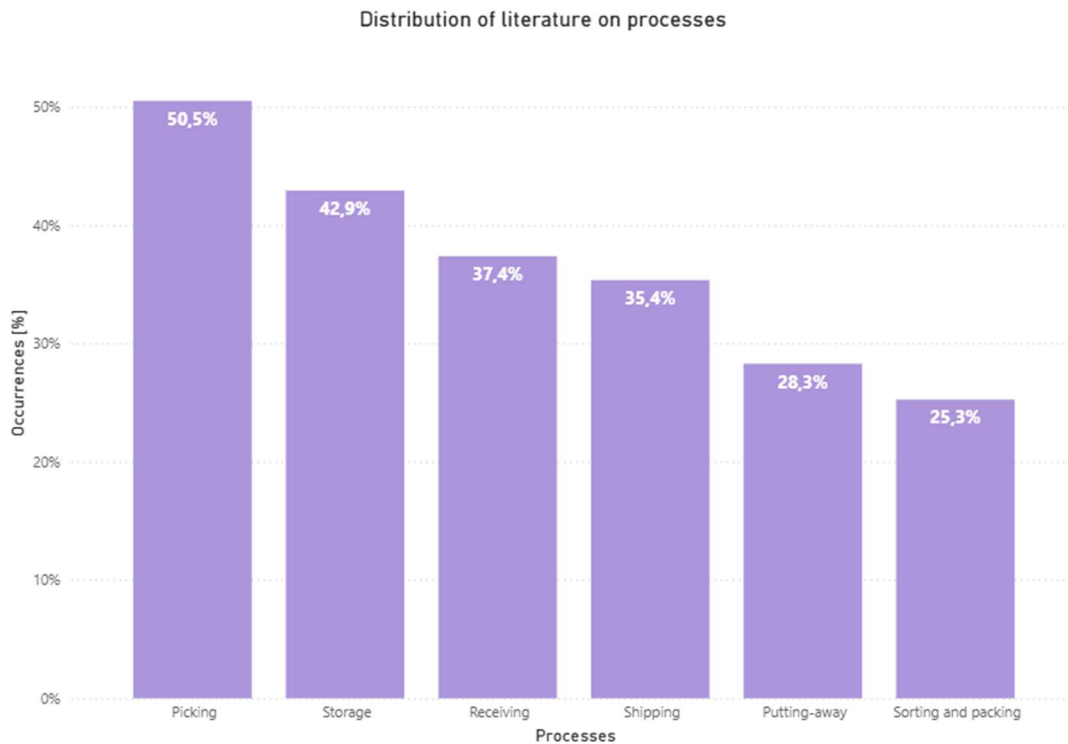


Figure 16. Distribution of literature on processes

The final dimension that allows smart warehouses to be framed as an integrated system encompassing design, operations, control, and performance is the operational dimension, which focuses on the specific warehouse processes and operations. The process stages covering the entire warehouse operation include receiving, putting-away, storage, picking, sorting and packing, and shipping. Overall, a relatively uniform treatment of the various warehouse processes emerges (Figure 16), with a slight predominance of picking, recognized as one of the most critical processes in warehouse operations management and responsible for approximately 55% of operating costs (Tompkins et al., 2010). This prevalence can be explained by the high informational content and decision-making complexity of picking activities, which rely on data related to orders, product characteristics, storage locations and batching strategies. Likewise, the storage process is widely discussed in literature, for its direct impact on inventory costs and product quality preservation; while receiving and shipping are increasingly supported by automation and identification technologies, such as RFID and UAVs, to improve traceability and operational speed. Finally, the literature highlights the growing adoption of automation, and robotic solutions across putting-away, sorting, and packing activities, with the aim of improving space utilization, reducing errors and enhancing overall warehouse performance.

Examining the relationships between the three interpretive dimensions

To investigate more comprehensively the relationships among the considered variables, a cross-analysis was conducted to examine the interconnections between the three interpretive dimensions of this SLR. As outlined in Section 1.3, the interpretation of the corpus was structured around a complementary lens made up of three dimensions: performance impacts, digital technologies and business processes. Accordingly, two intersections between these dimensions were analyzed: performance impacts and digital technologies, and business processes. The intersection between performance impacts and business processes was not analyzed, since performance impacts are assessed at the level of overall smart warehouse operations rather than individual processes; consequently, examining this relationship in the literature would not be meaningful. By contrast, due to the previously noted lack of attention to the topic of data in the literature, this dimension was analyzed in relation to all three interpretive dimensions above. This approach makes it possible to identify potential trends and gaps, and to better assess how valuable further investigation of this topic could be.

Accordingly, tables were developed to show the percentage of corpus papers simultaneously addressing elements associated with multiple dimensions.

Objectives	Internet of Things	Automation and Robotics	Augmented & Virtual Reality	Data Analytics and Artificial Intelligence	Simulation	Cloud Computing	Cybersecurity	Blockchain	Communication Technologies
Improvement of efficiency and cost reduction	43.3%	25.8%	8.8%	32.7%	10.6%	13.4%	1.8%	4.1%	18.9%
Increase in productivity	15.2%	10.1%	3.7%	9.2%	3.2%	3.7%	0.5%	0.9%	6.0%
Improvement of inventory management	25.8%	12.9%	3.7%	17.1%	6.0%	8.3%	1.4%	2.3%	10.1%
Innovation of logistics and supply chain processes	16.1%	11.1%	1.4%	9.7%	2.8%	4.6%	0.9%	1.4%	8.8%
Improved market positioning & competitiveness	7.4%	5.1%	1.4%	5.5%	2.3%	3.7%	0.5%	1.4%	3.7%
Increase in safety	20.3%	12.4%	4.6%	14.3%	4.6%	6.9%	1.4%	1.4%	9.2%
Increase in environmental sustainability	12.4%	9.2%	4.1%	11.1%	5.1%	6.0%	0.5%	2.3%	5.1%

Table 9. Concurrent presence of objectives and technologies

The analysis of the concurrent presence of objectives and technologies (Table 9) confirms efficiency improvement and cost reduction as the primary objectives across all Industry 4.0 technologies associated with smart warehouses, with particular relevance to Internet of Things and Data Analytics and Artificial Intelligence. The Internet of Things appears to exert a cross-functional impact across multiple operational dimensions, including inventory management and safety. This can be explained by its role in enabling continuous data collection and exchange, which supports improved system visibility and coordination across warehouse activities. As far as Data Analytics and Artificial Intelligence, the literature highlights how the application of optimization algorithms can lead to significant reductions in both transport and storage costs. In a broader perspective, the use of machine learning techniques enables substantial improvements in routing and forecasting processes, thereby enhancing inventory management and overall operational efficiency. Similarly, data analytics approaches are increasingly employed to support both preventive and corrective actions within warehouse operations.

Technologies	Receiving	Putting-away	Storage	Picking	Sorting and packing	Shipping
Internet of Things	25,8%	19,4%	29,0%	30,0%	17,5%	25,8%
Automation and Robotics	14,7%	11,5%	18,4%	23,0%	13,8%	16,1%
Augmented & Virtual Reality	4,1%	2,8%	5,1%	7,4%	3,2%	4,1%
Data Analytics and Artificial Intelligence	14,3%	11,1%	21,7%	23,0%	12,0%	14,7%
Simulation	7,8%	6,5%	10,1%	12,0%	7,4%	7,8%
Cloud Computing	8,8%	6,5%	10,6%	11,1%	6,5%	7,8%
Cybersecurity	1,4%	0,5%	1,8%	1,8%	0,9%	1,4%
Blockchain	2,3%	0,9%	2,8%	1,4%	1,8%	2,3%
Communication Technologies	11,1%	9,7%	13,4%	16,6%	8,3%	12,9%

Table 10. Concurrent presence of between technologies and processes

The analysis of concurrent presence of technologies and warehouse processes (Table 10) shows that the Internet of Things is the most frequently cited technology across all operational processes, with particular emphasis on picking and storage. This can be attributed to the increasing use of sensors and IoT technologies for collecting data on environmental parameters to ensure proper material preservation, monitoring shelf weight to actively track inventory levels, and supporting operators during picking activities. Automation and Robotics, as well as Data Analytics and Artificial Intelligence, are also found to be broadly associated with different warehouse processes, with a higher incidence in storage and picking, which can be reasonably regarded as the most extensively addressed processes in relation to Industry 4.0 technologies. Concerning these latter two technologies, the existing literature points to their ability to enhance warehouse performance by reducing picking errors and increasing overall productivity. Furthermore, robotic-enabled solutions are frequently associated with improvements in inventory management, especially in activities related to material handling, as they support increasingly autonomous goods movement, with the ability to perceive the surrounding environment, recognize obstacles, and dynamically adapt their trajectories in real time.

Objectives	Data on physical flows and warehouse infrastructure	Data on information flows	Data on human flows	Data on equipment flows
Improvement of efficiency and cost reduction	43,8%	21,2%	6,5%	22,6%
Increase in productivity	13,4%	7,8%	2,8%	7,8%
Improvement of inventory management	25,8%	14,3%	3,7%	12,4%
Innovation of logistics and supply chain processes	16,6%	6,9%	2,8%	9,2%
Improved market positioning & competitiveness	6,5%	5,5%	1,4%	3,2%
Increase in safety	18,9%	8,3%	3,2%	11,5%
Increase in environmental sustainability	13,4%	9,2%	1,8%	6,0%

Table 11. Concurrent presence of objectives and data

Continuing the analysis by focusing on the relationships between objectives and data types (Table 11), it clearly emerges that many papers that discuss or acknowledge the benefits of smart warehouses in terms of improving operational efficiency and reducing costs also address data related to physical flows or warehouse infrastructure. This suggests that the use of these types of data is indeed necessary to achieve such operational benefits, making it even more evident that further investigation is required to better understand the underlying cause-and-effect mechanisms. More generally, this objective is addressed across papers discussing all the data categories considered in the analysis. Nevertheless, it emerges that discussions

concerning human flow data remain confined to a limited number of studies, with their highest observed occurrence accounting for only 6.45% of the total corpus.

Technologies	Data on physical flows and warehouse infrastructure	Data on information flows	Data on human flows	Data on equipment flows
Internet of Things	42,4%	17,1%	8,3%	18,4%
Automation and Robotics	27,2%	12,9%	4,1%	14,7%
Augmented & Virtual Reality	9,7%	5,5%	2,3%	3,2%
Data Analytics and Artificial Intelligence	29,0%	13,8%	5,5%	10,1%
Simulation	12,9%	8,3%	1,8%	6,9%
Cloud Computing	15,7%	6,5%	2,8%	5,5%
Cybersecurity	1,8%	1,8%	0,5%	1,4%
Blockchain	2,8%	1,8%	0,5%	0,9%
Communication Technologies	20,7%	7,8%	4,6%	10,1%

Table 12. Concurrent presence of technologies and data

The analysis of concurrent presence of technologies and data (Table 12) also highlights a clear predominance of data on physical flows and warehouse infrastructure compared to the other data categories considered. This prevalence is because many activities, and consequently many technologies, require the management of large volumes of data, often related to warehouse space configuration, travel distances, as well as inventory data and related material movements, to enable forecasting and optimization strategies. This is particularly evident in the case of Internet of Things, Data Analytics and Artificial Intelligence, automation and robotics, and communication technologies. This also explains the relatively high references to data on information flows and data on equipment flows, which include information related to orders, suppliers, and customers, as well as the movement of autonomous robots within the warehouse environment.

Processes	Data on physical flows and warehouse infrastructure	Data on information flows	Data on human flows	Data on equipment flows
Receiving	31,3%	14,7%	6,5%	17,1%
Putting-away	23,0%	12,0%	3,7%	13,4%
Storage	37,3%	18,4%	5,5%	19,8%
Picking	40,6%	20,3%	6,0%	23,5%
Sorting and packing	21,2%	12,4%	3,7%	12,0%
Shipping	30,4%	16,1%	6,5%	17,1%

Table 13. Concurrent presence of processes and data

A similar pattern also emerges when analyzing the relationship between warehouse processes and data (Table 13), where data on physical flows and warehouse infrastructure is extensively addressed across nearly all operational processes. This reflects the fundamental role of inventory-related data in supporting transversal process optimization and enhancing overall warehouse efficiency.

4. Discussion

The interpretation of the findings of this Systematic Literature Review is aligned with the framework defined by the complementary lens presented in Section 1.3.1 and aims to outline how warehouse digitalization manifests at the level of digital technologies, business processes and performance impacts.

This chapter presents the resulting trends and gaps in smart warehousing research across these three dimensions and uses them to outline the proposed research agenda.

4.1. Research trends

The results of the Systematic Literature Review highlight a body of literature characterized by a strong focus on specific thematic areas and a high level of interconnection among the main research streams. Overall, the evidence shows that performance impacts, digital technologies and business processes are closely integrated. From this perspective, the smart warehouse emerges as a complex system in which multiple resources interact to ensure a highly connected and synchronized environment capable of supporting real-time decision-making.

Regarding performance impacts, the literature continues to identify efficiency improvement and cost reduction as the main benefits of warehouse digitalization. These improvements may concern both overall warehouse operations and specific activities within the process. Alongside this aspect, inventory management emerges as a key area of application for digital technologies. The ability to collect and process real-time data enables greater visibility over operational flows, significantly improving inventory management.

About digital technologies, the Internet of Things is confirmed as a central enabling technology in the digital transformation of warehouses, thanks to its ability to connect physical assets, operators and information systems within a continuous data flow. At the same time, there is growing interest in Data Analytics and Artificial Intelligence, which represent an evolution expected to significantly expand potential improvement margins and enable new technology-driven applications. Another relevant element is the progressive integration of digital technologies into increasingly interconnected and synchronized ecosystems. The literature moves beyond a fragmented view of individual technological solutions and instead describes integrated architectures in which all of them work in a complementary manner, thereby marking a structural transformation of the entire warehouse environment. These same technologies operate using different types of data. In particular, data related to physical flows and warehouse infrastructure represent the most frequently recurring type in the literature, highlighting how this is an essential topic for fully understanding how implemented technologies need to be supported. From this perspective, data are not merely an output of technologies but become a fundamental resource for value generation and performance improvement.

With regard to business processes, picking and storage are confirmed as the most extensively discussed processes, both due to their economic impact and the high level of intensity of information that characterizes them. Both require the continuous management of information related to orders, products, locations and operational resources, making them particularly suitable for the application of digital technologies and decision-support systems. In particular, picking stands out as a critical process not only from an operational perspective, but also as the main area for experimentation of intelligent technologies.

4.2. Research gaps

The analysis of the corpus made it possible to identify several significant gaps in existing literature.

The most relevant gap concerns the topic of data. Although this dimension is present in almost all the publications analyzed, no contribution addresses it in a structured manner. This gap is particularly evident when considering the central role of data as the raw material of any digitalization process: IoT solutions, AI-based predictive models, and, more broadly, the entire Big Data paradigm relies on the simultaneous and interconnected management of information. An initial classification, such as the one proposed in this SLR, may represent a starting point for developing more in-depth and structured analyses in future research.

Closely related to this topic is the gap concerning data associated with human resources. Among the data categories examined, this is the least represented across the entire corpus, despite the fact that its importance is clearly set to grow in the future, given the increasing attention to operator health and human–robot collaboration. This aspect becomes even more relevant in the context of the transition toward Industry 5.0, which identifies human-centricity as one of its fundamental principles. In addition to monitoring operational performance, it will be necessary to consider forms of emotional monitoring and to develop new KPIs capable of measuring the well-being and health of human resources. This will inevitably introduce new challenges related to privacy protection and the management of personal data.

A second area that remains relatively underexplored is environmental sustainability in the smart warehouse context. Although specific contributions on this topic exist (Nicoletti et Appolloni, 2024; Aravindaraj et Rajan Chinna, 2022; Perotti, Cannava, Ries et Grosse, 2025), they are limited in number compared to the complexity and relevance that the issue assumes specifically in the smart warehouse. This is an important aspect, especially considering the new environmental and energy-related needs that the international landscape is having to face. It will therefore be necessary to deepen the topic through new studies on energy consumption optimization and the reduction of CO₂ emissions in the warehouse context, as well as to investigate how to manage the energy trade-offs that arise with the introduction of energy-intensive robotic technologies.

A further gap concerns the geographical distribution of the academic debate: a strong international imbalance emerges, with a clear prevalence of China, followed by India. This

evidence raises important questions, especially considering that, at the European level, several countries historically regarded as industrial powers today show very weak participation in the debate on smart warehousing, including Italy.

Finally, from a thematic perspective, there are still technologies that remain largely unexplored in the international debate today, which it would instead be essential to investigate further in order to strengthen academic research. Among these, the most prominent is cybersecurity, which represents the least discussed technology in the corpus of papers analyzed, but which is likely to become a subject of great interest in the future. The digitalization of warehouses, through the use of IoT solutions, cloud computing and other interconnected technologies will increase exposure to cyberattacks, introducing new challenges in terms of data protection and system resilience. It will therefore be useful to broaden discussion on this topic, including understanding how to act to protect the ownership of information held within systems, supporting the secure and reliable operation of future smart warehouses.

4.3. Research agenda

The gaps identified in the previous section outline a structured agenda for future research on smart warehousing, organized around several areas that reflect the most critical and still underexplored dimensions of warehouse digitalization.

One pressing area concerns the systematic study of warehouse data. The existing lack of dedicated discussions that consider data as an object of inquiry in their own right, rather than as a secondary theme, suggests an open area for future research. Future studies should focus on developing structured frameworks for smart warehouse data management capable of defining the interdependencies among different data types, for example, the relationship between data on physical warehouse flows and equipment data, or between information flow data and human resource data. Such frameworks could also explain how these interdependencies vary across application contexts and warehouse functions.

Closely related to the broader lack of studies on data, the topic of human data may carry significant weight in shaping strategies aimed at operational sustainability. Future studies should develop metrics and monitoring tools capable of assessing workers' physical and psychological conditions in increasingly automated environments. Moreover, smart warehousing solutions should be designed by integrating human well-being as a core design requirement rather than treating it as a secondary consideration, in line with the broader transition toward Industry 5.0. As mentioned above, as digitalization continues to evolve toward a more human-centric approach, the psychophysical well-being of the individual is likely to become an increasingly central concern, rather than one subordinate to operational efficiency alone. This shift, however, will bring out a further research gap concerning the theme of privacy protection, particularly around biometric data and workers' health information.

With regard to environmental sustainability, an increasingly topical theme that is attracting growing attention from both the academic and political worlds, the discussion within smart

warehousing also needs to move toward a more in-depth and analytical approach. For example, future research should broaden its focus by incorporating empirical analyses of energy-related challenges and examining the role of emerging technologies, such as AI-based solutions. Indeed, although these technologies may increase energy consumption in operational contexts, they can also be leveraged to enable more targeted and accurate monitoring and management of energy use. Along the same research stream, future studies could conduct comparative analyses across industries and geographical contexts, particularly in light of the significant regulatory and infrastructural heterogeneity that characterizes different countries. Such evidence could provide valuable support for managers when evaluating strategic alternatives and making more informed decisions.

It would also be beneficial to broaden the scope of the current research by addressing topics that have received limited attention but are expected to become increasingly important in tackling future challenges. As previously discussed, one particularly relevant area for further investigation is cybersecurity. Studies aimed at identifying effective strategies to protect companies' information assets, particularly within the context of smart warehouses, could make a significant contribution to increasing both awareness of and preparedness for cyber threats. In turn, such research would help enhance the resilience and operational stability of smart warehouses against potential cyberattacks.

5. Conclusions and future perspectives

The research presented in this thesis aimed to conduct a Systematic Literature Review of the existing body of knowledge on smart warehousing. Given that smart warehousing is a relatively recent and rapidly evolving research field, such a review serves not only as a synthesis of the current literature but also as a valuable guide for both academics and practitioners. From an academic perspective, this study contributes to smart warehousing literature by providing a structured and integrated overview of a research field that is still evolving and fragmented. More specifically, it identifies the research areas that have attracted the greatest scholarly attention over time, highlights the themes that have recently gained momentum in response to emerging industrial and technological challenges, and sheds light on the main gaps that still characterize the existing body of knowledge. In doing so, the study helps clarify how smart warehousing research has progressively developed across different dimensions, including objectives, enabling technologies, managed data, and warehouse processes. It also offers a useful basis for future research by indicating underexplored topics, possible theoretical extensions, and promising directions for more comprehensive investigations. From a practical perspective, this review provides managers and practitioners with a clearer and more comprehensive understanding of the smart warehouse concept, moving beyond a purely technological interpretation and showing the multiplicity of dimensions involved in warehouse smartness. By distinguishing among different research streams and by linking technologies, processes, data, and objectives, the study supports a more informed interpretation of the opportunities and implications associated with warehouse digitalization. In particular, it may help decision-makers reflect more critically on strategic investment choices, recognize which technologies are more frequently associated with specific warehouse processes and goals, and better assess the organizational and operational changes required to support the transition toward smarter warehouse systems. More broadly, the findings can support a more conscious approach to innovation planning by increasing awareness of both the potential benefits and the areas that still require careful evaluation.

Nevertheless, this study has some limitations that may have influenced its findings. First, the review relied exclusively on the Scopus database. Although Scopus is one of the largest and most authoritative databases of peer-reviewed literature, this choice may still have led to the exclusion of some relevant contributions indexed elsewhere or not fully accessible through the platform. Second, the exclusion of highly technical papers focused mainly on optimization models or specific engineering solutions improved the thematic coherence of the corpus but may have reduced the visibility of some technically oriented contributions that are still relevant to the development of smart warehousing. Finally, given the rapidly evolving nature of smart warehousing research, the findings should be interpreted as a structured overview of the literature at the time of the review rather than as a definitive representation of a fully stabilized field. Despite these limitations, this thesis provides a useful foundation for future research by offering a comprehensive overview of the current state of the art in smart warehousing, proposing an interpretative lens through which existing studies can be analyzed, and providing

insights into the evolution of the field over time. Building on these findings, future research could build on the agenda outlined in Section 4.3, with particular attention to the structured analysis of warehouse data, the human-related dimension of digitalization, and environmental sustainability. Beyond these thematic directions, this work could also be extended methodologically. The limitations discussed above point directly to possible avenues for improvement: future SLRs could broaden the scope of the literature search by including additional databases beyond Scopus, in order to capture a more comprehensive picture of the field. They could also complement the current perspective by considering highly technical studies focused on optimization models, thus integrating the present thematic view with a more detailed understanding of the technical development of smart warehousing. In addition, future studies could move beyond the descriptive classification proposed in this SLR to examine more closely the interdependencies among the dimensions investigated here, thereby supporting increasingly informed and structured decision-making.

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7. Website list

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Appendix

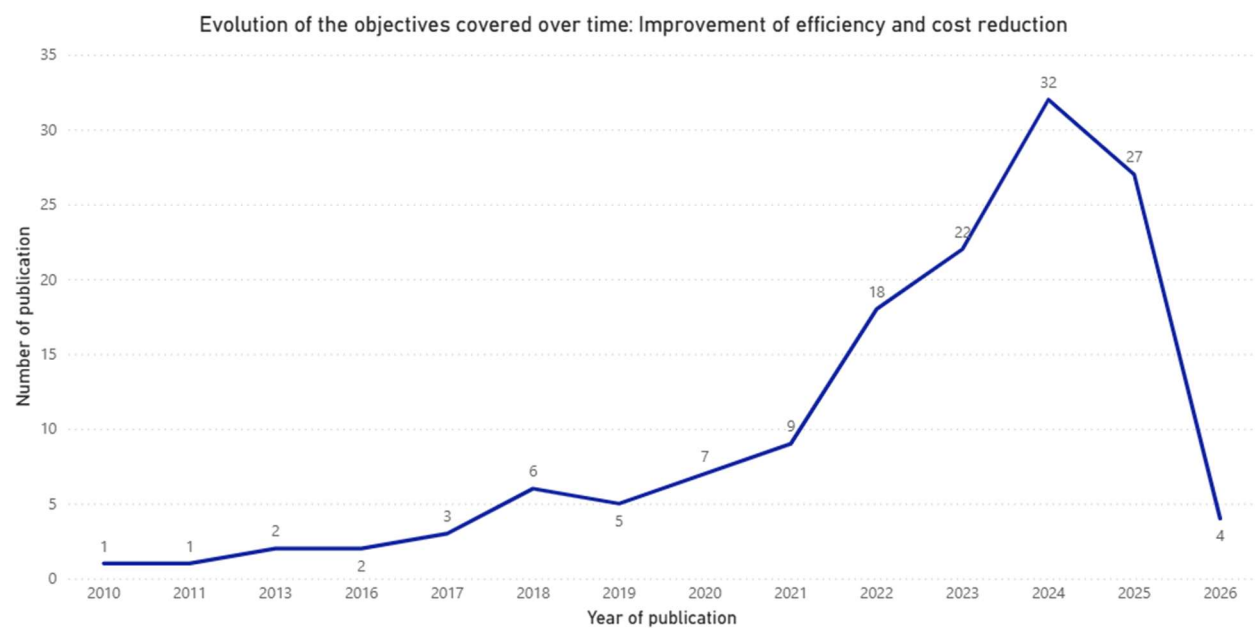


Figure 17. Evolution of the objectives covered over time: Improvement of efficiency and cost reduction

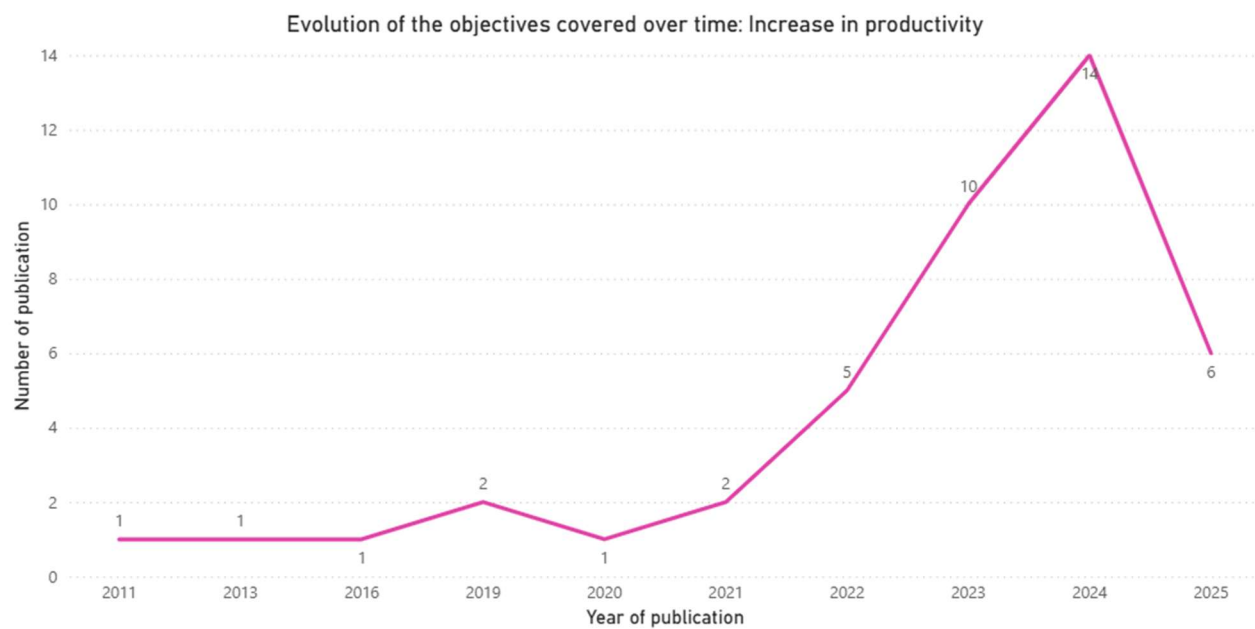


Figure 18. Evolution of the objectives covered over time: Increase in productivity

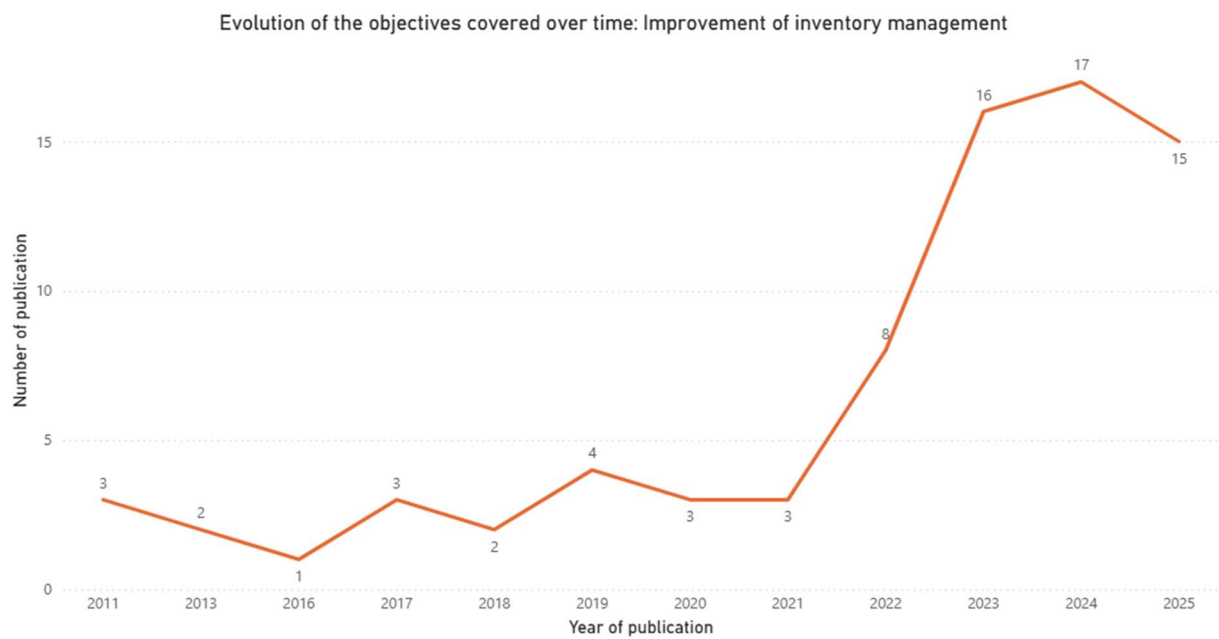


Figure 19. Evolution of the objectives covered over time: Improvement of inventory management

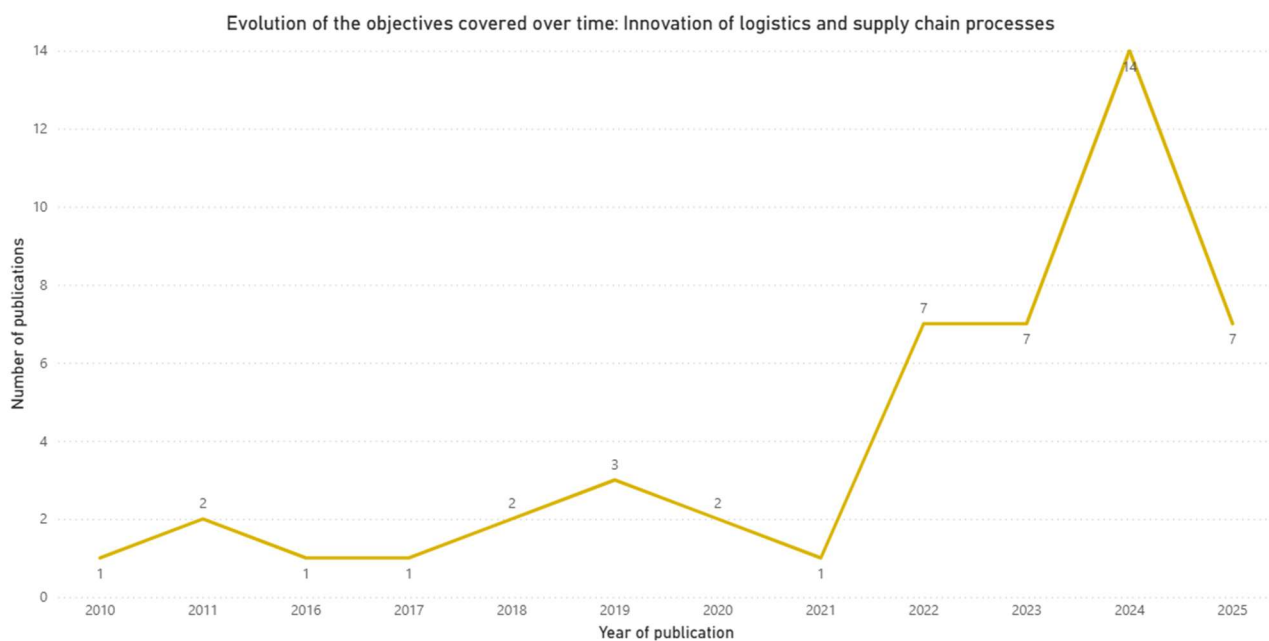


Figure 20. Evolution of the objectives covered over time: Innovation of logistics and supply chain processes



Figure 21. Evolution of the objectives covered over time: Improved market positioning & competitiveness

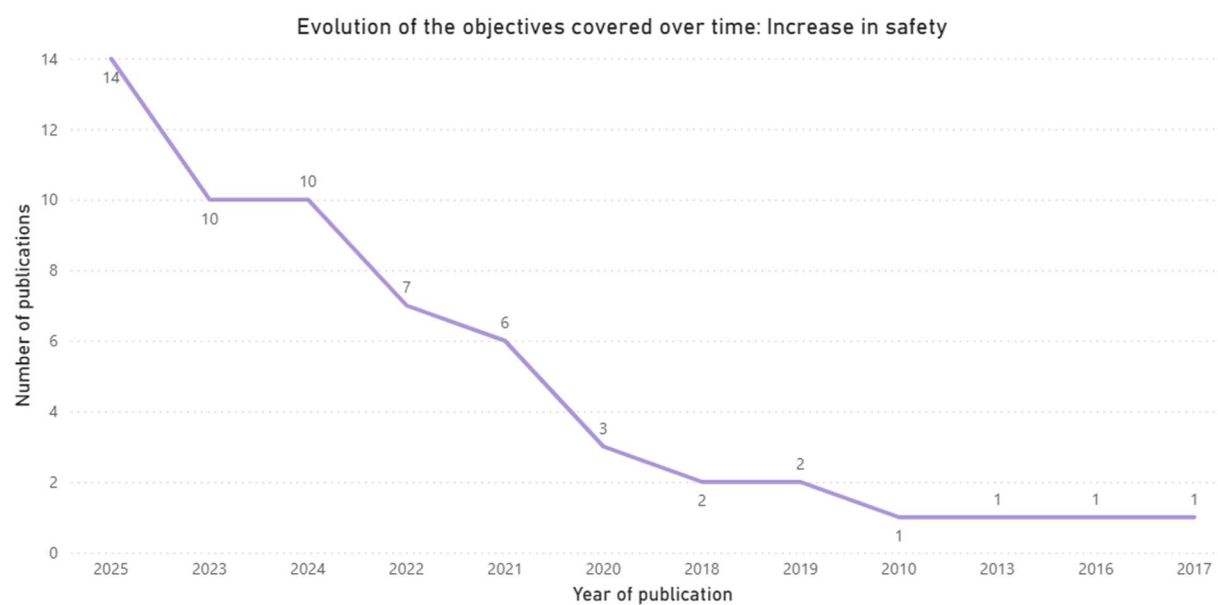


Figure 22. Evolution of the objectives covered over time: Increase in safety

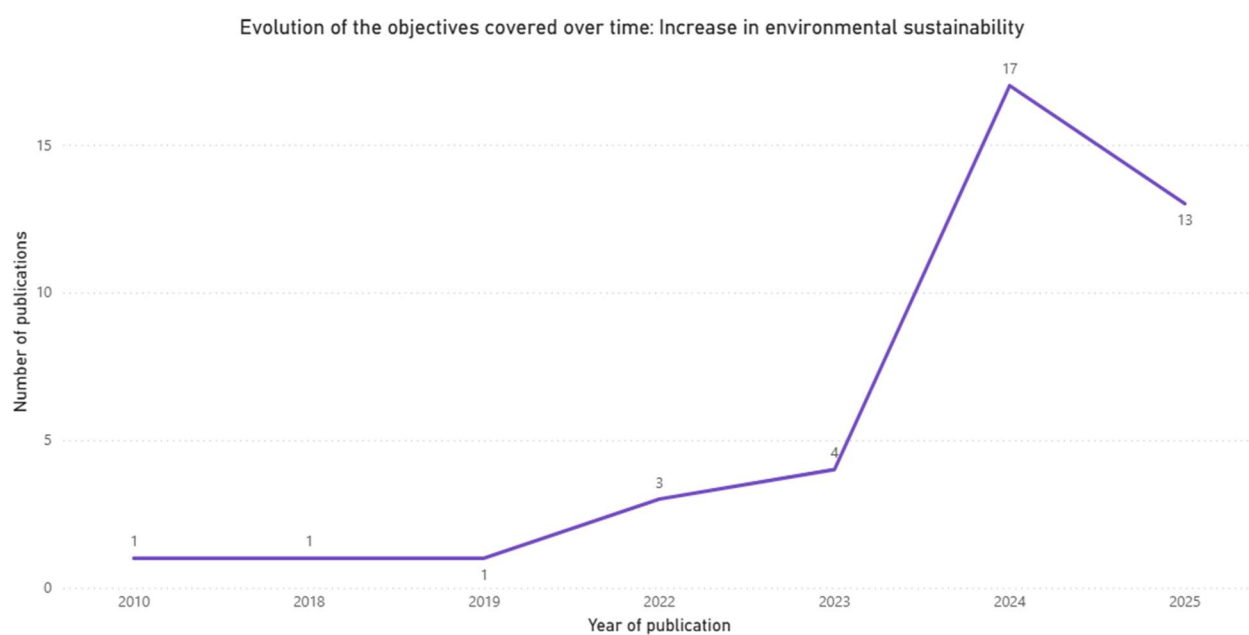


Figure 23. Evolution of the objectives covered over time: Increase in environmental sustainability