

Smart Warehouses: Rationale, Challenges and Solution Directions

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Abstract: Smart warehouses aim to increase the overall service quality, productivity, and efficiency of the warehouse while minimizing costs and failures. In recent years, several studies have proposed and discussed different types of smart warehouses, identified key challenges, and proposed several solution directions for coping with these challenges. The objective of this article is to identify, evaluate, and synthesize the relevant studies discussing the design of smart warehouses and the transition to these new types of warehouses. We applied a systematic literature review (SLR) protocol to select primary studies. The SLR resulted in the identification of the domains in which smart warehouses are applied, key motivations for adopting smart warehouses, current distinctive characteristics of smart warehouses, currently adopted technologies for realizing smart warehouses, and challenges and strategies for transitioning to smart warehouses. To the best of our knowledge, no SLR paper has been published yet on smart warehouses, and therefore, this is timely research as organizations are nowadays transitioning to smart warehouses.

Keywords: smart warehouse; Industry 4.0; smart systems; systematic literature review; robotics; automation



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1. Introduction

Ever since the beginning, humans have tried to enhance the production of goods in terms of quality, quantity, and efficiency. This ambition led to the first industrial revolution at the end of the 18th century, primarily with the developments in mechanization, driven by centralized thermic/mechanical power generation. At the beginning of the 20th century, power was decentralized and replaced by electrical energy in the second industrial revolution. The third revolution (in the early 1970s) concerned widespread digitalization and automation. Today, we are on the brink of a new revolution. This revolution follows up on the third revolution and concerns self-automation of the software and the use of new, rapidly advancing technological developments, also known as Industry 4.0 [1,2]. These developments are causing a shift from “centralized” to “decentralized” production, which is contrary to conventional logic. The path paved by smart production processes “will radically transform industry and production value chains and business models” [3]. Industry 4.0 is the collective term for a wide variety of concepts, namely smart factories, cyber-physical systems, corporate social responsibility, and smart warehouses [1]. This paper focuses on the concept of smart warehouses or warehousing 4.0. Industry 4.0 allows for warehouses to be significantly adjusted to new possibilities. In general, warehouses have four distinct activities—receiving, storing, picking, and shipping [4]—that offer many opportunities to make it “smart”.

According to Taliaferro et al. [5], warehouse-based stockpiling has shifted towards high-velocity operations aimed at lowering the overall costs. Therefore, warehouses are currently seen as a strategic advantage rather than as cost centers and are known as distribution centers.

In recent years, several studies have proposed and discussed different types of smart warehouses, identified key challenges, and proposed several solution directions for coping with these challenges. The main goal of this paper is to identify, evaluate, interpret, and

synthesize all this relevant and available research, which leads to the design of smart warehouses and the transition to these new types of warehouses. For this, we apply a systematic literature review (SLR) method to systematically collect, extract, and synthesize available research in the literature on specific research questions and a specific topic [6,7].

The SLR resulted in the identification of the smart warehouse sub-domains, key motivations for adopting smart warehouses, current distinctive characteristics of smart warehouses, currently adopted technologies for realizing smart warehouses, and current challenges and strategies for transitioning to smart warehouses.

The contribution of this paper is listed as follows: first of all, to the best of our knowledge, this is the first SLR paper that has been published on smart warehouses. It provides an important overview of the current studies in this topic and helps to understand the key concepts in this domain. Secondly, this SLR resulted in the identification of the domains in which smart warehouses are applied, the motivations for adopting smart warehouses and characteristics were determined, and technologies and challenges were identified. Hence, the literature review can pave the way for further research in this domain. Finally, based on the SLR results we provide important recommendations that can be of important benefit for both researchers and practitioners.

The remainder of this paper is organized as follows. In Section 2, we explain the background. Section 3 discusses the review protocol. Section 4 presents the results of the SLR. In Section 5, we discuss related work to this SLR. Finally, Section 6 presents the discussion, and Section 7 concludes this paper.

2. Background

At the end of the 18th century, the first iron-framed warehouse was constructed [8]. From the 18th century onwards, the scale use of warehouses grew rapidly and became more specialized. The 20th century altered the use of warehouses with the introduction of standardization and efficiency. The introduction of trucks and forklifts, and the replacement of basic skids, boxes, and crates used since the horrea with pallets and adjustable pallet racks, enabled efficient vertical storage.

The last evolution for warehouses is the technological revolution from the 1960s onwards. The most significant impact is made by the introduction of the barcode, enabling the first form of real-time warehouse management system (WMS) and automation [8]. In addition to barcode and automation technologies, Industry 4.0 is now more powerful with several technologies such as NarrowBand IoT (NB-IoT), near-field communication (NFC), radio-frequency identification (RFID), global positioning system (GPS), wireless sensor network, Wi-Fi, and robotics [9–11]. Although conventional warehouses were the most useful and successful so far, there are several problems. First of all, storing and fetching inventories is not an easy task and is time-consuming in many cases. Another drawback is that there is a huge need for storekeepers in this traditional type of warehouse, and this dependency causes the waste of human resources. The last problem is related to the record of stocks on account books, which in turn is not an environmentally friendly approach. On the other hand, a smart warehouse is mostly unmanned, paperless, and automated during the pickup, delivery, and bookkeeping operations [9].

With the help of the adoption of new technologies such as the Internet of things (IoT), blockchain, big data analytics, artificial intelligence, machine learning, deep learning, and robotics, it is highly possible that the operations of warehouses will be radically transformed.

The main advantages of smart warehouses are described as follows [12]:

- Smart warehouses provide real-time information, which is not possible in traditional warehouses
- In smart warehouses, manual tasks are minimized, and automation of tasks is maximized so that high-value tasks are performed by the employees
- Operational scalability is improved with smart warehouses because updating the infrastructure is easier than the update of the human capital within the organization

- In smart warehouses, automated decisions are made using different prediction models
- When customer demands or processes change, smart warehouses are easily adapted to the new cases compared to the traditional warehouses
- Smart warehouses use smart sensors to monitor expensive equipment and therefore, downtime is minimized

The disadvantages are the following:

- The cost of building a smart warehouse is more expensive than the traditional warehouses
- The transition to a smart warehouse is a time-consuming process, which requires a lot of effort
- The transition to a smart warehouse requires the support of top management

3. Review Protocol

Prior to conducting a systematic review, it is necessary to select a review protocol that is necessary to reduce the possibility of researcher bias [6]. The adopted protocol in our study is presented in Figure 1. Firstly, research questions are specified (Section 3.1) based on the objectives of this review. After the initial search strategy is executed on databases in several iterations, the final search string is determined (Section 3.2). Then, the selection criteria are defined to determine which papers are included or excluded in this research (Section 3.3). The primary studies are all screened on the basis of the selection criteria. Furthermore, peer reviews are conducted during this selection process. This process is followed by a quality assessment in which the primary studies are screened (Section 3.4). Once the final set of prior studies is established, the data extraction method is developed to define how to acquire the required information of each study (Section 3.5). Finally, the data synthesis process takes place in which the extracted data and identified results are presented (Section 3.6).

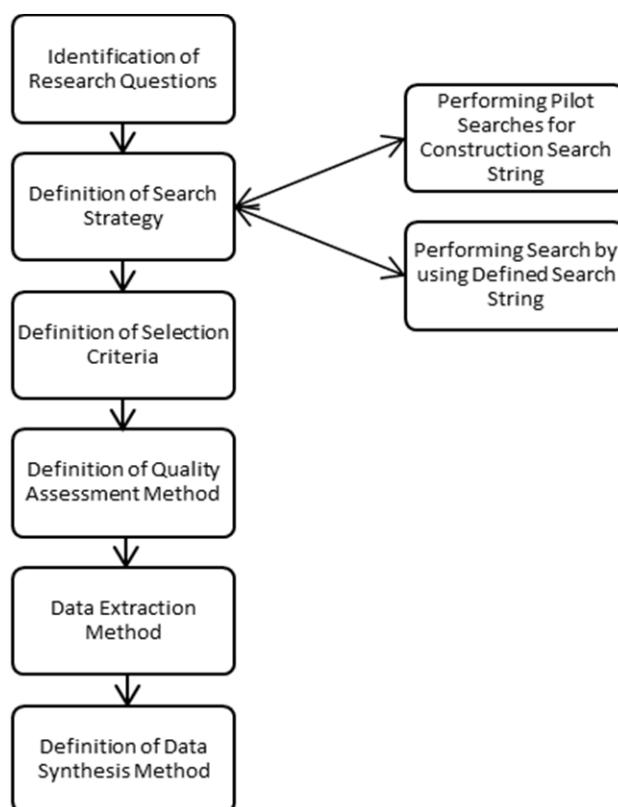


Figure 1. Adopted systematic literature review protocol.

3.1. Research Questions

With Industry 4.0, smart warehouses emerged, and many companies introduced different kinds of automation based on the smart warehouse concept. The main objective of our research is to present solid knowledge for companies that wish to build or transition to a smart warehouse in the near future. For this transition, first, there should be a clear motivation, and therefore, we defined our research question (RQ) 2 to identify these key motivations. As such, this RQ has the most impact compared to others. Once the motivation is established, the main features of smart warehouses must be identified. We defined RQ 3 to determine the distinctive characteristics of smart warehouses. When these features are selected, certain technologies are needed. Therefore, we defined RQ 4 to identify the adopted technologies for realizing smart warehouses. RQ 3 and RQ 4 are critical to know how to transition to a smart warehouse. We also wished to know which sub-domains adopted smart warehouses so far. The impact of this RQ (RQ 1) has the least impact compared to the other RQs. There are several challenges while transitioning to smart warehouses and therefore, we defined a RQ (RQ 5) to get more information on these challenges. This RQ has more impact than RQ 1. Solid knowledge on these issues is critical for successfully transitioning to smart warehouses. In this review, the following research questions are defined:

RQ1—What warehouse sub-domains adopted smart warehouse technology?

RQ2—What are the key motivations for adopting smart warehouses?

RQ3—What are the current distinctive characteristics of smart warehouses?

RQ4—What are the currently adopted technologies for realizing smart warehouses?

RQ5—What are the current challenges and strategies for transitioning to smart warehouses?

3.2. Search Strategy

The aim of a systematic literature review was to retrieve as much preliminary research as possible to answer the above-mentioned research questions. Our search scope included papers published after 2008. The following databases were used: *IEEE Xplore*, *Science Direct*, *SAGE Journals*, *Taylor & Francis Online*, and *Wiley Library Online*. Both automatic and manual search was used to browse the selected databases. The following search string was used for the IEEE database:

((*warehouse** OR *stor**) AND (*smart* OR *intelligent* OR *autom**))

For the other databases, the original string was split into fragments. In these databases, we also checked the abstracts, titles, and keywords. The results of the search strings in the databases are presented in Table 1. Appendix A—Table A1 shows the number of excluded papers for each exclusion criterion. As shown in this table, most papers were excluded based on EC-4. Since some databases are not very good at finding the most relevant papers, EC-4 was mostly used.

Table 1. Overview of the search results and study selection.

Source	# Studies after Queries	# Studies after Selection Criteria
IEEE Xplore	12	1
ResearchGate	127	1
SAGE Journals	1	1
ScienceDirect	45	10
SpringerLink	3	3
Taylor & Francis Online	443	4
Wiley Library Online	1	1
Total	632	21

3.3. Study Selection Criteria

In accordance with the SLR guidelines [7] we defined exclusion criteria on the large-sized samples derived in the first stage. Manual analysis was used to apply the exclusion criteria. The application of the exclusion criteria reduced the size of the first 632 papers to 21. The exclusion criteria of our study are listed as follows:

- EC-1: Papers without full text available
- EC-2: Papers not in English
- EC-3: Duplicate publications
- EC-4: Papers that are not related to Smart Warehouse/Warehousing 4.0
- EC-5: Survey papers

3.4. Study Quality Assessment

In addition to the selection criteria, an assessment of the quality of the resulting papers was performed. Kitchenham et al. [6] provided a summary quality checklist. The quality assessment checklist questions are presented as follows:

- Q1: Are the aims of the study clearly defined?
- Q2: Are the scope and context of the study clearly defined?
- Q3: Is the technology assessed clearly defined?
- Q4: Does the report have implications for research and/or practice?
- Q5: Do the conclusions relate to the aim of the purpose of the study?
- Q6: Is the research process documented adequately?
- Q7: Are the variables of the study likely to be valid and reliable?
- Q8: Are the main findings stated in terms of reliability, credibility, and validity?
- Q9: Are limitations explicitly stated?

The aim was to score the studies according to an overall quality score, and therefore, each quality question will be scored on a three-point scale (i.e., “no” = 0, “somewhat” = 0.5, and “yes” = 1).

3.5. Data Extraction

An in-depth reading of all selected papers was needed to extract the relevant data to answer the research questions. An extraction form was designed to collect all the information needed. The form included basic information columns such as ID, title, date of extraction, year of publication, authors, repository, publication title, type, and a column for additional notes. Data directly related to answering the research questions were also added in the fields corresponding to the specific research question.

3.6. Data Synthesis

Data synthesis is the process of collating and summarizing the extracted data in a suitable manner so that the questions this SRL seeks can be answered. At this stage, we performed a qualitative analysis of the data extracted from the reviewed papers. The combination of used journal articles and conference papers allowed us to relate observations to usage development and observe the flow of technological innovations.

4. Results

4.1. Main Statistics

This section covers the acquired results related to the five predefined research questions. Figure 2 presents the results from the study quality assessment. All articles included scored at least a 6.5 out of 9, which means that the articles are of high quality, and therefore, the data extracted are valid. The distribution of the publication years (Figure 2b) shows that most articles are from recent years, i.e., the past five years, which means there is a high interest in smart warehouses among researchers. Most of the papers were retrieved from the Science Direct database.

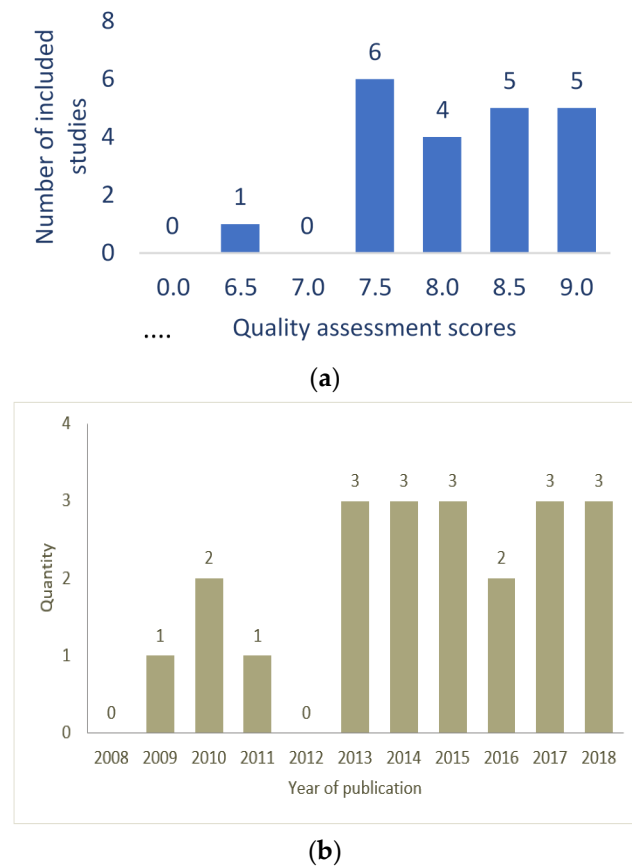


Figure 2. (a) Quality assessment of the 21 included studies. (b) Publication year distribution.

Table 2 presents a summary of the divisions of research methods used in the selected articles [13–32]. The most common research methods used among these papers are case studies and simulations. Finally, experiments are used to match software and hardware technology. The primary studies are coded, and these codes are in Table 3.

Table 2. Overview of the research methods of the selected studies.

Research Method	Studies	Count	Percent
Case Study	A, E, H, K, L, N, Q, U	8	38%
Simulation	B, C, F, G, M, O, P, R	8	38%
Experiment	D, J	2	10%
Literature Study	I, S, T	3	14%

Table 3. Selected primary studies.

Study	Article	Study	Article
A	[13]	L	[3]
B	[14]	M	[20]
C	[15]	N	[21]
D	[16]	O	[22]
E	[17]	P	[23]
F	[18]	Q	[24]
G	[19]	R	[25]
H	[26]	S	[30]
I	[27]	T	[31]
J	[28]	U	[32]
K	[29]		

In Appendix B, we have indicated the articles used for discussion in a summary table. The nomenclature of Table 3 has been adopted in Appendix B—Table A2.

4.2. RQ-1: What Warehouse Sub-Domains Adopted the Smart Warehouse Technology?

The total management of a warehouse consists of many sub-domains. The most important sub-domains from the literature that have adopted smart warehouse technology are presented in Figure 3. The most important sub-domains are warehouse operations and management, which are two key factors in which different operations are summed. The different sub-domains are explained in detail in the chapter.

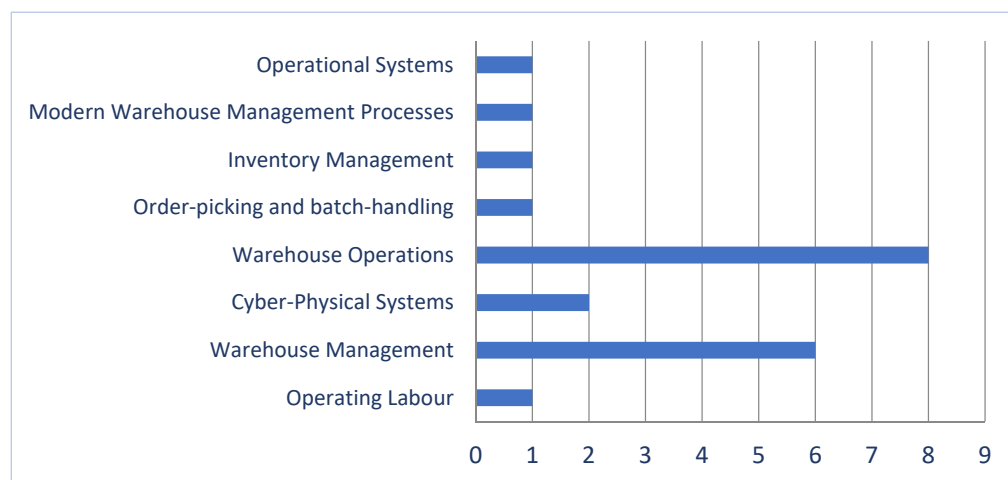


Figure 3. Summary of frequency of sub-domains.

Nowadays, technology is well-embedded in all warehouses. Due to complex and high varied customer orders, reduced inventory, and the demand for real-time information, the traditional (manual) warehouse operations are no longer adequate in Industry 4.0 [3,13,22,27,28,30,32]. Modern warehouse management processes are guided by database-driven software applications such as inventory management system (IMS) [26], advance planning and scheduling (APS), transport management system (TMS), warehouse management system (WMS), and enterprise resource planning (ERP) [29]. The most common domain where smart warehouse technology is adopted would be the WMS [24]. The time the products are within the warehouse is called a warehouses' life cycle, this cycle is managed by the WMS and consists of order receiving, storing, picking, and shipping [14,23,27,28]. Yan et al. [21] take WMS a broader perspective by stating that warehouse management consists of the following subdomains: warehouse-entry management, shelves management, warehouse-out management, and storage management.

Various technologies have been adopted in warehouses to improve performance: radio-frequency identification (RFID) is seen as the most promising. RFID addresses the two key demands when it comes to improving WMSs: higher efficiency and lower costs [16]. Furthermore, RFID allows for automatic identification and enables real-time data [17]. Other advantages of RFID technology are its (small) size, variety in shapes, reusability, relatively low cost, accuracy, and its ability to be read wireless [16].

As the products have numerous amounts of interactions during this process, focusing on the improvement of core functions makes warehouse management more efficient [32]. The functions to optimize a warehouse are product allocation, product picking, and product identification [23]. As part of smart warehouse automation, many 'online retailers have changed their warehouse pick-and-pack operations from human-to-goods to goods-to-human' [20]. Current Internet of things (IoT)-based tracking technologies, such as RFID, allow systems to cope with complex randomness [25,30]. Such randomness is the allocation of products to different slots of shelves while maximizing space occupation and minimizing handling costs [18,23]. For transportation, automated guided vehicles (AGV) are introduced

to enhance operations and efficiency [20]. The AGVs are supported by an order-picking operations system (OPOS), which guides the order-picking and batch-handling [19]. As “mechanical, physical, electrical, and software components cannot be isolated and do not function independently” [15], the various components are coined in cyber-physical systems (CPS). These CPSs require to be protected through cybersecurity when transitioning towards Industry 4.0 [31].

4.3. RQ-2: What Are the Key Motivations for Adopting Smart Warehouses?

Warehouses become more complex over time, and customer demand has taken on new forms. This results in a need to adapt to a smart warehouse. The identified key motivations are external threats, strategic advantages, increased quantity of data, warehouse complexity, operational agility, and customer demand. The most frequent key motivation is warehouse complexity, and the second one is customer demand.

The role of warehouses has dramatically changed as customer orders have become more complex and diverse [30]. Moreover, there is a need for real-time information, a faster response time, and accuracy [3,22,28,32]. Traditional warehouses/stores are no longer suitable for satisfying the demand of the new shopping habit (i.e., online shopping) [26], are no longer confined to keeping a large amount of stock-keeping units (SKU) [18,24,28], are incapable of responding to modern challenges and constraints in a timely matter [29], and are no longer locally based which requires a constant internet connection and new forms of protection [31].

Current developments create a challenge for the operation agility in terms of heterogeneous resources within warehouses, as well as the highly distributed across warehouses [21,30]. To survive in the highly competitive business environment [19], effective management of warehouses has become vital in current supply chains [17,28]. To enhance the contribution of warehousing in supply chain performance, the use of automatic identification technology has great potential [14].

As today's demand requires lower prices, fast delivery, and tailored products, retailers need more efficient distribution centers, with improved WMSs at the hand of automation [13,17]. Although WMS is widely used to obtain data to optimize costs, management and operations [16], most WMSs have been designed as material-tracking systems which are incapable of providing timely and accurate order execution information due to its unpredictability and concurrency [24]. Most WMS rely on human input and do not contain automated data retrieval or real-time data. As human errors account for 80% of false information, incorrect information is inevitable [16]. Inaccurate information may lead to uncertainties and complications on both demand and supply, potential detrimental influence on the logistics [25]. Warehouse systems and supply chain actors are being merged, requiring system improvement in responsiveness, flexibility, and agility [17,25,29], for the (human) error-based bottleneck to be solved [16,22,30], and able to handle the vast amount of data acquired [32].

An automated smart warehouse would allow more efficient order-picking and batch-handling, allowing for better customer-oriented services, offering a strategic advantage [19,20]. Automation and the use of have grown over time as robotics, electronics, and computer technologies improved in terms of affordability, ease of use, functionality, ability to communicate with other devices [15]. Simultaneously, its complexity grows drastically, as well. To further benefit and cope with the complexity, innovation is required [15,16]. With an increase of complexity, controlling, and interaction have become a major challenge in warehouse management. Innovation on communication between different objects is needed on three levels: object-to-environment (O2E), object-to-object (O2O), and object-to-human (O2H). Improvements in warehouse operations are ensured with safety control mechanisms, which detect potential hazards and disturbance [23,27].

4.4. RQ-3: What Are the Current Distinctive Characteristics of Smart Warehouses?

A key feature of a smart warehouse is automation with no or a little human interaction. The smart warehouse is perceived as being flexible both to the environment and within the warehouse, and for it to be in constant connection with the cloud. With all sorts of tracking abilities and other forms of data gathering, data management became a crucial factor. The identified distinctive characteristics are presented in Figure 4.

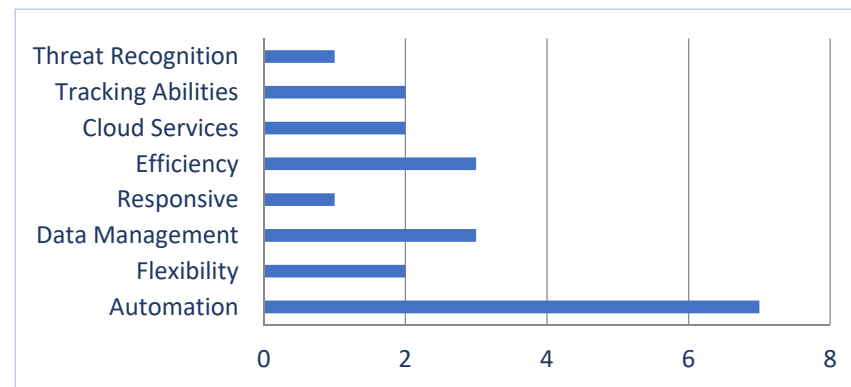


Figure 4. Summary of the frequency of current distinctive characteristics.

Warehouses are no longer confined to keeping large amounts of SKUs [24]. Current orders are often of low quantity and a wide variety. Modern warehouses must be highly responsive by enhancing order cycle times, cutting costs, and excelling in customer service [19]. Flexibility is key in a changing environment, and reducing the total cycle time ensures smooth inbound and outbound logistics, including amongst others stock accuracy, process management, space utilization, and optimized picking [3,30]. The goal is to “allocate minimum warehouse resources and satisfy customer demands within a short period of time”. To optimize order-picking, the concept of order-batching will be a crucial element [19]. The concept of public warehouses (PW) anticipates this where small quantities of goods are delivered when requested [24].

Current automated warehouses are often known for having manually operating [22] or programmed equipment. Examples of this equipment are AGV [20], palletizing robots, carton flow racks, rotary storage cabinets, and AS/RSs [13]. Automated storage and retrieval system (AS/RS) is a material handling mechanism that is a key element of automated warehouses or distribution centers [26]. Automated guided vehicle systems (AGVS) are used as their movements are directed and programmed by sensors, which enables more flexibility in the routing and dispatching [15]. Optimization is also increased efficiency and technological support for processes that cannot be technologically atomized [27,28]. Hu and Chang [18] argue to integrate an auto-access multi-level conveying device (IMCD) into the AS/RS to enable three-dimensional movement through conveyors.

WMSs have tracking abilities through RFID [24,25]. An RFID-inventory management system is a part of future generation automated warehousing systems [14,26]. RFID-based order scheduling and execution monitoring system (RFID-OSEMS) combines the advanced data collecting performance of RFID with real-time data-based order scheduling to coordinate all order handling devices [24]. The RFID-OSEMS has two subsystems (1) real-time order scheduling (RTOS), storing and retrieval (R/S) orders from different customers are stored in an order pool, and (2) an RFID-based order executing and monitoring (ROEM). ROEM is the joint of four sub-models (1) RFID configuration strategy (RFCS) creating a ubiquitous monitoring environment through the use of different types of RFID devices, (2) RFID-based order executing (RFOE), which reduces order executing time and facilitates the collection of related data, (3) real-time data collecting (RTDC) on-site by vehicle-mounted RFID readers, and (4) RFID-based executing monitoring (RFEM), which processes all data and is in direct contact with the RTOS in case rescheduling is needed, creating a closed-loop system [24]. Hub processors for RFID data flow are used to pre-process

the data and provide classified, filtered, and uniform data for all systems. This will form the basis for an IoT-based warehouse [16].

WMSs have tracking abilities through IoT [25,30]. A WMS integrated with autonomous components which support the communicating object (CO), having intelligent interactions and decision making, will turn this IoT-based system towards a smart warehouse system [23,32]. IoT can be apportioned into a sensor, transmission, and application network [30]. The computer of things (CoT), as an evolution on IoT and cloud computing, combines the physical resources with the management through cloud services, allowing it to be accessed independently from the location with simple and common methods [21]. In addition to an IoT infrastructure, a multi-agent system (MAS) is also recommended to support modern warehouse management processes [29]. Furthermore, a data capturing and processing module is crucial [32]. This module collects data from different management systems such as the sales system, WMS, and transportation management system (TMS) and provides filtered, sorted, and uniform outputs for decision support models to base decisions on. The decision system automatically performs risk analysis and formulates the ideal workflow [17].

Finally, all warehouse operations have to be protected from cybercrime. In order to cope with this, a multi-level strategy is proposed by Lezzi et al. [31]. On a top-level, consultation for the security strategy is advised, followed by risk management to prevent attacks and training from identifying and controlling them. Self-learning from software through monitoring and detecting could provide a solution.

4.5. RQ-4: What Are the Currently Adopted Technologies for Realizing Smart Warehouses?

Many developments are intertwined and part of the whole process. When we analyze the current technologies, the same pattern can be observed. Most technologies that are implemented to realize a smart warehouse are either on a system level or on a data-providing level. On a data-providing level, RFID is clearly present in the papers. RFID is linked to technologies such as IoT and various operation management systems. In this chapter, the summary of the technologies, as presented in Figure 5, is described in detail.

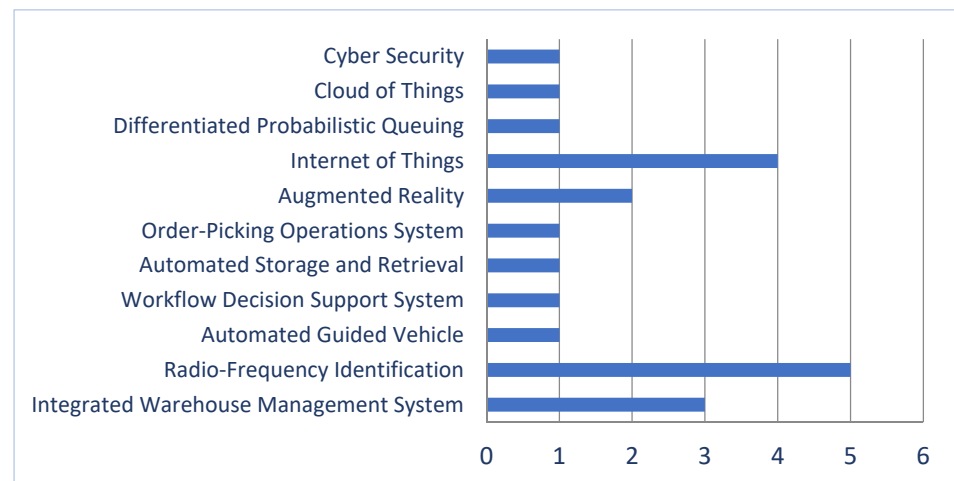


Figure 5. Summary of frequency of adopted technologies.

RFID technology can be seen as “one of the most important technologies in IoT” [24], it is key for the automated warehousing systems [14,26]. An RFID-based intelligent warehouse management system (RFID-IWMS) realizes the effective management of spacing, automatic recognition, and tracking of goods in the whole warehouse process, and the exchange of real-time data between operations and the WMS [16]. To develop a “smart” self-adjusting warehouse, it is required to apply RFID-tags to both inventory items and warehouse storage equipment. In this machine-to-machine (M2M) network, the shelves or parts of the shelves are automatically allocated to other locations [25]. Together with a dy-

dynamic bottom-up approach linked to an IoT infrastructure, enabling the system to have self-organizing behavior and interconnecting all warehouses within the supply chain [29,32].

An IoT-based WMS is a WMS in which all incoming/outgoing products and activities are controlled, and deviation in order quantity can be automatically managed and solved [3,22,30]. Integrated WMSs (iWMS) and communication networks (cabled/wireless) are linked with smart labels (barcodes, RFID, automatic identification (Auto-ID)) and facilitate identification, storage, tracking, and control for all incoming and outgoing goods at a warehouse [13]. The use of a CO in WMS creates a product-driven system that represents products, resources, and workers. In short, an IoT-approach in which communication and decision making are endorsed to secure joint, reactive, and smart operations [23]. Enhanced with CoT, everything is seen as a “thing”, allowing heterogeneous resources to be amassed and abstracted to the variation in demand [21]. Finally, the WMS should also be integrated with the enterprise resources planning (ERP) system to manage and control all data and support supply chain decision-making and planning [13].

The application of path development algorithms and ceiling-mounted cameras will allow the AGVs to be self-instructing and cope with alterations. The purpose of the mounted cameras is tracking and dynamic control [15]. Further development in robotics could include the interaction between all robotics, conveyor belts [18], and other technological applications on site. Differentiated probabilistic queuing (DPQ) is suggested for the scheduling of the AGVs. With DPQ, priority can be given to the different orders coming in. Possible forms of priority are the willingness to pay and the urgency of order [20]. Besides AGVs, artificial reality (AR) can be embedded in warehouses by having the employees use smart glasses in their work. AR speeds up processes, and employees do not have to use hand mobile devices to scan/operate warehouse products and instruments [27,28]. Another system to optimize labor resources, reduce in-warehouse travel distance, and define order-picking priority could be the OPOS. The OPOS interacts with the WMS for the stock and data storage [19]. To determine operations workflow and keep risk management into consideration, a workflow decision support system (WDSS) is suggested. The WDSS is integrated with RFID, the analytical hierarchy process (AHP), and case-based reasoning (CBR). AHP allows both quantitative and qualitative criteria to be taken into consideration. CBR uses former solutions to help in the current decision-making [17]. The goal of WDSS is to capture real-time data, identify and rank the potential risks, and formulate warehouse operations workflow, respectively. The potential risks could be on the three exposure layers of the CPS being physical, network, and computation [31].

4.6. RQ-5: What Are the Current Challenges and Strategies for Transitioning to Smart Warehouses?

Transitioning is mainly executed through self-learning of technology, the application of multiple systems, or automation. Besides strategies, there are different kinds of challenges. The applied technologies should be robust and secure and be able to cope with a changing environment within the supply chain and other factors that might affect the everyday process. The different kinds of strategies and challenges are described as follows:

4.6.1. Strategies

The implementation of RFID on systems through integration is an important aspect that needs to be addressed for the warehousing system [25,26]. Altering the WMS from a materials-tracking to a decision-making system as the former are ineffective in providing accurate and timely order execution information [24], the effective use of AR could present as key decision technology during the transition phase [27]. By expanding the current use of tracking technologies from product to the whole warehouse, so the warehouse becomes a “smart” self-regulating and allocating warehouse [25,30]. To realize this, a storage and output conveyor-based system, where each conveyor is controlled by a programmable logic controller (PLC). The PLC uses a local area network (LAN) to communicate with mounted sensors [13]. The PLC can be substituted or parallel-used with an IMCD [18]. Items are preloaded on pallets/totes (of non-identical size) and are attached with an RFID-

tag. Potential RFID-tags could be both active or passive depending on the product criteria and the overall costs [19].

Another strategy could be to integrate the advanced WMS with the fuzzy clustering technique. This technique suggests the best applicable order-picking method and increases the efficiency of the order-picking process [3]. This advanced WMS can be further developed with the use of CPSs to evolve it into a CPS-WMS, making the system (more) autonomous. According to Trab et al. [23], future WMS might have a collaboration between products, and storage units will determine the storage location. To determine the storage location, the system first applies the product allocation problem (PAP). PAP comes down to distributing and storing products amongst the warehouse while maximizing space and minimizing costs. Second, it checks whether there are compatibility constraints (CC) present. CC are shelves and slots capabilities checks to see if there are any restrictions such as size, capacity, product compatibility, policy, and time. Basically, all factors could limit the stocking of a product. Finally, the “IoT Infrastructure associates RFID technology with wireless sensors network (WSN), communicating object paradigm and multi-agent systems” [23]. This all comes together at a multi-agent architecture (MAA) based on IoT for PAP/CC for a collaborative warehouse environment that uses negotiation mechanisms. The negotiation mechanisms check for restraints on products or shelves in relation to other products and shelves and will argue whether the said product can be stored at said shelf. Strategically, this WMS will be supported by developing AGVs into Autonomous Automated Guided Vehicles (AAGV) [15]. Combined with the OPOS or DPQ, it could optimize labor resources, reduce in-warehouse travel distance, and define order-picking priority [19,20].

4.6.2. Challenges

Overall, there is a lot of uncertainty due to developments as globalization and supply chain interdependence, which poses some great challenges for the warehouse management [16,29]. The current research limits itself to configurations with selected parameters on capacity and location, so it is not yet adapted to big data [18,25] and the reading performance on passive and active RFID-tags in different systems and parts of the system is unclear [13,14]. Moreover, in a world that is getting smaller and in constant connection due to technological developments in relation to globalization, not all systems are currently able to interact with various systems from different supply chain actors [14,16]. As programming languages are not standardized, it is a challenging and costly process for companies to link various systems together, whether it is within the warehouse or amongst the actors [22,28]. Besides the initial investment and development costs, one also has the cost of maintenance and operations in mind [18,25].

More research is required on the robustness of the system [21,29]. Former solutions will reduce potential risks [17]. Furthermore, there is a lack of knowledge on the use of artificial intelligence (AI) and robotics in warehousing in relation to the adoption of IoT [3]. The life expenditure of remote hardware might be improved to ensure the system does not fail [28]; systems must be highly reactive and adaptable to changes on local as well as market/global levels (e.g., supply and demand) or concerning technological changes [25,29]. Finally, the system must also be resistant to and even eliminate human errors [22,28], a human-friendly interface could provide a solution [15].

Another challenge in realizing a smart warehouse would be the security of the system [21,23,31]. The need for technological advancements is undisputed, but its acceptance is not. There are major issues when it comes to privacy and confidentiality of the data collected by the system [28]. Another security risk that should be taken into account is any hazardous damage due to incompatibility between products within the warehouse, as the system should also be able to prevent those kinds of risks [23]. Finally, the system must also take human safety into account [15,23,27,28].

It is challenging to see how current flexible systems are in terms of data processing, storage, adapting to new technologies, security, and combining various systems from different supply chain actors.

5. Related Work

SLR studies are widely performed by researchers who focus on the application of information and communication technology (ICT) in the industry [33–36]. In addition to the SLR studies, researchers publish traditional literature review papers on the application of ICT in the industry [31,37,38]. There are a few traditional literature review articles on smart warehousing. The first survey discusses the underlying technologies for CPS-based smart warehouses. Liu et al. [9] explain how the existing techniques in CPS can help to build smart warehouses and focused on four issues during the application of CPS in smart warehouses. They presented the following research directions: Blockchain-based bookkeeping subsystem, shelf-life prediction with multi-source data fusion, multi-robot collaboration via reinforcement learning, and high-level activity recognition with deep learning. Yerpude and Singhal [39] synthesized the knowledge gathered from several reports, such as Gartner reports and interviews performed with managers having several warehouses. They discuss how the Internet of Things can contribute to smart warehouses. Kamali [40] reviewed and compared smart warehouses and traditional warehouses. As for the disadvantages of smart warehouses, he explained that smart warehouses require high investment costs, new machines, and different skills. Moreover, he states that a software fault can cause the entire warehouse system to stop. Despite these challenges in smart warehouses, traditional warehouses have more disadvantages such as over-handling items, inefficient operations, damaged materials due to the processes, inefficient space management, and inefficient materials handling the equipment. As in the case of the company Amazon, a smart warehouse might cost around \$775 million, but its return on investment (ROI) is far beyond this investment cost.

6. Discussion

We observed an increasing amount of interest in smart warehouses amongst researchers as the publication years show that most articles are from recent years. From analyzing the applied research methods in selected studies, we observe that most papers are based on case studies (38%) and simulations (38%). This can be explained as simulating is an often-used tool when it comes to software technologies and its programming, and case studies are observations of the applied software technology. Experiments, on the other hand, are more in the relation of matching the software and the hardware technology and are a costlier and time-consuming process. Regarding the threats to validity, we applied the study quality assessment criteria to cover the threat of publication bias. In addition, we used exclusion criteria to cover the threat of selection bias and performed all the selection criteria independently. In the case of conflicts, a meeting was organized for discussion and consensus. The use of our selection criteria enabled us to exclude non-relevant papers. There is, however, always a chance that we missed some articles with our selection criteria. Furthermore, technology is under development and of high value to companies and their competitive advantage. Therefore, there may be other or further developed systems that are classified and thus not presented in the literature. Since the number of papers analyzed in this paper is limited and new papers are published frequently in this field, some of our conclusions will be affected when more papers are included in this research. Moreover, if different variations of the search string are made, different papers can be identified, and therefore, new observations can be made.

7. Conclusions

We reviewed the research on smart warehouses to answer the research questions. To the best of our knowledge, no SLR paper has been published yet on smart warehouses, and therefore, this is timely research as organizations are nowadays transitioning to smart

warehouses. The results of this study are useful for researchers in this domain and for practitioners who wish to build or transition to a smart warehouse in the near future. In this article, we identified that the key subdomains where smart warehouse technology has been adopted are receiving the order, storing and shelving management, order picking, and order shipping. The motivation for transitioning to a smart warehouse comes from the need to adjust to a complex and diverse market in which real information, flexibility, and accuracy are imperative. Radio-frequency identification (RFID) and the Internet of things (IoT) are seen as current features to turn a warehouse into a smart warehouse. Warehouse management systems (WMS) have tracking abilities through these features, and real-time data is provided. To realize a smart warehouse, current technologies such as IoT and RFID should be integrated into the WMS. This enhanced WMS in combination with an enterprise resource planning system, and a workflow decision support system allows us to manage and control the data and identify potential risks.

To realize the goals, the WMS has to transition from a material-tracking to a decision-making system. Potential strategies are to create a self-regulating and allocating warehouse with a programmable logic controller or create an autonomous system by combining the WMS with a cyber-physical system. Trends such as globalization and supply chain interdependence, together with challenges as coping with big data, robustness, and security, and life expenditures of the remote technologies, pose some great challenges for realizing a smart warehouse.

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Appendix A

Table A1. Exclusion of papers based on each exclusion criterion.

Source	EC1	EC2	EC3	EC4	EC5	# of Studies Excluded
IEEE Xplore	1	0	0	11	0	12
ResearchGate	0	0	0	125	1	126
SAGE Journals	0	0	0	0	0	0
ScienceDirect	0	0	2	32	1	35
SpringerLink	0	0	0	0	0	3
Taylor & Francis Online	9	0	0	430	0	439
Wiley Library Online	0	0	0	0	0	0
Total	10	0	2	598	2	615

EC-1: Papers without full text available; EC-2: Papers not in English; EC-3: Duplicate publications; EC-4: Papers that are not related to Smart Warehouse/Warehousing 4.0; EC-5: Survey papers.

Appendix B

Table A2. Summary table for Discussion section.

Research Question	References
RQ 1	H, K, Q, N, I, B, J, P
RQ 2	S, O, L, U, J, H, Q, F, K, T, N, G, E, A, D, R, M, C, I, P
RQ 3	Q, G, S, L, G, O, M, A, H, C, I, J, F, R, B, D, P, N, K, U, E, T
RQ 4	Q, B, H, R, U, K, O, S, L, A, P, N, C, M, I, J, G, E, T
RQ 5	H, R, Q, I, S, A, F, G, L, P, C, M, D, K, B, O, J, N, E, T

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