L'industrie 4.0 et l'internet des objets, innovations dans les entrepôts intelligents : Une revue des tendances

Industry 4.0 and the Internet of Things, Innovations in Smart Warehouses: A Review of Trends

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RÉSUMÉ. Cet article passe en revue les technologies Industry 4.0 les plus récentes et les plus remarquables appliquées aux entrepôts intelligents. L'industrie 4.0 intègre des innovations telles que l'internet des objets (IoT), la robotique et l'analyse de données massives (Big Data) afin de transformer la gestion et le fonctionnement des entrepôts.

Conception/Méthodologie – Cet article passe en revue les innovations les plus récentes dans les technologies de l'industrie 4.0 appliquées aux entrepôts intelligents et propose un modèle d'entrepôt étendu intégrant l'IoT et l'IA afin d'améliorer l'efficacité opérationnelle. En évaluant la mise en œuvre de ces technologies, l'article donne un aperçu de la manière dont ces outils améliorent l'efficacité opérationnelle, la précision du contrôle des stocks et l'optimisation des processus grâce à la génération massive de données.

Résultats – La gestion efficace des entrepôts est confrontée à des défis tels que le traitement de grands volumes de données, les coûts élevés d'acheminement, l'optimisation de l'espace et les complexités liées à la personnalisation massive des produits qui ont un impact sur les stocks, le contrôle et l'efficacité. Cette étude met en évidence les technologies de l'industrie 4.0 telles que l'IoT, l'IA, le Big Data et la robotique, en tant que facteurs clés de la mise en place d'entrepôts intelligents et autonomes. Si ces innovations améliorent les opérations, des défis subsistent en matière d'interopérabilité, de cybersécurité et d'investissement. Les conclusions soulignent la nécessité d'une validation basée sur la simulation, de mesures spécialisées et d'un cadre solide pour soutenir l'adoption évolutive et durable et le transfert de technologies dans tous les secteurs.

ABSTRACT. This article reviews the most recent and outstanding Industry 4.0 technologies applied in smart warehouses. Industry 4.0 integrates innovations such as the Internet of Things (IoT), robotics, and Big Data analytics to transform warehouse management and operation.

Design/Methodology – This article reviews the most recent innovations in Industry 4.0 technologies applied to smart warehouses and proposes an extended warehouse model incorporating IoT and AI to enhance operational efficiency. By evaluating the implementation of these technologies, the article provides an overview of how these tools improve operational efficiency, inventory control accuracy, and process optimization through massive data generation.

Findings – Efficient warehouse management faces challenges like handling large data volumes, high routing costs, space optimization, and complexities from mass product customization that impact inventory, control and efficiency. This study highlights Industry 4.0 technologies such as IoT, AI, Big Data, and robotics, as key enablers of intelligent, autonomous warehouses. While these innovations enhance operations, challenges remain in interoperability, cybersecurity and investment. The findings stress the need for simulation-based validation, specialized metrics, and a strong framework to support scalable, sustainable adoption and technology transfer across industries.

MOTS-CLÉS. L'industrie 4.0, entrepôt intelligent, internet des objets, innovation, chaîne logistique.

KEYWORDS. Industry 4.0, smart warehouse, IoT, Innovation, supply chain

1. Introduction

The history of industrial development has been marked by significant transformations across various stages, each characterized by innovative advancements. This trajectory of change is not only a reflection of past developments but also a foundation for the future trends associated with Industry 4.0. The first revolution heralded the advent of steam engines, which facilitated mechanical production. The second revolution introduced electric power, leading to mass production lines supported by electrical equipment, while the third revolution was defined by the rise of automation through electronics and computing. The current phase, Industry 4.0, is distinguished by the integration of intelligent systems into production processes, leveraging technologies such as the Internet of Things (IoT), cloud computing, and data science [VAN 22]. In this context, warehousing emerges as a critical operational focus within Industry 4.0, playing an essential role in the efficient organization of resources across supply chains [VAN 21]. The modern warehouse not only manages physical goods but also orchestrates digital information flows to enhance product organization and access efficiency. However, these operations can be resource-intensive and complex, often requiring significant time and energy investments [TUB 23].

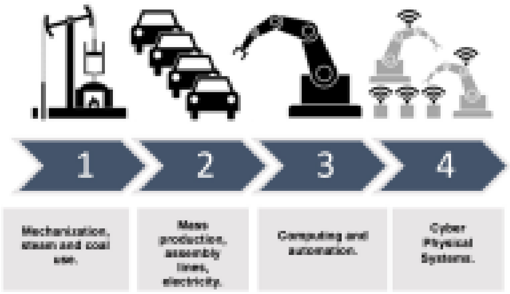

Figure 1: *Evolution of the stages of the industry. Source:(Hafo, 2024).*

To address these challenges and optimize storage processes, the implementation of emerging technologies focused on automation becomes paramount. Among these technologies, the Internet of Things (IoT) stands out as a transformative tool that creates intelligent environments aimed at improving organization and reducing retrieval times for stored items [KHA 23].

1.1. *Objectives and Scope of the Review*

This article aims to provide a comprehensive review of the most recent trends in smart warehouse solutions and how they can drive efficiency and innovation in supply chain management. Through the exploration of IoT integration and AI enhancement within warehouse operations, it will highlight the transformative potential of these technologies in creating agile and responsive logistics environments. In addition to the critical analysis of recent literature, an extended modeling technique for characterizing variables is proposed. Alongside the benefits, this article also acknowledges the limitations and emerging challenges of implementing Industry 4.0 technologies.

1.2. *Structure of the Article*

This article is structured into sections to provide a successive understanding of how Industry 4.0 technologies are transforming warehouse operations. It begins with an overview of the evolution of warehousing within the industry 4.0 paradigm, followed by a description of modeling approaches used to optimize smart warehouse systems. The next section explores the implementation of specific technologies, including the Internet of Things (IoT), Big Data, robotics, cloud computing, and others, emphasizing their role in enhancing efficiency and operational intelligence. Afterwards, this article identifies research challenges including technical issues and security concerns associated with these advancements. Finally, it concludes with a summary of findings and implications for future research.

2. Industry 4.0 and Smart Warehousing

The evolution of industry has been marked by a series of technological revolutions, each significantly transforming the way goods are produced and distributed. The First Industrial Revolution introduced mechanical production powered by steam engines. The Second brought electric power and mass production systems, while the Third saw the rise of automation through electronics and computing [VAN 22]. The current phase, known as Industry 4.0, is characterized by the seamless integration of digital technologies into manufacturing and logistics processes. This transformation is driven by data-driven decision-making and automation, which are essential for meeting the demands of modern consumers who expect rapid delivery and personalized services.

Within this context, warehousing has emerged as a key area of innovation. It plays a critical and increasingly strategic role as a central node in the supply chain where goods are stored, processed, and distributed. It is essential for efficiently organizing both physical and digital resources, improving the management of product and information flows. By optimizing space utilization and enabling faster access to stored items, smart warehousing enhances overall operational performance and supports the dynamic demands of modern logistics [VAN 21].

As warehouses evolve from traditional storage facilities into smart warehouses, they increasingly rely on advanced technologies such as IoT devices, robotics, and Big Data analytics. These tools facilitate real-time monitoring and management of inventory levels, environmental conditions, and product movements. By harnessing data generated from these technologies, warehouses can optimize space utilization, enhance order accuracy, and improve overall operational efficiency.

However, this process can be complex and resource-intensive, often requiring significant time, energy, and investment [TUB 23]. To address these challenges and make storage processes more efficient, emerging technologies focused on process automation offer effective solutions. Among them, the Internet of Things (IoT) stands out as one of the most important tools. IoT enables the creation of intelligent storage environments that enhance organization and significantly reduce the time needed to locate and retrieve stored items [KHA 24].

2.1. *The Impact of Industry Evolution and Innovation on Warehouses*

Changes are constantly occurring to meet the evolving needs of society over time. An example of this is warehousing, a relatively recent area in which emerging technologies are being integrated to improve the efficiency of operations, storage, and logistics by transforming manual techniques into intelligent processes. This shift aims to significantly enhance operational performance by optimizing the physical layout, product placement, and aisle arrangements within storage facilities [KEM 22].

Innovation in warehouses is evident in various aspects, particularly in the use of modelling techniques that address the complex challenge of physical product placement. These models manage the intricacies of storing items with varying dimensions and weights in spaces that are limited in area and subject to constant change. The logistics of these warehouses heavily rely on the efficiency of inbound and outbound product processes. In the context of Industry 4.0 and smart warehouses, these modeling techniques have evolved to incorporate advanced technologies such as the Internet of Things (IoT), robotics, and Big Data analytics. These innovations transform traditional warehouse management by optimizing space utilization, improving inventory accuracy, and enhancing overall operational efficiency [HEC 17].

The following section develops how modern modeling approaches leverage these technologies to create dynamic, responsive systems capable of adapting to the challenges posed by mass customization and the need for real-time inventory control. By applying these advanced models, the impact of Industry 4.0 technologies on warehouse performance can be measured, addressing key challenges outlined in the study's findings and highlighting the transformative potential of smart warehouse solutions.

2.2. *Modeling Techniques for Smart Warehouses*

Smart warehouse models employing the Internet of Things (IoT), smart agents, and genetic algorithms aim to reduce costs, alleviate congestion, and improve operational performance [HEA 13].

A comparative model of smart and traditional warehouses is designed to evaluate the impact of implementing Industry 4.0 technologies. This recent model is based on a previous one proposed for warehouse design and product allocation [HER 05] and [ENE 12].

2.2.1. *Characterize variables*

The main variables used to determine the performance of this model were selected from a review of key performance indicators in the warehouses [SAT 15]. These variables are classified in the dimensions of time, productivity, and quality:

Time KPIs	Productivity KPIs	Quality KPIs
Order delivery time, Reception time, Order preparation time, Delivery time, wait time, Order entry time, Ship ping time, Dock travel time to inventory.	Labor productivity, Office productivity, Transportation utilization, Use of the warehouse, Productivity of the preparation of the order, Use of inventory space, Use of external space, Reception productivity, Product rotation.	On time delivery, Customer satisfaction, Rate of completed orders, Accuracy of the physical inventory, Accuracy of the inventory, ordering accuracy requested, Shipping accuracy, Accuracy of delivery, Perfect orders, Waste rate, Orders shipped on time.

Table 1: *Selected key performance indicators for warehouse*

2.2.2. *Model designing and applications*

To formulate the design model and dynamically allocate storage spaces, three typical operations are recognized in several areas of the warehouse: reception of products, storage in the reserve area of the warehouse and shipments preparation area from the warehouse.

2.2.3. *IoT Sensor Parameters*

The mathematical model incorporates IoT sensor data through additional parameters and constraints: IoT Sensor Parameters:

- σ^t_i: Real-time occupancy rate for product *i* in period t measured by IoT sensors.
- θ^t_i: Environmental conditions vector (temperature, humidity, vibration) for product *i* in period *t*
- ρ^t_i: Product movement frequency detected by RFID sensors for product *i* in period *t*

Modified Objective Function:

$$min\, Z = 2\sum_i^t \sum_j \sum_t q^t_{ij} H^t_{ij} \lambda^t_i X^t_i + \sum_i \sum_j \sum_t q^t_{ij} C_{ij} Q^t_i X^{t/2}_{ij} + \sum_i \sum_t f(\sigma^t_i, \theta^t_i \rho^t_i)$$

Where $f(\sigma^t_i, \theta^t_i \rho^t_i)$ represents the IoT-based adjustment function that modifies costs based on real-time sensor data.

The objective function minimizes the total cost of handling the average load per period of each product assigned to an area, as well as its storage costs per period [ALE 19].

2.2.4. *Extended Warehouse Model with IoT and AI*

The integration of Internet of Things (IoT) and Artificial Intelligence (AI) within warehouse operations represents a significant evolution in the management of logistics and inventory. This extended warehouse model leverages advanced technologies to enhance operational efficiency, optimize resource allocation, and improve decision-making processes.

2.2.4.1. *Overview of the Extended Warehouse Model*

The extended warehouse model incorporates IoT and AI to create a dynamic and responsive system capable of meeting the challenges posed by modern supply chains.

The model focuses on:

- Real-time Data Collection: Utilizing IoT sensors to gather data on inventory levels, environmental conditions, and product movement.
- Enhanced Decision-Making: Implementing AI algorithms to analyze this data for predictive analytics, demand forecasting, and operational optimization.
- Cost Reduction: Streamlining processes to minimize handling costs and improve overall productivity.

2.2.4.2 *Key Components of the Model IoT Integration*

Sensor Deployment: IoT sensors monitor various parameters:

• σ_{it}: Real-time occupancy rate for product *i* in period *t*.

• θ_{it}: Environmental conditions vector (temperature, humidity, vibration) for product *i* in period *t*.

• ρ_{it}: Product movement frequency detected by RFID sensors for product *i* in period *t*.

These sensors provide critical data that inform inventory management and operational strategies.

AI Utilization

Predictive Analytics: AI analyzes historical data to forecast demand patterns, allowing warehouses to adjust inventory levels proactively.

Optimization Algorithms: AI-driven algorithms optimize storage space and picking routes, enhancing efficiency and reducing lead times.

2.2.4.3 *Artificial Intelligence Enhancement*

The model incorporates machine learning components through:

1. Predictive Analytics Layer:

• Demand Forecasting: ML models process historical data and IoT sensor inputs to generate λ^t_j (predicted demand).

• Space Utilization Prediction: Neural networks estimate future space requirements based on current allocation patterns.

• Environmental Impact: AI models predict product deterioration based on sensor data.

2. Dynamic Constraints:

$$\sum_i X^t_{ij}=1 \forall i,t$$

$$g(\sigma^t_i) \leq a\alpha^t \text{TS} \ \forall t$$

$$h(\theta^t_i) \leq b\beta^t \text{TS} \ \forall t$$

$$k(\rho^t_i) \leq c\gamma^t \text{TS} \ \forall t$$

Where g(), h(), and k() are AI-driven functions that adjust space constraints based on real-time conditions.

2.2.4.4 *IoT Sensor Data*

Let S = S1, S2, . . . , S_m be the set of IoT sensors in the warehouse, where each sensor S_i collects data of type $T_i \in$ {temperature, location, availability}. For each sensor S_i, we define:

$$D_i(t) = f_i(t) + \varepsilon_i(t) \quad (1)$$

where Di(t) is the data reading at time t, fi(t) is the true value, and εi(t) is the measurement error.

2.2.4.5 *IoT Data Processing*

We define a data processing function P that takes raw sensor data and returns processed information:

$$P(D_1(t), D_2(t), . . . , D_m(t)) = (I_1(t), I_2(t), . . . , I_k(t)) \quad (2)$$

where $L_j(t)$ represents processed information such as average temperature, item locations, or stock levels.

2.2.4.6 *Neural Network for Optimization*

We define a neural network NN with L layers. For each layer l ∈ {1, . . . , L}, we have:

$$a^{(l)} = \sigma(W^{(l)}a^{(l-1)} + b^{(l)}) \quad (3)$$

where at(l) is the activation of layer l, W(l) is the weight matrix, b(l) is the bias vector, and σ is the activation function.

The input to the neural network is the processed IoT data and current warehouse state:

$$a^{(0)} = [I_1(t), I_2(t), . . . , I_k(t), X^t_1, X^t_2, . . . ,X^t_n] \quad (4)$$

where Xt1 represents the state of product i at time t.

The output of the neural network provides optimized recommendations:

$$[R_1, R_2 \ldots, R_p] = NN(a^{(0)}) \tag{5}$$

where Rj represents recommendations such as optimal product placement or picking routes.

2.2.4.7 *Ranking Mechanisms Priority*

We introduce a priority function PR for each order:

$$P\,R(o_I, t) = w_i \cdot (t - t_i) + w_2 \cdot u_i + w_3 \cdot v_i \tag{6}$$

where o_i is the order, t_i is its entry time, u_i is its urgency factor, v_i is its value, and w_1, w_2, w_3 are weights.

2.2.4.8 *Extended Objective Function*

We extend the original objective function to include the IoT and AI components:

$$\min \left(2 \sum_{i=1}^{n} \sum_{j=1}^{4} \sum_{t=1}^{Tmax} q^t_{ij} H^t_{ij} \lambda^t_{ij} X^t_{ij} + \sum_{i=1}^{n} \sum_{j=1}^{4} \sum_{t=1}^{Tmax} \frac{qtjHtij\lambda tijXtij}{2}\right) + \alpha \cdot \sum_{t=1}^{Tmax} \sum_{i=1}^{m} (D_i(t) - f_i(t))^2 + \beta \cdot \sum_{j=1}^{p} (R_j - R^*_j)^2 + \gamma \cdot \sum_{i=1}^{|O|} P\,R(o_i, T_{max}) \tag{7}$$

where α, β, γ are weighting factors, R*j is the ideal recommendation, and O is the set of all orders.

2.2.4.9 *Additional Constraints*

Constraints were added to ensure that the IoT data and AI recommendations are properly utilized:

$$|D_i(t) - f_i(t)| \leq \varepsilon_{max} \ \forall i, t \tag{8}$$

$$\sum_{j=1}^{p} |R_j - R^*_j| \leq \delta_{max} \tag{9}$$

$$P\,R(o_i, t) \leq P\,R_{max} \ \ \forall o_i \in O, t \tag{10}$$

These constraints ensure that sensor errors are bounded, AI recommendations are reasonably close to ideal values, and order priorities don't exceed a maximum value.

2.2.5 *Integration Methodology*

The enhanced model operates through a closed-loop system:

1. Data Collection Layer:

- IoT sensors continuously monitor warehouse conditions.
- RFID tracking captures product movement.

- Environmental sensors monitor storage conditions.

2. Processing Layer:

- Edge computing devices process raw sensor data.
- AI models analyze patterns and predict future states.
- Real-time optimization adjusts allocation decisions.

3. Decision Layer:

- Dynamic reallocation triggers based on AI predictions.
- Automated adjustment of storage parameters.
- Real-time cost optimization.

2.2.6 *Model implementation and benefits*

The implementation follows a hierarchical structure:

1. Base Level:

- Original mathematical constraints remain active.
- Static allocation rules serve as a baseline.

1. IoT Enhancement Level:

- Sensor data integration
- Real-time monitoring
- Dynamic constraint adjustment

2. AI Optimization Level:

- Predictive modeling
- Pattern recognition
- Adaptive decision-making

This enhanced model significantly improves upon the original formulation by:

- Enabling real-time optimization.
- Incorporating environmental factors.
- Predicting and preventing allocation conflicts.
- Adapting to changing warehouse conditions.

- Reducing operational costs through predictive maintenance.
- Optimizing space utilization through dynamic allocation.

The integration of IoT and AI transforms the static allocation model into a dynamic, self-adjusting system capable of responding to real-world conditions while maintaining optimal performance metrics.

3. Technology implementation

Industry 4.0 provides a wide range of technologies that drive the improvement of smart warehouses, facilitating the creation of new storage spaces. When implementing these technologies, key aspects such as hardware and software are highlighted. Hardware includes physical devices such as IoT sensors, RFID tags, and automated robots, among others. These devices are designed to optimize operations from inventory tracking, merchandise picking to delivery. Software includes systems for warehouse and inventory management and data analysis for process optimization, which are essential to improve efficiency and accuracy in logistics management [TIK 23].

3.1 *IoT*

The Internet of Things (IoT) refers to the interconnection of electronic devices with each other through the network [DHO 20]. This has led to a significant improvement in the management of supply chains and warehousing operations, ensuring that goods, facilities and logistics elements are connected and communicate with one another [ZHE 22]. Thanks to the interconnection of low-power devices, the process of data transfer via sensors or mobile devices becomes more efficient [DHO 20]. For this reason, the implementation of IoT technologies generates a useful alternative for monitoring supply chain operations, product tracking and data to forecast demand trends in real time [KHA 24]. Consequently, by tracking activities in real time, data can be analyzed and interpreted, allowing for the identification of weaknesses in the security system and greater operational efficiency [EFT 21] which enables a better service through improved labor and economic productivity [KHA 24].

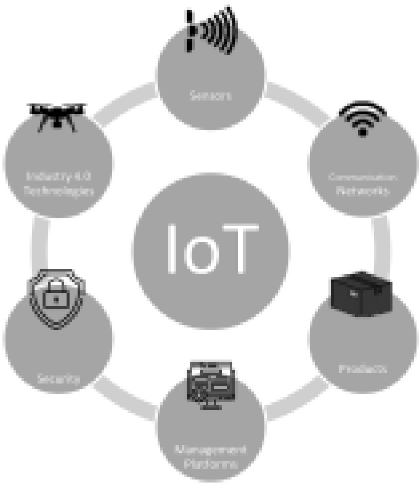

Figure 2: *Diagram of IoT in Smart Warehouses.*

Source: [KHA 24]

A successful example of IoT implementation in smart warehouses is in agri-food logistics; when reducing food waste in storage facilities, it facilitates the monitoring of temperature and humidity of perishable products, as well as their quality [ARA 22].

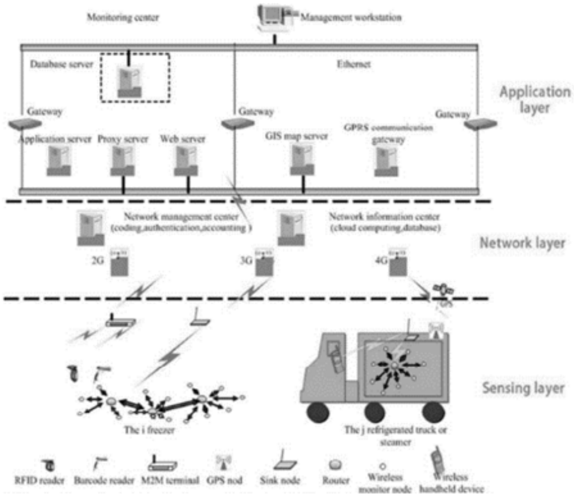

Figure 3: *Diagram of agri-food logistics operations.*

Source: [ARA 22]

3.2 Big Data Analytics

With the growing demand for data analysis and processing, the problem of insufficient storage space arises, so the need to store large volumes of information allows the emergence of techniques such as Big Data, one of the technologies implemented in the storage area. IBM defines it as the set of information that exceeds the capacity of databases and that must be stored to carry out its capture, management and processing (IBM, s.f.). It has become essential for companies to implement this tool to improve the visibility and flexibility of operations and the efficiency of processes due to the large amount of information and data coming from the movements made in the supply chain (logistic paths) [EFT 21].

Figure 4: *Characteristics of Big Data.*

Source: [TAL 21]

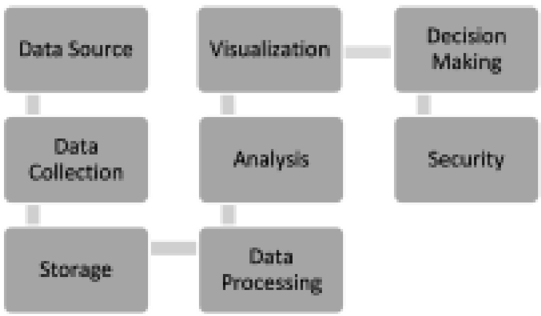

Figure 5: *Characteristics of Big Data.*

Source: [TAL 21]

3.3 *RFID*

In order to make the process of identifying products in inventory more efficient, warehouses have implemented Radio Frequency Identification (RFID) technology. Which, in intelligent environments, is used to sign a tag to each product, in order to offer a more accurate inventory tracking by being able to locate the objects along the supply chain. This results in more efficient management and organization of warehousing by facilitating the exchange of information [ZHE 22].

It should be noted that RFID is used for order scheduling, order execution monitoring and real-time data exchange and effective space management to achieve high efficiency, flexibility, configurability and cost reduction [VAN 22].

Figure 6: *RFID module MFRC522.*

Source: [DHO 20]

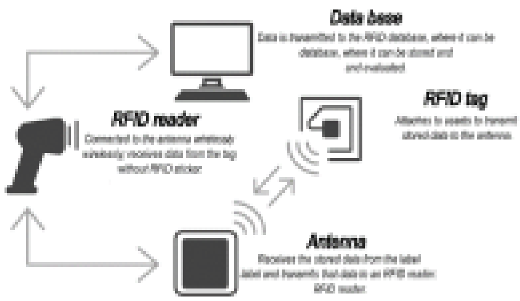

Figure 7: *RFID operation diagram.*

Source: [ALM 23]

3.4 *Warehouse Management Systems (WMS)*

A Warehouse Management System (WMS) allows the management and control of warehouse movements during supply chain operations [SAP 24].

Van Geest mentions in a 2022 publication that WMS is compatible with other systems and technologies [VAN 22] such as Augmented Reality (AR) and Enhanced Learning that improve the interconnection between the different processes of an intelligent warehouse [ZHE 22].

These systems have tracking capabilities through the Internet of Things (IoT), enabling real-time access to information and data about warehouse operations. This data is automatically reflected in the enterprise resource planning (ERP) system and the workflow decision support system. These systems help identify potential risks within the warehouse [DHO 20].

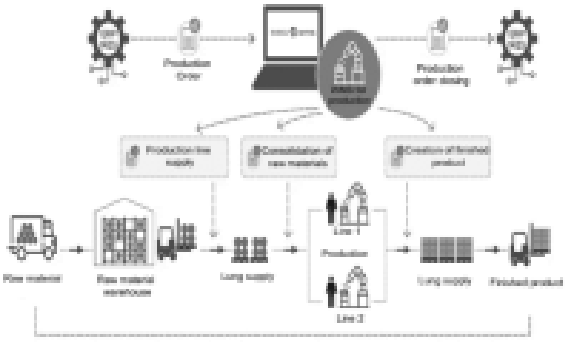

Figure 8: *WMS logistics process for Production.*

Source: [MEC 24]

3.5 *Augmented Reality (AR)*

It is crucial to maintain effective communication within a warehouse, and to achieve this, technologies such as Augmented Reality (AR) create interconnections between systems that lead to better warehouse management. To optimize these systems, Augmented Reality can be implemented with other technologies such as reinforced learning to help improve the connection between different processes and entities [ZHE 22] or even with IoT for video monitoring, achieving a significant improvement in the efficiency and accuracy of logistics operations [KHA 24].

This allows to reduce the human error factor and increase the speed of work thanks to the automation of processes through tools such as tag reading where the AR devices can be automatically adjusted to perform readings at different distances, either far or near depending on the existing needs [VAN 21].

As a result of the application of AR for 12 an automotive assembly line, it was learned that the use of this too reduces the time to search and identify items, facilitating the work and achieving a better performance in terms of speed and accuracy by the personnel [FAN 20].

3.6 *Cyber-Physical Systems (CPS)*

Cyber-Physical Systems or better known as CPS are indispensable in Industry 4.0 and intelligent warehouse management to address organizational issues, error and risk reduction of perishable products [ARA 22]. As a result of its implementation, it has improved time efficiency, energy consumption and accuracy in inventory tracking and management, which in return leads to a reduction in costs and expenses [EFT 21].

Warehouses perform picking and packing tasks that demand a large workload and amount of time for the personnel operating in these spaces, so in 2020 a CPS-based Multiobjective Heuristic Genetic Algorithm was proposed to minimize the waiting time in case of emergency replenishment, the un even distribution in the allocation of tasks between production cells and its ability to handle a large number of orders simultaneously that traditional warehouse systems are unable to handle [TUM 21].

3.7 *Cloud Computing*

One of the most important tools among data management and storage technologies, it is found within Cloud Computing and is used to manage IoT data in order to improve efficiency and accuracy in logistics operations [KHA 24]. This is classified into 3 categories; private, public and hybrid, which are subclassified according to security, the number of people using it and the size of their network [KOE 20]. Due to its scalability and flexibility, companies do not need to invest in the purchase and sale of servers, but can rent services in the Cloud having as an advantage that its infrastructure automatically adapts to the needs of the company allowing to process large volumes of information efficiently [BEL 23].

Amazon Redshift is a cloud data warehousing service offered by Amazon Web Services (AWS) that uses SQL and Machine Learning to enable organizations such as McDonald's and Moderna to analyze and store data from supply chain operations [AMA 23].

3.8 *Robots*

In industrial applications, Automated Guided Vehicle (AGV) and autonomous robots are of great importance for the improvement of efficiency and sustainability in the management of an intelligent warehouse [ARA 22]. AGVs allow goods to be transported autonomously (without human intervention) [AER 22]. In this way, the implementation of automated systems has improved productivity, safety and inventory procurement, facilitating warehouse management and minimizing errors, as well as being able to locate products more easily by using 3D maps [ARA 22].

A fundamental factor of AGV is the safety for its operation inside the intelligent warehouse, it must be aware of its environment and adapted to a traffic management module [VAN 21].

An example of a robot used in intelligent warehouses is an automatic picking robot, called "Pick-it-Easy" from the KNAPP company, which uses images for recognition and processing to detect the item and the way it is to be picked [EFT 21].

Figure 9: *AGV-assisted order picking*

Source: [ZHE 22]

3.9 *Drones*

By including drones within supply chains, it is possible to improve essential features of a smart warehouse, such as efficiency, productivity and safety. Drones are capable of scanning and tracking inventory in real time, improving the flow of goods within the warehouse, allowing the identification of products in high demand, preventing shortages and avoiding product backlogs [SAD 23].

With the support of technologies such as RFID, drones are able to identify and pick small items from storage areas, reducing the need for human labor, as well as being able to detect potential hazards or maintenance problems, helping to keep workers safe and prevent accidents [SAD 23].

Figure 10: *Drone operating in IKEA warehouse.*

Source: [CHA 23]

3.10 *Simulation and Digital Twins*

In smart warehouses, various problems can arise due to unforeseen events, resulting in increased costs and delays in the supply chain. The modeling and simulation of systems makes it possible to foresee these situations through the virtual representation of different scenarios in the intelligent warehouse, so that problems can be identified in the simulation model before adapting it to the real world. Implementing this technology reduces costs, optimizes storage processes, improves efficiency in the supply chain and improves operational planning [EFT 21].

3.11 *Machine Learning*

Machine Learning (ML) is used to discover knowledge from data [HAS 19], this is done through algorithms that use information to recognize patterns, make predictions and make decisions, focusing on developing systems that improve performance based on the data they consume [ORA 23].

ClearMetal is a machine learning company that uses machine learning algorithms and intelligent analytics to provide supply chain solutions for better decision making [EFT 21].

3.12 *Blockchain*

In the area of warehouses it is important to consider security measures to protect data, so it is opted to use systems such as Blockchain, a term that refers to a decentralized chain of blocks that contain information between different devices where the blocks are made up of data, chaining with the previous block. The hash is a chain made up of numbers and letters that help identify a block, with each new block a new hash is created which allows connections to be made between them [MEG 22].

Some of the features of blockchain include real-time updating of the database and cryptographic linking of blocks, i.e., when a block is created it cannot be modified without altering subsequent blocks, (being an irreversible process) resulting in a more secure database [SAN 23]. Generating an advantage within your security system based on the detection of unauthorized access by external agents, which, when detected, interrupt the connections between hashes, causing them to be mismatched with each other. In addition, when the attack is perceived, an automatic proof of work is made which makes cyber-attacks more difficult, because it causes new blocks to be created more slowly, so accessing them would take much more time and work [MEG 22].

A successful example of blockchain implementation in the supply chain occurred when IBM developed a blockchain-based system for Walmart that reduced the food tracking process from 7 days to 2.2 seconds [MEG 22].

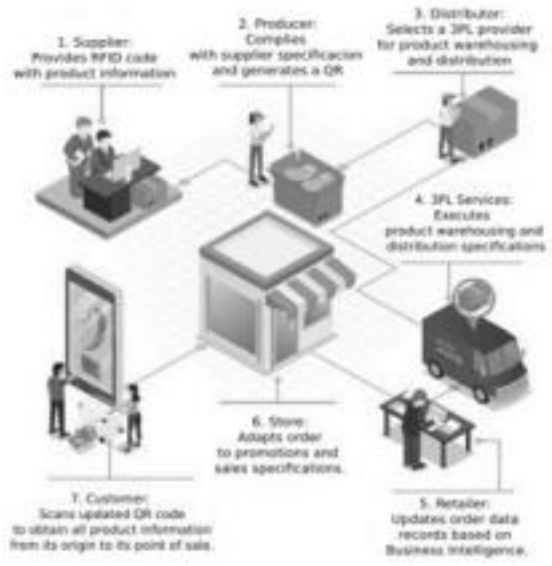

Figure 11: *Diagram of blockchain operation in the supply chain.*

Source: [OLI 23]

4. Research Challenges and Emerging Issues

4.1 RFID Implementation Barriers

There is concern about the negative influence of non-ionizing radiation used by RFID technology to communicate. Some research suggests that prolonged exposure to this type of radiation could have negative impacts on human health in the long term [VUK 21].

4.2 Robot challenges

As for fully autonomous vehicles, the disadvantage faced is the legislative barriers in each country [EFT 21]. Another factor it faces is the lack of skilled labor and the infrastructure of warehouses [ARA 22]. On the other hand, object localization, the programming required for time communication, and multi-robot collaboration are major challenges that are present in smart warehouses [VAN 21].

4.3 Data Security and Privacy

Another safety risk to consider is potential damage due to incompatibility between products within the warehouse. In addition, the safety of personnel operating in these spaces must also be a priority in the design and implementation of these intelligent systems [PRI 19].

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4.4 Cybersecurity Threats and Mitigation

Automated intelligent warehouses are susceptible to cyber-attacks due to the constant exchange of digital information. Therefore, companies face this vulnerability challenge by using different measures, protocols and technologies that help prevent risks. Some of the solutions to address this problem are to make backup copies of data so that in the event of a cyberattack or loss of data, they can be recovered quickly without affecting warehouse operations. Other measures to address this problem include restricting access to information to unauthorized personnel and encouraging the use of strong passwords to prevent confidential information from being stolen [MEG 22].

5. *Conclusion*

5.1 *Summary of Key Findings*

The literature review conducted in this study has enabled the identification and critical analysis of the most relevant and disruptive Industry 4.0 technologies applied within the context of smart warehouses. This analysis empirically confirms their transformative and strategic role in the contemporary management of global supply chains. The findings highlight the emergence of an integrated technological paradigm in which multiple digital innovations converge to create intelligent and autonomous logistics ecosystems. Among the most significant findings of the systematic analysis is the intensive and synergistic implementation of the Internet of Things (IoT) as a foundational technological in infrastructure, artificial intelligence (AI) as a driver of optimization and autonomous decision-making, Big Data analytics as a catalyst for real-time operational insights, and advanced robotic automation as an abler of operational efficiency. This technological convergence demonstrates exceptional capabilities for addressing the most complex contemporary challenges in industrial warehousing, including the management of mass product customization, multi-dimensional optimization of physical space, comprehensive inventory traceability, and real-time adaptive control of critical logistics operations. Each of these technologies represents an evolutionary milestone in the development of industrial digital ization and marks a critical stage in the transition toward fully interconnected, cognitively intelligent, and operationally self-managed cyber-physical warehouses.

Table 2 summarizes all core Industry 4.0 technologies presented in this article, outlining their operating principles, key functions, and the operational challenges they address.

Technology	How does it work?	What can it do?	Problems it solves
IoT (internet of things)	Connected sensors that gather and transmit data in real time	Condition monitoring, asset tracking, and predictive maintenance	Lack of real-time visibility, human error, reactive maintenance
AI (artificial intelligence)	Algorithms that analyze data and learn decision-making patterns	Route optimization, demand forecasting, process automation	Operational inefficiency, slow or inaccurate decision-making
Big Data Analytics	Processing large volumes of data to gain insights	Performance analysis, bottleneck detection, continuous improvement	Lack of actionable information for decision-making
RFID	Electronic tags that enable automatic identification via radio frequency	Accurate tracking of inventory and assets	Manual counting errors, inventory loss
WMS (Warehouse Management System)	Software that manages warehouse operations	Inventory control, order management, task assignment	Disorganization, poor warehouse management efficiency
AR (augmented reality)	Superimposition of digital information onto the physical environment via devices	Picking assistance, training, guided maintenance	Picking errors, steep learning curve for new employees

CPS (Cyber-Physical System)	Integration of physical systems with smart software and networks	Advanced automation, real-time human-machine interaction	Poor synchronization between physical and digital systems
Cloud Computing	Data storage and processing in remote servers	Remote data access, scalability, real-time collaboration	Local infrastructure limitations, lack of flexibility
Robots	Programmed machines to perform repetitive or complex tasks	Picking, packaging, internal transport	Labor costs, human error, hazardous tasks
Drones	Unmanned aerial vehicles with sensors and cameras	Aerial inventory, inspection of large warehouse areas	Slow or dangerous tasks in hard-to-reach zones
Simaluation and digital twins	Digital replicas of physical processes for testing and analysis	Scenario simulation, process optimization before real-world implementation	Costs of physical testing errors, lack of foresight
Blockchain	A distributed and secure database for transaction recording	Traceability, data security, process verification	Lack of trust in the supply chain, data manipulation
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Table 2: *Comparative overview of key technologies and its applications*

The evidence analyzed reveals that technological integration goes beyond the mere automation of traditional processes to generate emerging capabilities in continuous learning, dynamic adaptation, and predictive optimization.

Nevertheless, the analysis also reveals that, despite the accelerated technological progress, significant systemic challenges persist, including interoperability among heterogeneous systems, cybersecurity in critical industrial environments, specialized workforce training, and the justification of substantial investments in infrastructure.

Additionally, individual technologies present specific constraints: Data Analytics demand substantial software and hardware resources as well as skilled personnel, potentially limiting its adoption. RFID performance can be affected by environmental interference and require consistent tag maintenance. Solutions like WMS, AR tools and most of the technologies may involve a learning curve, disrupting short-term productivity. CPS and cloud computing depend on robust infrastructure which can create latency of synchronization issues. Robotics, digital twins and drones require significant upfront costs, including initial investment all the way to ongoing maintenance. Blockchain, though secure, can be complex to install into existing supply chain systems. These limitations highlight the need for balanced implementation strategies that consider both the technical and organizational implications.

5.2 *Implications for Practice and Research*

One of the most relevant practical implications derived from this study is the imperative need to integrate advanced digital simulation and modeling methodologies prior to the implementation of technological solutions in real industrial environments. These cyber-physical simulations enable the anticipation of complex operational behaviors, the proactive identification of systemic bottlenecks, the quantitative assessment of the profitability and return on investment of technological implementations, and the empirical validation of the projected impact of digital solutions on highly complex logistical processes. From an academic research perspective, the analysis highlights the strategic importance of using well-designed frameworks and emerging technologies to validate decisions with evidence and support effective industrial digital transformation. This methodological approach generates evidence-based best practices that can be systematically replicated, adapted, and scaled across diverse industrial, geographical, and organizational contexts. The research also emphasizes the critical importance of developing specialized performance metrics and key performance indicators (KPIs) specifically tailored to assess the effectiveness of Industry 4.0 implementations in smart warehouses, thereby enabling objective comparisons between different technological approaches and implementation strategies.

5.3 *Future Research Directions*

The conceptual and methodological framework proposed in this article, together with the emerging technological trends identified and analyzed, provides a solid and structured foundation for future applied research in specialized logistics environments and next-generation storage systems. In particular, the systematic evaluation of the applicability and scalability of the proposed model across different vertical industrial sectors, geographic regions with varying levels of technological development, and diverse organizational contexts could significantly enhance both academic and practical understanding of its versatility, adaptability, and potential for technology transfer. Strategic opportunities exist for inter disciplinary collaborative research between academic institutions and advanced technology industries. Tech industries specially focused on developing functional prototypes, advanced computational simulations, and controlled experimental environments (testbeds). Such testbeds enable the empirical validation of the operational effectiveness of integrated Industry 4.0 solutions. Collaborative initiatives like these can catalyze joint innovation processes and also strengthen technology transfer mechanisms between universities and industry.

Ultimately, this can accelerate the widespread adoption of smart warehouses in emerging economies and strategic industrial sectors. Additionally, future research should address the development of interoperability standards, specialized cybersecurity protocols, and technological integration methodologies that facilitate the scalable and sustainable implementation of these solutions in diverse industrial contexts. Research on environmental sustainability and energy efficiency in smart warehouses also represents a significant opportunity to contribute to global sustainable development goals and corporate social responsibility.

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