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REVIEW ARTICLE

Reviewing and conceptualising the role of 4.0 technologies for sustainable warehousing

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ABSTRACT

In recent years, various 4.0 technologies have been implemented to support or automate manual warehouse activities to meet the ever-increasing demands for lead time, service quality, productivity, and efficiency. In terms of sustainability, however, the impact of these 4.0 technologies remains underexplored. This study aims to address this gap by developing a conceptual framework for sustainable warehousing in the context of Industry 4.0, thereby focusing on the Triple Bottom Line (economic, environmental, social) and the United Nations Sustainable Development Goals. The framework is facilitated through a systematic review and classification of the literature based on warehouse processes – receiving, storage, order picking, packing and shipping, production logistics, and cross-docking. It enables the systematic evaluation of existing research, while considering 4.0 technology applications and their sustainability impact. The study also aims to identify opportunities for advancing intelligent, sustainable warehousing and discusses implications for researchers and managers.

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Sustainable warehousing; triple bottom line; sustainable development goals; 4.0 technologies; systematic literature review

SUSTAINABLE DEVELOPMENT GOALS
SDG 8: Decent work and economic growth

Introduction

Warehouses are critical to supply chains, enabling the efficient and reliable flow of materials and products (Boysen, De Koster, and Weidinger 2019; Gu, Goetschalckx, and McGinnis 2007) and accounting for approximately 20% of the total logistics costs (Kersten et al. 2017). Over time, their operations have evolved from local storage facilities to multifunctional integrated logistics centres, driven by increasing demands for product variety, availability across multiple distribution channels, and the need for flexible, swift distribution within complex logistics systems (Boysen, De Koster, and Weidinger 2019; Kumar, Narkhede, and Jain 2021). To meet these increasing demands, warehouse managers are relying on a combination of digitally supported human labour and automated warehouse systems that balance flexibility and efficiency (Winkelhaus, Grosse, and Morana 2021). Consequently, employment in the warehouse sector is currently at its peak (United States Bureau of Labor Statistics 2022), while investments in warehouse automation are increasing (Barbee et al. 2021). This trend is also driven by the advent of 4.0 technologies, which enable interconnected, automated, and decentralised logistics and distribution systems (Frank, Dalenogare, and Ayala 2019; Pereira and Romero 2017), thereby offering considerable opportunities for innovative warehouse designs and operations (Kumar, Narkhede, and Jain 2021). Consequently, specific concepts such as 'Logistics 4.0' (Winkelhaus and Grosse 2020a), 'Logistics Operator 4.0' (Cimini et al. 2020), 'Smart Warehousing' (Winkelhaus and Grosse 2022; Zhen and Li 2022) or 'Order Picking 4.0' (Winkelhaus, Grosse, and Morana 2021) have emerged and highlight the economic benefits of different technologies within integrated and increasingly automated warehouse systems (Grosse 2024).

However, these developments come with considerable environmental and social implications, thereby causing pressure from stakeholders, particularly investors and the public, to consider the sustainability effect of logistics decision-making (McKinnon et al. 2015). This underscores the crucial role of warehouses in ensuring sustainability across the global chain, thereby necessitating further investigation. Not surprisingly, researchers and practitioners are increasingly concerned with the impact of 4.0 technologies on the sustainability of warehousing operations (Perotti, Prataviera, and Melacini 2022). The literature on warehousing spans various economic (Staudt et al. 2015), environmental (Bartolini, Bottani,

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and Grosse 2019) and social (Winkelhaus, Grosse, and Morana 2021) effects. Environmental impacts often relate to greenhouse gas (GHG) emissions (McKinnon et al. 2015), measured in carbon dioxide equivalents (CO2e) (Yang et al. 2019). Through their intermediate effect on spatial demands and stock movements, advanced warehouse systems based on 4.0 technologies are expected to impact energy consumption and emissions (Fichtinger et al. 2015), which are considerable components of the overall environmental performance (Doherty and Hoyle 2009). Social impacts associated with stakeholder orientation and human-centricity often centre around employee well-being, safety and working conditions (Gimenez, Sierra, and Rodon 2012). Consequently, human factors and ergonomics principles adapted from warehouse research (Loske et al. 2021) are crucial for social sustainability (Zink and Fischer 2013), notably in the context of assistive technologies that enhance human work by alleviating work demands and workloads for operators (Grosse 2024).

While 4.0 technologies are expected to yield economic benefits by enabling a self-regulated, decentralised, and flexible approach to value creation (Hofmann and Rüsch 2017; Pereira and Romero 2017), their environmental and social implications require a more detailed consideration (Awan et al. 2022; Beier et al. 2020). Despite the benefits such as resource conservation, waste reduction, and improvement in health and safety (Awan, Sroufe, and Shahbaz 2021), there is a dearth of research on warehouse sustainability (Beltrami et al. 2021; Ejsmont, Gladysz, and Kluczek 2020; Jamwal et al. 2021). Moreover, recent studies have shown that 4.0 technologies can negatively impact environmental and social sustainability (Beltrami et al. 2021). This ‘dark side’ of 4.0 technologies which has rarely been addressed in the literature (Bohnsack, Bidmon, and Pinkse 2022; Dieste et al. 2024; Grosse et al. 2023; Menti, Romero, and Jacobsen 2023; Perotti and Colicchia 2023; Singh and Bhanot 2020), has important implications for the sustainability balance of warehouses.

Given that 4.0 technologies impact warehouse design, processes, energy utilisation, emissions and working conditions (Grosse 2024), it is crucial to investigate the sustainability implications of these technologies more holistically. This study contributes to the literature by evaluating the existing body of research on the sustainability effects of 4.0 technologies in warehousing and identifying areas for future investigation. The following research questions (RQs) were addressed:

> RQ1: How do 4.0 technologies affect the sustainability of warehouse processes at their current level of implementation?

Research on sustainable warehousing and the impact of 4.0 technologies has experienced a notable surge in recent years. This study aims to systematically evaluate how 4.0 applications influence the sustainability of warehousing by assessing their intermediate effects on warehouse processes.

> RQ2: What opportunities for improving the sustainability of warehouse processes arise from the evolution of 4.0 technologies?

Numerous companies fail to fully leverage technologies to enhance the sustainability of warehouse processes (Oleśków-Szłapka and Stachowiak 2019). This study aims to identify opportunities for 4.0 technologies to enhance the sustainability of warehouse processes and to develop strategies for environmentally conscious, human-centric warehousing.

These research questions are investigated through a systematic literature review (SLR), thereby facilitating the development of a conceptual framework for sustainable warehousing in a 4.0 setting. The framework is built on a deductive-inductive approach, ensuring a robust theoretical foundation and enabling the identification of new research directions. The role of 4.0 technologies for sustainable warehousing is defined and refined based on the results of the SLR, while opportunities for improving the sustainability of warehouse processes by implementing 4.0 technologies are reported based on four different perspectives: processual, technological, measurement, and sustainability. Key findings highlight the potential of 4.0 technologies to enhance the sustainability of warehouse processes, thereby offering implications for both research and practice. The remainder of this paper is structured as follows: Section 2 discusses related literature reviews and proposes a conceptual framework; Section 3 outlines the review methodology and presents descriptive results of the literature analysis; Section 4 discusses the key findings; and Section 5 concludes the paper.

Background and conceptual framework

Related literature reviews

While several reviews of literature on warehouse research exist, only few focus on the environmental and social sustainability of warehousing or the implications of an increased adoption of 4.0 technologies in warehouse operations. To highlight the contribution made by this study, we briefly discuss the differences between this work and published reviews. Table 1 presents an overview of related literature reviews on sustainable warehousing and warehouse digitalisation, thereby highlighting how this study contributes to the literature by assessing the current

Table 1. Literature reviews related to sustainability or 4.0 technologies in warehouse operations.

				Sustainability dimension(s) examined							
Author (Year)	Examined timeframe	Sample overlap	Sample size	Economic	Environmental	Social	SDG-based perspective	Human centricity perspective	4.0 technology(ies)	Specific warehouse process(es) examined	Main content
Ries, Grosse, and Fichtinger (2017)	2006–2015	-	19	☐	✓	☐	☐	☐	4.0 technologies (general)	None	Environmental impact of warehouse infrastructure and processes
Bechtsis et al. (2017)	2009–2016	-	39	✓	✓	✓	☐	☐	Autonomous vehicles	1 (Order picking)	Contribution of AGVs towards sustainable warehousing
Bartolini, Bottani, and Grosse (2019)	2006–2018	-	38	☐	✓	☐	☐	☐	4.0 technologies (general)	None	Environmental sustainability in green warehouse management
Azadeh, De Koster, and Roy (2019)	2002–2019	-	55	☐	✓	✓	☐	✓	Autonomous vehicles, Collaborative Robots, 4.0 technologies (general)	2 (Order picking, Storage)	Design and control of robotised and automated picking systems
Glock et al. (2021)	1994–2020	-	67	✓	☐	✓	☐	✓	Augmented and virtual reality (cognitive assistance), Collaborative robots, Exoskeletons (physical assistance), RFID/beacon tags and identification, Sensors	3 (Order picking, Receiving, Storage)	Economic and human factors impact of assistive material handling devices
Winkelhaus, Grosse, and Morana (2021)	2008–2020	-	75	✓	☐	✓	☐	✓	Augmented and virtual reality (cognitive assistance), Collaborative robots, Exoskeletons (physical assistance), Cyber-Physical System (Internet of Things and Digital Twin), RFID/beacon tags and identification, Sensors	1 (Order picking)	Substitutive and supportive technologies in Order Picking 4.0
Sun et al. (2022)	2012–2020	2,5%	115	✓	✓	✓	☐	✓	Artificial Intelligence, Augmented and Virtual Reality (Cognitive Assistance), Autonomous Vehicles, Big Data Analytics, Blockchain, Cloud Computing, Collaborative Robots, Exoskeletons (Physical Assistance), 4.0 technologies (general), Cyber-Physical System (Internet of Things, and Digital Twin), RFID/beacon tags and Identification, Sensors	None	Implications of Industry 4.0 technology for sustainable logistics
Zhen and Li (2022)	2010–2020	-	657	☐	✓	☐	☐	☐	Autonomous Vehicles, Collaborative robot, 4.0 technologies (general), Cyber-Physical System (Internet of Things and Digital Twin)	3 (Order picking, Receiving, Storage)	Interconnection, automation, and integration in smart warehouses
Ali and Phan (2022)	2010–2021	2,5%	46	✓	✓	✓	☐	☐	Artificial Intelligence, Augmented and Virtual Reality (Cognitive Assistance), Big Data analytics, Blockchain, Cloud Computing, Collaborative robot, 4.0 technologies (general), Cyber-Physical System (Internet of Things and Digital Twin), RFID/beacon tags and Identification	4 (Order picking, Packing and shipping, Receiving, Storage)	Implications of Industry 4.0 for sustainable warehousing

(continued).

Author (Year)	Examined timeframe	Sample overlap	Sample size	Sustainability dimension(s) examined			SDG-based perspective	Human centricity perspective	4.0 technology(ies)	Specific warehouse process(es) examined	Main content
				Economic	*Environmental*	*Social*					
Aravindaraj and Chinna (2022)	2008–2021	7,4%	63	✓	✓	✓	✓	☐	Artificial Intelligence, Augmented and Virtual Reality (Cognitive Assistance), Autonomous Vehicles, Blockchain, Cyber-Physical System (Internet of Things and Digital Twin), RFID/beacon tags and Identification	None	Benefits and challenges of Industry 4.0 for warehousing under SDGs
Oloruntobi et al. (2023)	2015–2022	2,5%	75	✓	✓	☐	✓	☐	4.0 technologies (general)	None	Warehouse environmental impact reduction methods to promote green practices in the warehouse sector
Cannava, Perotti, and Petrillo (2023)	1997–2023	1,2%	38	☐	✓	☐	☐	☐	5G, Artificial Intelligence, Augmented and Virtual Reality (Cognitive Assistance), Big Data Analytics, Cloud Computing, Cyber-Physical System (Internet of Things and Digital Twin), Sensors	4 (Order picking, Packing and shipping, Receiving, Storage)	Improving energy efficiency at logistics facilities through digital technologies application
This study	2017–2023	-	79	✓	✓	✓	✓	✓	5G, Artificial Intelligence, Augmented and Virtual Reality (Cognitive Assistance), Autonomous Vehicles, Big Data Analytics, Blockchain, Cloud Computing, Collaborative Robots, Exoskeletons (Physical Assistance), Cyber-Physical System (Internet of Things and Digital Twin), RFID/beacon tags and Identification, Sensors	6 (Cross-docking, Order picking, Packing and shipping, Production logistics, Receiving, Storage)	Sustainability of warehouse processes according to the TBL view and SDGs

impact and future opportunities for sustainable warehouse operations in the context of an increasing application of 4.0 technologies. It examines the time frames, sample sizes and scope of these studies, while considering the sustainability dimensions, 4.0 technologies and warehouse activities. As can be seen, the sample overlap is marginal, highlighting the novel scope and contribution of this work.

Contrary to existing reviews, this study adopts a micro-level perspective to assess the implications of 4.0 technologies for sustainable warehousing by examining their impact on intermediate warehouse processes, which is an aspect often overlooked in previous analyses. Existing literature reviews either consider the effect of 4.0 technologies on warehouse sustainability at an aggregated level, wherein relationships and causalities are less clear (Aravindaraj and Chinna 2022; Oloruntobi et al. 2023; Sun et al. 2022), or focus on a subset of warehouse processes or sustainability effects, thereby hampering a comprehensive assessment (Ali and Phan 2022; Azadeh, De Koster, and Roy 2019; Glock et al. 2021; Winkelhaus, Grosse, and Morana 2021; Zhen and Li 2022). On the other hand, information systems research generally acknowledges that digital technologies do not create value per se but enable value creation when combined with complementary organisational resources, including business processes (Bayer, Haug, and Hvam 2020). This implies that 4.0 technologies must be implemented effectively into warehouse processes to leverage their capabilities for improving economic, environmental, and social performance. Further, the performance effect of 4.0 technologies cannot be assessed without understanding their influence on warehouse processes and that of warehouse processes on performance metrics at the micro level.

This study aims to address this gap and contribute to the literature by providing a comprehensive understanding of the impact of 4.0 technologies on all relevant warehouse processes by considering various sustainability dimensions, and a perspective of SDGs and human centricity.

Applications of 4.0 technologies to sustainable warehouse processes

Essential warehouse processes

Warehousing, defined as the intermediate storage of materials and goods to address discrepancies in time, quantity, and assortment, including associated value-added processing (Gu, Goetschalckx, and McGinnis 2007), has traditionally been regarded as a local, operational, and low-technology activity (Kumar, Narkhede, and Jain 2021). However, it has become indispensable in any supply chain, thereby undergoing a considerable evolution of facilities over time, coupled with an increasing complexity in their operations. Warehouses are generally characterised by their design, which is based on technical and economic considerations, and operation within the given technical environment (De Koster, Le-Duc, and Roodbergen 2007; Gu, Goetschalckx, and McGinnis 2007; Rouwenhorst et al. 2000). Their design comprises selecting a specific storage system, which is characterised by the dimensions, layout, technical infrastructure, and key operating principles (Gu, Goetschalckx, and McGinnis 2010; Rouwenhorst et al. 2000). Warehouse operations refer to the specific processes that occur as items move through a warehouse (De Koster, Le-Duc, and Roodbergen 2007).

Regarding warehouse processes, the conventional flow of goods commences with receiving, which involves unloading goods from the means of transport of the carriers, inspecting the deliveries for discrepancies in quantity and/or quality and updating the inventory records (De Koster, Le-Duc, and Roodbergen 2007; Rouwenhorst et al. 2000). Although the receiving process has garnered less research interest (Gu, Goetschalckx, and McGinnis 2007), it remains a crucial component of warehouse processes, thereby ensuring the accurate receipt of products in terms of timing, quantity and quality (Richards 2018). Following receipt, items are transferred to their storage locations, which involves the physical movement and potentially repackaging of products into storage units (De Koster, Le-Duc, and Roodbergen 2007), wherein they remain until requested (Gunasekaran, Marri, and Menci 1999). The storage process aims to optimise space utilisation and facilitate efficient material tracking and handling (Gu, Goetschalckx, and McGinnis 2007). Stored items are generally categorised into various compartments (reserve areas with pallet racks for replenishing forward areas with easily accessible shelves), with zones selected to accommodate subsets of items (Gu, Goetschalckx, and McGinnis 2007; Rouwenhorst et al. 2000). The required items are retrieved from their storage locations to fulfil customer orders through order picking (De Koster, Le-Duc, and Roodbergen 2007). This process encompasses scheduling and clustering orders, stock assignment, routing, including item handling, sorting, and disposal (De Koster, Le-Duc, and Roodbergen 2007). Order picking is a critical task in numerous warehouses (De Koster, Le-Duc, and Roodbergen 2007) and is a considerable cost factor (Richards 2018) owing to its high labour or capital cost, which directly impacts the cycle flow time and service levels (Grosse et al. 2015). Once the items are retrieved from their picking locations, they proceed to packing and shipping, thereby marking the final phase of the order fulfilment in warehouse processes (De Koster, Le-Duc, and Roodbergen 2007). Packing involves controlling, verifying, and handling items for shipping to ensure their protection, containment, preservation, and/or provision of information during distribution (Hellström and Saghir 2007). Shipping entails the movement of consolidated orders, their transfer, and loading onto selected carrier means of transport, coupled with updating shipping information for all involved parties (Rouwenhorst et al. 2000). The process of transferring items from the receiving area to the shipping area of the warehouse for sorting and loading without intermediate storage is referred to as cross-docking (Baker and Canessa 2009; De Koster, Le-Duc, and Roodbergen 2007). This process can be performed in dedicated logistics facilities or warehouses with storage facilities. Cross-docking reduces inventory costs, enhances the flow of goods, and shortens shipping cycles (Ladier and Alpan 2016). Handling and storing (intermediate) items on the shop floor – such as between the receiving or (intermediate) storage location and production area in larger production sites – are considered part of the shop floor or production logistics (Klumpp et al. 2019). Production logistics ensures the requisite delivery capability and reliability at the lowest feasible cost (Nyhuis and Wiendahl 2009). It comprises transporting (intermediate) items within a factory and supporting processes related to storage, inventory control, material handling equipment and production feeding (Zhang, Winkelhaus, and Grosse 2021).

Applications of 4.0 technologies

Warehousing has evolved considerably in recent years owing to the increase in the demand for product variety and availability and need for flexible and rapid distribution of small orders, thereby resulting in the adoption of 4.0 technologies (Boysen, De Koster, and Weidinger 2019; Grosse 2024; Kumar, Narkhede, and Jain 2021). Coined in 2011, 'Industry 4.0,' which is also known as the Fourth Industrial Revolution, refers to a new phase of industrial development wherein physical manufacturing and digital technology converge to establish interconnected, automated, and decentralised manufacturing systems (Frank, Dalenogare, and Ayala 2019; Hofmann and Rüsch 2017; Pereira and Romero 2017). This concept encompasses various technological advancements, including cyber-physical systems (CPS) and the Internet of Things (IoT), that enable information exchange among products, machines, systems and individuals, and facilitating a self-regulated, decentralised and flexible approach to value creation (Hofmann and Rüsch 2017; Pereira and Romero 2017).

While these technologies support information integration and decision-making, they also impact the coordinating factors and control mechanisms employed in supply chains, thereby highlighting the importance of warehouses as central components in complex supply chains (Barbieri et al. 2021). 4.0 technologies encompass front-end technologies that facilitate the delivery of products and services as well as base technologies that provide connectivity and intelligence solutions (Frank, Dalenogare, and Ayala 2019). The concept of Industry 4.0 has been extended to the logistics domain (Winkelhaus and Grosse 2020a), with focus on warehousing (Menti, Romero, and Jacobsen 2023; Winkelhaus, Grosse, and Morana 2021). In this context, emerging 4.0 warehouses are envisaged as highly automated, autonomous, and flexible entities, which use real-time information to ensure optimal utilisation and quality, and the seamless flow of goods through efficient processes (Van Geest, Tekinerdogan, and Catal 2021). An overview of relevant technologies is provided in the Appendix.

Dimensions of sustainability

In accordance with the principle of sustainable development outlined in the 1987 Brundtland report, sustainable supply chain management has garnered considerable attention in both academic (Koberg and Longoni 2019) and practitioner-oriented literature (Bové and Schwartz 2016). It focuses on aligning and achieving economic, environmental, and social objectives by configuring and coordinating business processes across organisations and supply chains to realise sustainable outcomes (Carter and Rogers 2008; Seuring and Müller 2008), as presented in the dimensions of the triple bottom line (TBL) framework (Elkington 2013). The economic dimension underscores the significance of long-term economic value to meet the financial needs of stakeholders and foster economic growth (Andersson et al. 2022; Carter and Rogers 2008). The environmental dimension concerns the responsibility of an organisation to minimise its environmental footprint through resource conservation, waste reduction and environmental pollution mitigation (Dekker, Bloemhof, and Mallidis 2012; Koberg and Longoni 2019). The social dimension encompasses the ethical obligations of the organisations concerning the responsible business conduct towards employees, suppliers, customers and communities they engage with (Koberg and Longoni 2019; Yawar and Seuring 2017). In addition to the aforementioned core dimensions, supply chain sustainability may encompass other dimensions such as risk management, transparency, strategy or culture (Carter and Rogers 2008). The 17 Sustainable Development Goals (SDGs) established by the United

Nations in 2015 as part of the 2030 Agenda for Sustainable Development offer a comprehensive framework for categorising sustainability impacts across diverse dimensions (United Nations 2022).

In line with sustainable supply chain management, sustainable warehousing can be defined as the alignment and attainment of economic, environmental, and social objectives in the design and operation of warehouses to facilitate efficient, resilient, and human-centric processes (Oloruntobi et al. 2023). It integrates the principles of green warehousing (Bartolini, Bottani, and Grosse 2019) and human-centric warehousing (Grosse 2024). Sustainable warehousing constitutes a crucial component of the sustainable supply chain management with a considerable impact on profitability (Kumar, Narkhede, and Jain 2021), resource utilisation, carbon footprints (Ries, Grosse, and Fichtinger 2017), as well as employee well-being, ergonomics, safety, technology acceptance and working conditions (Glock et al. 2021). The SDGs relevant in the context of sustainable warehousing encompass SDG 3 (good health and well-being), 7 (affordable and clean energy), 8 (decent work and economic growth), 9 (industry, innovation, and infrastructure), 11 (sustainable cities and communities), 12 (responsible consumption and production) and 13 (climate action) (Aravindaraj and Chinna 2022). These SDGs are directly affected by technology adoption. The use of 4.0 technologies in warehouses, for example, raises concerns in terms of increased energy and resource requirements. To greatly impact sustainability, it is crucial for these applications to consider power consumption, resource utilisation and waste generation (Perotti, Prataviera, and Melacini 2022). Both industry and academia are presently addressing these aspects to find a balance between warehousing process requirements and sustainability implications. Recent research has focused on optimising the picking routes of autonomous vehicles (Bock et al. 2024; Khoei, Süral, and Tural 2023), designing and using automated warehouses with refrigeration (Hahn-Woernle and Günthner 2018; Meneghetti and Monti 2015) and evaluating connectivity using 4.0 technologies to reduce waste

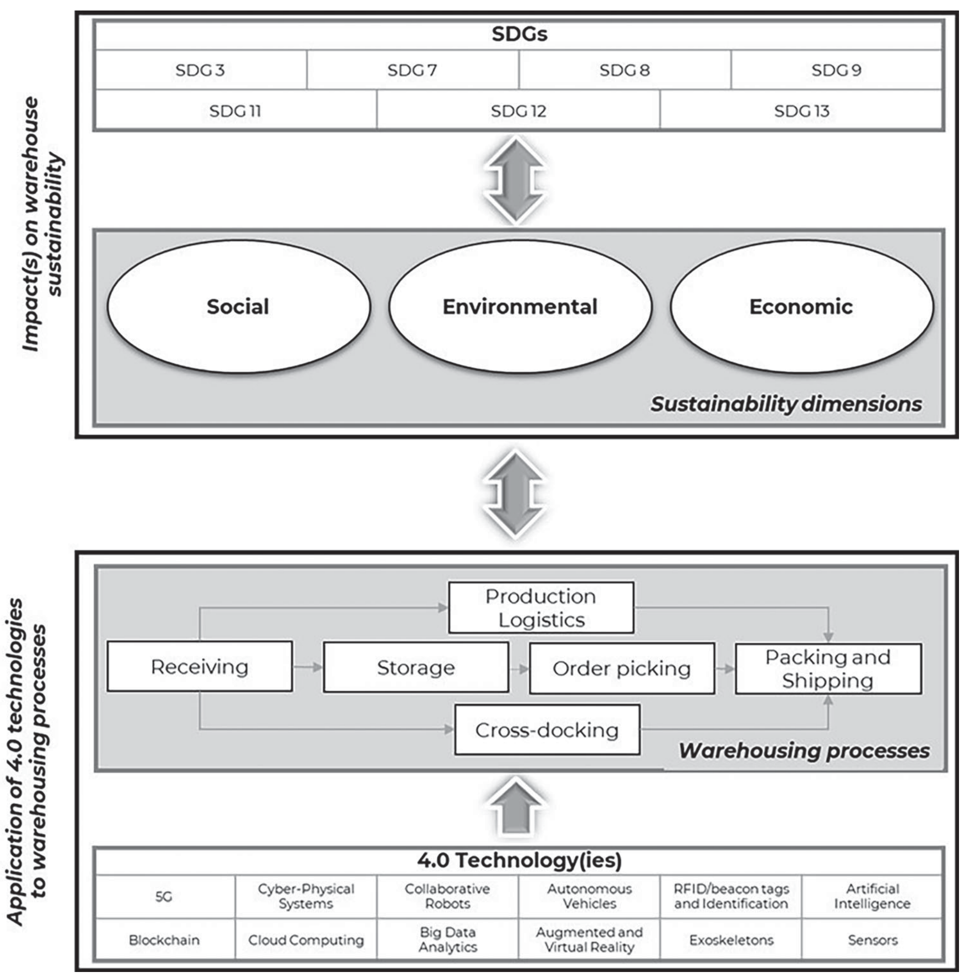

Figure 1. Conceptual framework for sustainable warehousing applying 4.0 technologies.

and resource consumption (Nantee and Sureeyatanapas 2021). These practises not only minimise energy, resources and waste but also promote the development of 4.0 technologies. At the same time, 4.0 technologies offer numerous benefits to the social sustainability of warehouse processes, such as increased efficiency and productivity, reduced human errors and enhanced safety, and improved working conditions with less repetitive and strenuous activities. To support human workers in 4.0 warehouses, various augmentation technologies are employed, such as data glasses or exoskeletons (Grosse 2024).

Conceptual framework

Figure 1 summarises the discussion and proposes a framework outlining the impact of the 4.0 technologies on sustainable warehouse processes. This study adopted a deductive-inductive approach as proposed by Orzes et al. (2018). Initially, it defined numerous categories (warehouse processes, technologies, and sustainability dimensions) based on insights presented in Section 2 (deductive approach, as shown in Figure 1). These categories were refined and expanded during the coding process, thereby incorporating the insights gained using an inductive approach.

Methodology and descriptive results

Literature search and selection strategy

SLRs have gained prominence in academic research, as discussed in the seminal work of Tranfield, Denyer, and Smart (2003). SLRs follow 'a systematic, explicit and reproducible method for identifying, evaluating, and synthesising the existing body of completed and recorded work produced by researchers, scholars, and practitioners' (Fink 2019). This approach mitigates bias and ensures replicability by conducting impartial assessments of existing literature outcomes, quality, and design (Do et al. 2021). In the relatively new area of sustainable warehousing with 4.0 technologies, SLRs are crucial for categorising available studies and promoting replicable knowledge to facilitate further investigation. As highlighted by Lagorio, Pinto, and Golini (2016), SLRs have been widely employed in other emergent sustainability areas within logistics and supply chain management. Our study applied the five-step methodology proposed by Denyer and Tranfield (2009) to ensure replicability and mitigate potential bias, as shown in Figure 2.

In Phase 1 (formulation of the research question), this review aimed to explore, based on available literature, how the increasing adoption of 4.0 technologies in warehouses can contribute to current and future improvements in sustainability. We aimed at defining the concept of sustainable warehousing through comprehensive research, developing a framework for consolidating existing knowledge, and identifying future research areas for integrating 4.0 technologies into warehouse operations.

In Phase 2 (identifying articles), keywords were selected based on the deductive development of the sustainable warehousing concept (Section 2.2) and insights from published literature reviews (Section 2.1) and related concepts. The authors discussed all the keywords

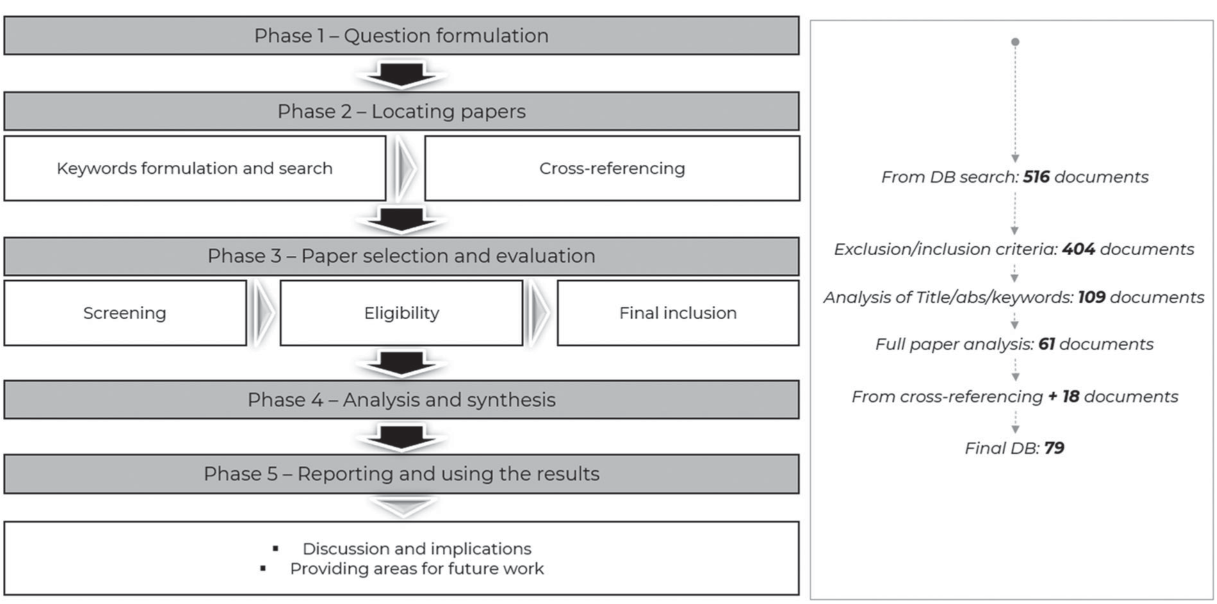

Figure 2. Systematic literature review methodology.

and agreed upon those that corresponded with the objectives of this study. The search strategy excluded keywords tied to specific 4.0 technologies to maintain a holistic view. The keywords were categorised into three groups based on the conceptual framework as follows:

- *Category 1*: Keywords relating to the topic of digitalisation and 4.0 technologies ('digital transformation' OR 'digitalisation' OR 'digitalization' OR '4.0' OR '5.0').
- *Category 2*: Keywords on the topic of sustainability according to the (extended) TBL perspective and SDG framework ('green' OR 'carbon footprint' OR 'GHG' OR 'CO2' OR 'emission' OR 'eco-efficien∗' OR 'energy-efficien∗' OR 'circular economy' OR 'sustainab∗' OR 'SDG' OR 'human' OR 'social' OR 'ergonomics').
- *Category 3*: Keywords related to warehousing ('ware house∗' OR 'distribution cent∗' OR 'cross-dock∗' OR 'material∗ handling' OR 'logistics building' OR 'logistics facility' OR 'internal logistics' OR 'intralogistics' OR 'picking').

The keyword categories were later combined (using operator 'AND') to define the search string. Scopus was selected for document searching owing to its comprehensive database of peer-reviewed journals and conference articles. It stores a wide range of high-quality scientific publications from different fields (Crossan and Apaydin 2010) and is widely used in SLRs for logistics, production, and operations management (Jaghbeer, Hanson, and Johansson 2020). The Scopus searches yielded 516 articles.

In Phase 3 (paper selection and evaluation), non-English articles were excluded, and only those published in peer-reviewed international journals or conference proceedings were retained to ensure high quality, thereby corresponding with established review practices (Aravindaraj and Chinna 2022; Oloruntobi et al. 2023). Consequently, grey literature, such as technical reports and secondary sources, was omitted. This process yielded a sample of 404 articles. The titles, abstracts, and keywords of these documents were carefully analysed, and articles that did not relate to 4.0 technologies and sustainable warehousing were excluded. The working sample comprised 109 papers. Four authors independently reviewed each paper to ensure the rigour of the SLR, thereby reducing subjective bias and improving validity. This thorough examination resulted in the exclusion of 48 documents. Based on the recommendation of Marchet, Melacini, and Perotti (2014) and Hohenstein et al. (2015), we conducted a backward analysis of all the references in our sample to include relevant studies not initially identified in Scopus (cross-referencing approach). This process identified 18 additional papers, thereby resulting in a final database comprising 79 articles.

In Phase 4 (analysis and synthesis), each paper was comprehensively analysed and classified as follows:

- *Bibliometric information* (year of publication, source type and title).
- *Methodology applied*: According to Glock et al. (2017), papers were categorised into eight research methodologies: conceptual work, surveys, case studies, illustrative cases, data analyses, decision support models, analytical models and simulations. To avoid potential overlap, our review did not include existing literature review papers on the topic under study. These are discussed separately in Section 2.1.
- *Warehouse processes supported*, as described in Section 2.2.1, 'Essential warehouse processes.'
- *Technologies investigated*, as described in Section 2.2.2, 'Applications of 4.0 technologies.'
- *Sustainability impact considered*, as described in Section 2.2.3, 'Dimensions of sustainability.'

Descriptive results of literature sample

The analysed papers spanned from 2017 to 2023 (Figure 3), with the majority published in 2021, thereby indicating a growing interest in the topic. This suggests that the impact of 4.0 technologies on sustainable warehouse processes is an emerging theme that has yet to be extensively investigated in academic research, unlike broader areas such as sustainable logistics or logistics 4.0, which have garnered considerable attention. Despite including possible 5.0-related contributions in the keyword search, only two relevant papers were identified, thereby highlighting a considerable research gap and an opportunity for future investigation. The studies examined in this study were published in 25 conference proceedings and 54 international journals. Conference proceedings were the primary source of articles; however, journal articles have steadily increased, particularly in 2021. These journals covered three principal areas: sustainability and related topics ('Sustainability' (6) and 'Journal of Cleaner Production' (1)), general logistics and supply chain management ('International Journal of Logistics Research and Applications' (2), 'Transportation Research Part E: Logistics and Transportation Review' (1), 'International Journal of Supply Chain Management' (1), and 'International Journal of Logistics Management' (1)) and production and manufacturing ('International Journal of Advanced Manufacturing Technology' (2) and 'Computers in Industry' (1)).

Based on the methods employed in the reviewed papers (Figure 4), a notable portion is conceptual (33

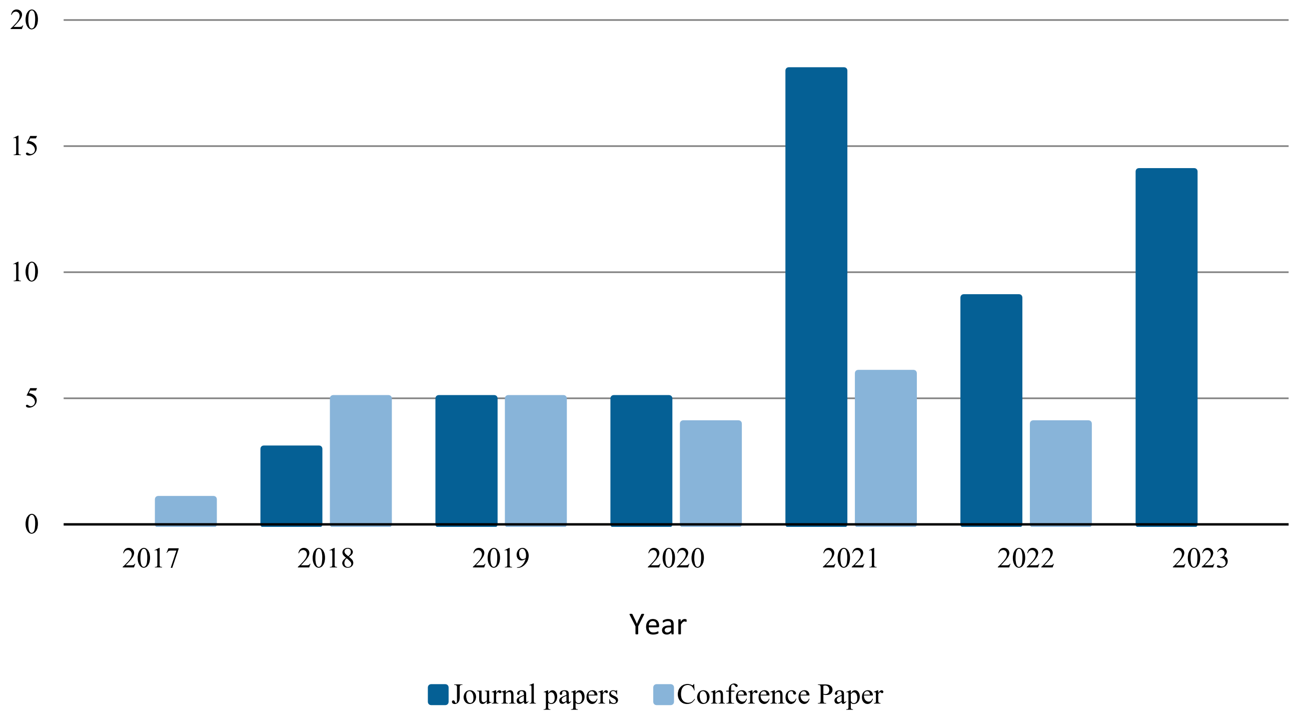

Figure 3. Distribution of the publications over time.

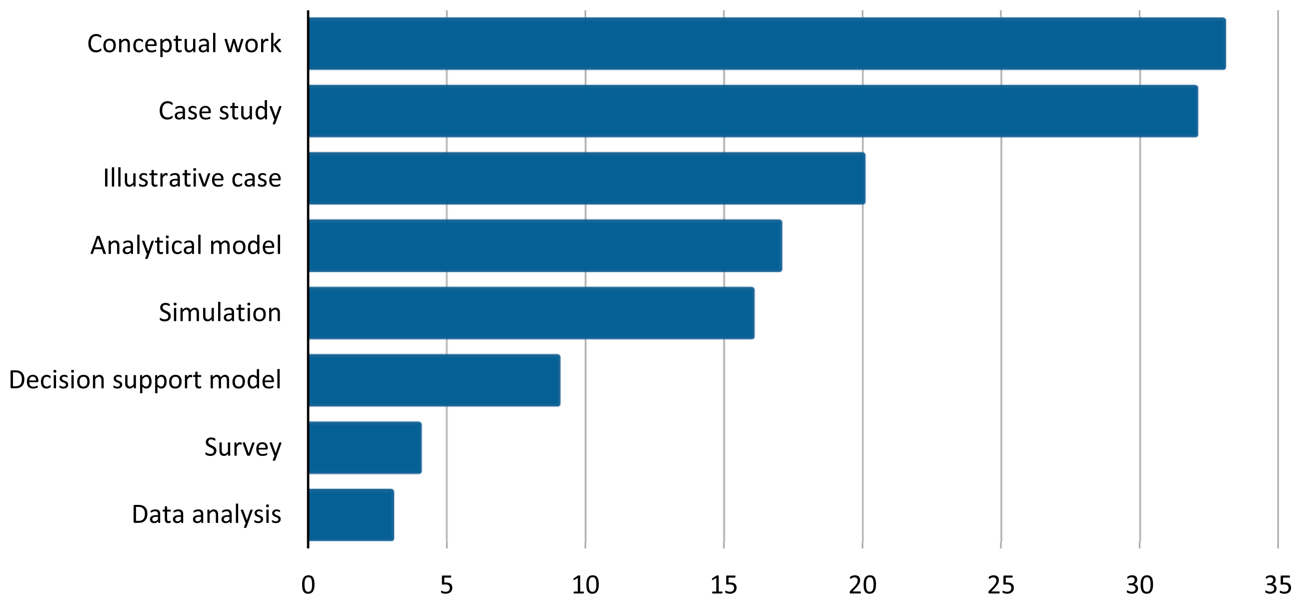

Figure 4. Distribution of publications by methodology.

works). Contrary to earlier reviews, there exist numerous empirical studies including encompassing case studies (32 works), illustrative cases (20 works), and surveys (4 works), thereby indicating a shift in interest from pure conceptualisation to practical applications. This shift reflects the growing need to comprehend the sustainability implications that arise when companies implement 4.0 technologies to support warehouse processes. Conversely, decision-support models (9 works), analytical models (17 works), and simulations (16 works) were less common.

In examining the warehousing processes (Figure 5), a considerable number of the reviewed papers investigated warehousing without specifying warehouse processes (36 works). Others focus on specific aspects such as order picking (37 works), storage (23 works), packing and shipping (14 works), production logistics (14 works) and receiving (13 works). Cross-docking (3 works) was less common.

Some studies discuss the 4.0 technologies broadly without providing detailed analyses of specific technologies (20 works), while others discuss specific technologies and

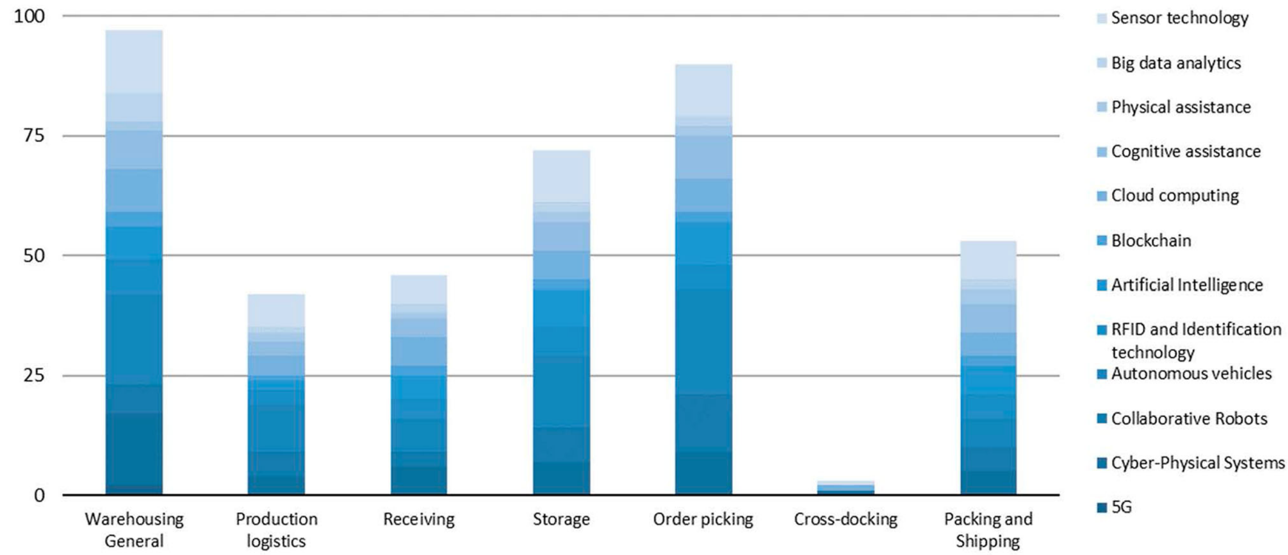

Figure 5. Relationship between the 4.0 technologies and warehouse processes.

their impact on warehousing sustainability. The technologies frequently discussed in the analysed papers include autonomous vehicles (AGVs and drones; 41 works), CPS (Internet of Things and Digital Twin; 23 works), sensor technology (e.g. real-time location systems; 23 works), and collaborative robots (18 works). Base technologies such as sensors are widely utilised in different warehouse processes, including receiving, storage, order picking, packing, and shipping (13 works), and production logistics (7 works) and cross-docking (1 work). Other technologies, such as collaborative robots and autonomous vehicles, are primarily utilised in order picking (12 and 22 applications, respectively) and storage (7 and 15, respectively). From a sustainability perspective, the economic viewpoint is dominant (40 works), which often corresponds with either the environmental or social perspective in numerous studies (30 and 21, respectively). The human-centric perspective has garnered academic interest (40 works), notably in recent studies, while a broader social sustainability perspective is found in fewer contributions (21 works). Thirty papers examined the environmental impact of 4.0 technologies in warehousing.

Regarding the SDGs, the majority of impacts relate to SDG 3 (good health and well-being, 28 works), which corresponds with the human-centric viewpoint, and SDG 7 (affordable and clean energy, 29 works), which highlights the economic/efficiency impacts. This is followed by SDG 8 (decent work and economic growth, 28 works). Fewer studies addressed SDG 9 (resilient infrastructure, inclusive and sustainable industrialisation, innovation, 11 works), SDG 11 (sustainable cities and communities, 5 works), SDG 12 (responsible consumption and production, 9 works) and SDG 13 (climate action, 2 works). For a comprehensive summary and classification of the sampled papers, refer to Table 2.

Findings and discussion

Findings related to RQ1: How do 4.0 technologies affect the sustainability of warehouse processes at their current level of implementation?

Thirty-seven studies examined the impact of 4.0 technologies on the sustainability of warehouse processes from a cross-sectional perspective, without focusing on specific warehouse processes. Numerous studies referred to specific 4.0 technologies, such as autonomous vehicles (19), CPS (Internet of Things Digital Twin) (15), sensor technology (13) and radio frequency identification (RFID) (7). The sustainability implications and environmental and social perspectives (30 and 21 papers, respectively) were frequently linked with economic considerations (42). The majority of contributions examined the implications of 4.0 technologies through the ‘human centricity’ lens (41), thereby emphasising human needs and interests. Some studies proposed frameworks and KPIs that encompassed all the sustainability dimensions. For example, Nantee and Sureeyatanapas (2021) investigated the influence of 4.0 technologies on corporate sustainability, wherein they outlined a set of sustainability indicators which corresponds with the TBL perspective, thereby categorising them into environmental, social, and economic dimensions.

The remaining studies focused on examining warehousing processes and their associated sustainability implications owing to the application of 4.0 technologies. These studies will be discussed in detail in subsequent

Table 2. Classification of the sampled papers.

				Focus of each paper according to the framework			
No.	Author(s)	Year	Methodology	Warehouse process(es)	4.0 technology(ies)	Sustainability perspective(s)	SDG(s)
1	Jost et al.	2017	Illustrative case	Receiving, Packing and Shipping	4.0 technologies (general), CPS, Artificial Intelligence, Big Data Analytics, Sensors	Economic, Social (human centricity)	N.A.
2	Kattepur et al.	2018	Conceptual work, Illustrative case, Simulation	Receiving, Storage, Order Picking	4.0 technologies (general), Collaborative Robots, Autonomous Vehicles	Economic, Social (human centricity)	SDG 3
3	Yazdi et al.	2018	Analytical model	Production logistics	Sensors	Environmental	N.A.
4	Gružauskas et al.	2018	Survey, Simulation	Warehousing (general)	CPS, Autonomous Vehicles, Big Data Analytics	Economic, Environmental	SDG 7, SDG 11
5	Dregger et al.	2018	Conceptual work	Order Picking	4.0 technologies (general)	Social (human centricity)	SDG 3, SDG 8
6	De Felice et al.	2018	Illustrative case, Simulation	Warehousing (general)	4.0 technologies (general), CPS	Economic	SDG 7
7	Ojo et al.	2018	Case study	Warehousing (general)	4.0 technologies (general), CPS, RFID/beacon tags and Identification, Cloud Computing, Big Data Analytics	Economic, Environmental, Social (human centricity)	SDG 3, SDG 7, SDG 12
8	Kayikci	2018	Case study	Warehousing (general)	CPS, Collaborative Robots, Autonomous Vehicles, Cloud Computing, Augmented and Virtual Reality (Cognitive Assistance), Big Data Analytics, Sensors, Additive Manufacturing	Economic, Environmental, Social (human centricity)	SDG 3, SDG 7, SDG 11, SDG 12
9	Klumpp et al.	2019	Conceptual work, Simulation	Production logistics, Packing and Shipping	4.0 technologies (general), Collaborative Robots, Artificial Intelligence	Economic, Social (human centricity)	N.A.
10	Merdin and Ersoz	2019	Survey	Warehousing (general)	4.0 technologies (general), CPS, Autonomous Vehicles, RFID/beacon tags and Identification, Artificial Intelligence, Blockchain, Augmented and Virtual Reality (Cognitive Assistance), Additive Manufacturing	Economic, Environmental, Social (human centricity)	SDG 7, SDG 12
11	Land et al.	2019	Survey	Production logistics	Collaborative Robots	Social (human centricity)	N.A.
12	Perussi et al.	2019	Conceptual work	Warehousing (general)	4.0 technologies (general), Autonomous Vehicles	Economic, Social (human centricity)	SDG 3
13	Bányai et al.	2019	Analytical model	Warehousing (general)	CPS, Autonomous Vehicles	Environmental	N.A.
14	Yazdi et al.	2019	Simulation	Storage, Order Picking	Collaborative Robots, Sensors	Economic, Environmental	SDG 7
15	Guerin et al.	2019	Conceptual work	Order Picking	4.0 technologies (general)	Social (human centricity)	N.A.
16	Yao et al.	2020	Illustrative case, Analytical model	Production logistics, Receiving, Storage, Order Picking	CPS, Autonomous Vehicles	Economic, Environmental	SDG 7, SDG 9
17	Cantini et al.	2020	Decision Support Model	Warehousing (general)	Sensors	Social (human centricity)	SDG 3
18	D'Souza et al.	2020	Case study	Storage, Order Picking	4.0 technologies (general), Collaborative Robots, Autonomous Vehicles	Social (human centricity)	N.A.
19	Minashkina and Happonen	2020	Illustrative case	Receiving, Storage, Cross-docking	4.0 technologies (general)	Economic, Environmental, Social (human Centricity)	SDG 7
20	Winkelhaus and Grosse	2020b	Case study	Order Picking	4.0 technologies (general)	Social (human centricity)	N.A.

21	Plakas et al.	2020	Conceptual work	Order Picking	Augmented and Virtual Reality (Cognitive Assistance)	Economic, Social (human centricity)	SDG 3
22	Sutawijaya and Nawangsari	2020	Case study	Warehousing (general)	4.0 technologies (general), CPS	Economic, Environmental	SDG 7, SDG 12
23	Yavaş and Ozkan-Ozen	2020	Decision Support Model	Production logistics, Receiving, Storage, Order Picking, Packing and Shipping	Autonomous Vehicles, RFID/beacon tags and Identification, Sensors	Economic, Environmental	SDG 11, SDG 12, SDG 13
24	Cimini et al.	2020	Conceptual work	Production logistics, Storage, Order Picking, Packing and Shipping	Collaborative Robots, Autonomous Vehicles, Augmented and Virtual Reality (Cognitive Assistance), Exoskeletons (Physical Assistance), Sensors	Economic, Social (human centricity)	SDG 3, SDG 8
25	Rubio et al.	2021	Illustrative case, Analytical model	Production logistics	4.0 technologies (general), Autonomous Vehicles	Economic, Environmental	SDG 7
26	Bavrin et al.	2021	Conceptual work	Warehousing (general)	CPS, RFID/beacon tags and Identification, Blockchain, Big Data Analytics	Economic, Social (human centricity)	SDG 3
27	Klumpp and Loske	2021	Illustrative case, Decision Support Model	Order Picking, Packing and Shipping	4.0 technologies (general)	Economic	N.A.
28	Periša et al.	2021	Illustrative case	Receiving, Storage, Order Picking, Cross-docking, Packing and Shipping	CPS, Cloud Computing, Sensors	Economic, Social (human centricity)	SDG 3, SDG 7
29	Javed et al.	2021	Conceptual work, Illustrative case	Receiving, Storage, Order Picking	4.0 technologies (general), Autonomous Vehicles, Cloud Computing	Social (human centricity)	SDG 3, SDG 9
30	Keivanpour	2022	Conceptual work, Simulation	Warehousing (general)	CPS	Environmental, Social (human centricity)	N.A.
31	Aliev et al.	2021	Illustrative case	Warehousing (general)	4.0 technologies (general), Collaborative Robots, Autonomous Vehicles	Economic, Environmental	SDG 7
32	Kumar et al.	2022	Decision Support Model	Warehousing (general)	4.0 technologies (general)	Economic, Environmental	SDG 7, SDG 9
33	Nantee and Sureeyatanapas	2021	Conceptual work, Case study, Decision Support Model	Receiving, Storage, Order Picking, Cross-docking, Packing and Shipping	4.0 technologies (general)	Economic, Environmental, Social (human centricity)	SDG 3, SDG 7, SDG 8, SDG 12
34	Shee et al.	2021	Survey	Warehousing (general)	4.0 technologies (general)	Environmental	SDG 11
35	Niu et al.	2021	Analytical model	Order Picking	Collaborative Robots, Artificial Intelligence	Social (human centricity)	SDG 3
36	Khan et al.	2021	Illustrative case, Decision Support Model	Warehousing (general)	4.0 technologies (general)	Economic	SDG 9
37	Gruchmann et al.	2021	Case study, Decision Support Model	Warehousing (general)	Autonomous Vehicles, Augmented and Virtual Reality (Cognitive Assistance)	Social (human centricity)	SDG 3

(*continued*).

Table 2. Continued.

				Focus of each paper according to the framework			
No.	Author(s)	Year	Methodology	Warehouse process(es)	4.0 technology(ies)	Sustainability perspective(s)	SDG(s)
38	Van Geest et al.	2021	Conceptual work, Illustrative case	Receiving, Storage, Order Picking, Packing and Shipping	CPS, Collaborative Robots, Autonomous Vehicles, RFID/beacon tags and Identification, Artificial Intelligence, Augmented and Virtual Reality (Cognitive Assistance), Sensors	Economic, Social (human centricity)	N.A.
39	Zhang, Pee, and Cui	2021	Case study	Storage, Order Picking	Autonomous Vehicles, Artificial Intelligence, Big Data Analytics	Economic, Environmental, Social (human centricity)	SDG 3, SDG 7
40	Cimini et al.	2021	Conceptual work, Case study	Warehousing (general), Receiving, Storage, Order Picking, Packing and Shipping	4.0 technologies (general), Autonomous Vehicles, RFID/beacon tags and Identification, Artificial Intelligence, Cloud Computing, Sensors	Economic, Social (human centricity)	SDG 3
41	Lagorio et al.	2021	Conceptual work	Production logistics, Storage, Order Picking, Packing and Shipping	Collaborative Robots, Autonomous Vehicles, RFID/beacon tags and Identification, Augmented and Virtual Reality (Cognitive Assistance), Exoskeletons (Physical Assistance), Sensors	Social (human centricity)	SDG 3, SDG 8
42	Dobos et al.	2021	Analytical model	Warehousing (general)	4.0 technologies (general), Big Data Analytics	Economic, Environmental	SDG 7, SDG 11
43	Muslikhin et al.	2021	Analytical model	Order Picking	CPS, Artificial Intelligence	Economic, Environmental	SDG 7, SDG 12
44	Dolgui and Ivanov	2022	Conceptual work	Warehousing (general)	5G	Economic, Environmental	SDG 7, SDG 12
45	Diefenbach et al.	2023	Case study	Receiving, Packing and Shipping	Augmented and Virtual Reality (Cognitive Assistance), Exoskeletons (Physical Assistance)	Economic, Social (human centricity)	SDG 3
46	Winkelhaus et al.	2022	Case study	Receiving, Storage, Order Picking, Packing and Shipping	4.0 technologies (general), Augmented and Virtual Reality (Cognitive Assistance)	Social (human centricity)	SDG 3, SDG 8
47	Vitolo et al.	2022	Simulation	Order Picking	4.0 technologies (general), Collaborative Robots, Autonomous Vehicles	Economic, Social (human centricity)	SDG 3, SDG 7
48	Niermann et al.	2023	Conceptual work, Illustrative case	Warehousing (general)	4.0 technologies (general), CPS, Autonomous Vehicles, Augmented and Virtual Reality (Cognitive Assistance)	Social (human centricity)	SDG 3, SDG 8, SDG 9
49	Menti et al.	2023	Case study, Decision Support Model	Warehousing (general), Production logistics	4.0 technologies (general), CPS, Collaborative Robots, Autonomous Vehicles, Cloud Computing, Augmented and Virtual Reality (Cognitive Assistance), Big Data Analytics, Sensors.	Social (human centricity)	SDG 3, SDG 8

50	Thylén et al.	2023	Conceptual work, Case study	Production logistics	4.0 technologies (general), Autonomous Vehicles	Social (human centricity)	SDG 3, SDG 8
51	Loske and Klumpp	2022	Case study, Analytical model, Simulation	Order Picking	4.0 technologies (general), Clou Computing	Social (human centricity)	SDG 8
52	Kihel	2022	Conceptual work, Case study	Receiving, Storage, Order Picking, Packing and Shipping	4.0 technologies (general), CPS, Collaborative Robots, Autonomous Vehicles, RFID/beacon tags and Identification, Artificial Intelligence, Blockchain, Cloud Computing, Augmented and Virtual Reality (Cognitive Assistance), Big Data Analytics, Sensors	Economic, Environmental, Social (human centricity)	SDG 7, SDG 9, SDG 12
53	Stefanini and Vignali	2022	Case study, Analytical model	Production logistics	4.0 technologies (general), Autonomous Vehicles, Sensors	Economic, Social (human centricity)	SDG 7, SDG 8, SDG 13
54	Chou et al.	2022	Case study, Data analysis	Storage, Order Picking	Autonomous Vehicles, Artificial Intelligence	Social (human centricity)	SDG 8
55	Proia et al.	2022	Case study, Analytical model	Order Picking	4.0 technologies (general), Autonomous Vehicles	Social (human centricity)	SDG 8, SDG 9
56	Facchini et al.	2022	Case study, Analytical model	Production logistics	4.0 technologies (general), Cloud Computing,	Economic, Environmental, Social (human centricity)	SDG 7, SDG 8
57	Vlachos et al.	2024	Conceptual work, Case study	Production logistics	4.0 technologies (general), CPS, Autonomous Vehicles, RFID/beacon tags and Identification, Cloud Computing, Sensors	Social (human centricity)	SDG 9
58	Konstantinidis et al.	2022	Conceptual work	Warehousing (general)	4.0 technologies (general), 5G, Autonomous Vehicles, Artificial Intelligence, Cloud Computing, Sensors	Social (human centricity)	SDG 8
59	Bright and Ponis	2021	Conceptual work, Illustrative case	Order Picking	4.0 technologies (general), Augmented and Virtual Reality (Cognitive Assistance)	Social (human centricity)	SDG 8
60	Fontaine et al.	2021	Case study, Simulation	Storage	4.0 technologies (general), Autonomous Vehicles, RFID/beacon tags and Identification, Artificial Intelligence, Sensors	Social (human centricity)	SDG 8
61	Schmidtke et al.	2018	Conceptual work, Illustrative case	Warehousing (general)	4.0 technologies (general)	Social (human centricity)	SDG 8
62	Cimini et al.	2019	Case study	Warehousing (general)	4.0 technologies (general), Autonomous Vehicles, RFID/beacon tags and Identification, Cloud Computing, Sensors	Social (human centricity)	SDG 3, SDG 8

(*continued*).

Table 2. Continued.

No.	Author(s)	Year	Methodology	Focus of each paper according to the framework: Warehouse process(es)	4.0 technology(ies)	Sustainability perspective(s)	SDG(s)
63	Mahroof	2019	Conceptual work, Case study	Warehousing (general)	4.0 technologies (general), Artificial Intelligence	Social (human centricity)	SDG 8
64	Zhang, Winkelhaus, and Grosse	2021	Simulation	Order Picking	Autonomous Vehicles	Economic, Social (human centricity)	SDG 3, SDG 8
65	Papcun et al.	2019	Conceptual work, Simulation	Storage, Order Picking	4.0 technologies (general), CPS, Autonomous Vehicles, Augmented and Virtual Reality (Cognitive Assistance), Sensors	Social (human centricity)	SDG 8
66	Pasparakis et al.	2023	Conceptual work, Case study	Order Picking	Collaborative Robots, Autonomous Vehicles	Social (human centricity)	SDG 3, SDG 8
67	Zhang, Groose, and Glock	2023	Conceptual work, Illustrative case, Simulation	Order Picking	Collaborative Robots, Autonomous Vehicles	Economic, Social (human centricity)	SDG 3, SDG 8
68	Füchtenhans et al.	2023	Case study, Simulation	Warehousing (general), Storage, Order Picking	CPS, Sensors	Economic, Environmental	SDG 7
69	Li et al.	2022	Illustrative case, Data analysis, Analytical model	Warehousing (general)	CPS, Artificial Intelligence, Sensors	Environmental	SDG 7
70	Mejri et al.	2022	Illustrative case, Analytical model, Simulation	Order Picking	Autonomous Vehicles, Artificial Intelligence	Environmental	SDG 7
71	Xie and Yao	2023	Conceptual work, Case study	Warehousing (general), Order Picking	4.0 technologies (general), CPS, Autonomous Vehicles, Augmented and Virtual Reality (Cognitive Assistance), Sensors	Social (human centricity)	SDG 7, SDG 8
72	Tang et al.	2023	Conceptual work, Case study, Simulation	Warehousing (general)	4.0 technologies (general), Artificial Intelligence, Cloud Computing, Sensors	Social (human centricity)	SDG 8
73	Sierra-García et al.	2023	Conceptual work, Case study	Warehousing (general)	Autonomous Vehicles	Social (human centricity)	SDG 8
74	Simic et al.	2023	Conceptual work, Case study Analytical model	Warehousing (general)	Collaborative Robots, Autonomous Vehicles	Economic, Environmental, Social	SDG 7, SDG 9
75	Scholz	2023	Conceptual work, Illustrative case, Analytical model, Simulation	Production logistics	Autonomous Vehicles, Artificial Intelligence	Environmental	SDG 7
76	Taş	2023	Case study	Warehousing (general), Storage, Order Picking	Autonomous Vehicles	Economic	SDG 7, SDG 8
77	Helm et al.	2024	Conceptual work, Case study	Warehousing (general), Receiving, Storage, Order Picking, Packing and Shipping	Artificial Intelligence, Cloud Computing	Social (human centricity)	SDG 9
78	Vijayakumar and Sobhani	2023	Illustrative case, Analytical model	Order Picking	Collaborative Robots, Autonomous Vehicles	Social (human centricity)	SDG 3, SDG 8
79	Berns et al.	2021	Data analysis, Decision Support Model, Analytical model	Storage	Artificial Intelligence	Environmental	SDG 9

Table 3. Effects of the implementation of 4.0 technologies on the sustainability of warehouse processes.

		TBL PERSPECTIVE(S)		
		Economic	Environmental	Social
WAREHOUSE PROCESSES	**Receiving**	↑ Efficiency (RFID) ↑ Productive teamwork (Cloud Computing; IoT) ↑ Self-management (Cognitive Assistance)	↓ Energy consumption (Autonomous vehicles and AI; IoT)	↑ Safety (IoT; Cognitive assistance) ↓ Workload (Physical assistance) ↓ Risks (Sensors)
	Storage	↑ Space utilisation (AI) ↑ Visibility (Big Data Analytics) ↑ Responsiveness rate (AI) ↑ Tracking	↑ Reusable material (RFID and Sensors) ↓ Waste material (AI) ↓ Space-related energy consumption (AI; Big Data Analytics; Blockchain)	↑ Safety (IoT) ↓ Workload (Physical assistance) ↓ Risks (Collaborative robots)
	Order picking	↑ Routing optimisation (AI) ↑ Efficiency (IoT) ↑ Flexibility (Collaborative robots) ↑ Communication (5G) ↓ Costs (Autonomous vehicles)	↓ Energy consumption (Autonomous vehicles and AI; IoT)	↑ Staff well-being (IoT) ↑ Safety (IoT) ↓ Workload (Collaborative robots; physical assistance)
	Packing and shipping	↑ Efficiency (Collaborative robots) ↓ Costs (Big Data Analytics, AI)	↓ Material usage (Big Data Analytics, AI) ↓ Waste material (AI)	↑ Safety (IoT; Cognitive assistance) ↓ Workload (Collaborative robots) ↓ Risks (Collaborative robots)
	Cross-docking	↑ Productivity (sensors) ↑ Space utilisation (Cloud computing)	N.A.	↑ Safety (IoT)
	Production logistics	↑ Efficiency (AI) ↑ Flexibility (IoT) ↑ Quality (Collaborative Robots) ↓ Costs (Autonomous vehicles)	↓ Energy consumption (Autonomous vehicles and AI)	↑ Safety (IoT) ↑ Ergonomics (Collaborative robots) ↓ Risks (Collaborative robots)

sections. Table 3 presents a comprehensive summary of the analysis, thereby categorising the effects of integrating 4.0 technologies into warehouses based on the affected warehouse process(es) and sustainability dimension(s). Where explicitly addressed in the studies, the specific type(s) of 4.0 technology are also noted in parentheses.

Receiving

The literature sample included 13 studies on the receiving process, with autonomous vehicles (7), IoT (6) and sensor technology (6) being among the top technologies investigated. Periša et al. (2021) exemplified the alignment of economic and social perspectives by proposing a conceptual work that demonstrated the opportunities associated with introducing innovative smart wearable devices to support warehouse-receiving tasks. Their proposed architecture combined IoT, cloud computing, RFID, and sensors to enhance business process efficiency, such as expediting data availability and increasing process speed. From a social perspective, these technologies provide human support and accommodate individuals with disabilities in the work environment. Cimini et al. (2020) investigated the social ramifications of 4.0 technologies in warehousing, focusing on the human-centric factors and associated advantages of employing 4.0 technologies. They examined the control of incoming goods during the receiving process and observed that digital technologies, including RFID systems, wearables, warehouse management systems (WMS), transportation management systems (TMS), and information technology (IT) mobile devices (such as tablets and smartphones), offered different levels of support. This support can be physical, such as substituting or assisting logistics operators in hazardous tasks, improving workplace ergonomics, aiding material-handling equipment and mitigating accident risks; cognitive, including assisting operators in stressful and repetitive tasks and aiding in decision-making processes; organisational, such as enhancing the contextual aspects of the work environment or organisational practices that influence task performance, such as communication, teamwork and self-management.

Storage

In the literature sample, there were 23 papers on storage, with autonomous vehicles (15), IoT (7) and collaborative robots (7) as prominent technologies under investigation. The storage process optimises warehouse space utilisation and efficiently manages material handling in storage and retrieval operations (Gu, Goetschalckx, and McGinnis 2007), with considerable implications for environmental (Ries, Grosse, and Fichtinger 2017) and social (Nantee and Sureeyatanapas 2021) sustainability in warehousing. However, the review identified only nine studies that address environmental issues and 17 that address social issues (particularly focusing on human centricity) in the context of 4.0 technologies related to storage.

Minashkina and Happonen (2020) highlighted the potential of integrating existing warehouse management systems with RFID tags, reusable containers, and energy-efficient material-handling technologies to reduce the environmental impact while enhancing warehousing efficiency. Furthermore, 4.0 technologies are expected to improve environmental sustainability by reducing movement- and space-related energy consumption and the amount of waste material used for packaging through increased visibility, planning accuracy, and speed. They suggested that advanced algorithms could enhance the efficacy of warehouse operations, while intelligent automated storage and retrieval systems (AS/RS) can optimise space utilisation and improve safety. Zhang, Pee, and Cui (2021) investigated the application of artificial intelligence (AI) in warehouse processes and arrived at analogous conclusions. They observed that the deployment of AI-driven 4.0 technologies in warehouse settings, coupled with existing information systems, improved storage space utilisation and material-handling efficiency. The incorporation of AI capabilities in forecasting, planning, and learning enables the maximal exploitation of available warehouse space and allocation of storage locations based on demand projections. Nantee and Sureeyatanapas (2021) highlighted other advantages of the smart AS/RSs and WMS, including the 30% enhancement in space utilisation, improved tracking of storage locations and inventory quantities, and mitigation of damage and loss risks. Despite the augmented electricity consumption attributed to the utilisation of electrical equipment and control systems, the overall outcome on warehouse performance indicates a net positive environmental impact.

Cimini et al. (2020, 2021) highlighted the advantages of supporting and enabling material-handling technologies (sensors, drones, exoskeletons, collaborative robots and AGVs, smart fast-rotation storage systems, smart AS/RS cranes and smart mini loaders) with improvements in locating, lifting, and moving heavy objects during inventory audits or storage processes. These technologies considerably enhance warehouse performance owing to their cost-effectiveness. Safety is increased by preventing workplace injuries during hazardous physical tasks and alleviating fatigue resulting from demanding and repetitive cognitive operations. Zhang, Pee, and Cui (2021) revealed that automating storage processes, devoid of human intervention, reduces errors and mitigates the risk of human injury. Nantee and Sureeyatanapas (2021) confirmed that 4.0 technologies not only enhanced worker health and safety by reducing occupational injuries and illnesses but also fostered the development of analytical and IT-related skills of individuals, thereby facilitating skill acquisition through job expansion and/or rotation.

Order picking

The sample included 37 studies on order picking, with a majority focusing on the utilisation of autonomous vehicles and collaborative robots (22 and 12, respectively). Li et al. (2020) examined order picking using a robotic mobile fulfilment system wherein AGVs transport shelf units to order pickers. Through simulation, they assessed the impact of varying numbers of AGVs on energy consumption and order-picking efficiency. They proposed a storage assignment approach aimed at creating a balance between the aforementioned aspects while ensuring environmentally sustainable warehouse operations. Füchtenhans et al. (2023) developed a simulation for an order-picking warehouse and determined that IoT-enabled smart lighting systems could reduce energy consumption by 87% more than conventional full-time warehouse lighting, thereby improving environmental sustainability. They noted that apart from environmental advantages, smart lighting systems also improved staff well-being (by influencing circadian rhythms of individuals) and hampered accidents in the workplace (Füchtenhans, Grosse, and Glock 2021, 2023), thereby contributing to social sustainability.

Utilising AGVs for order picking can help reduce the workload and error rate of human order pickers, and increase system efficiency, as shown in a study conducted at smart warehouse of Alibaba (Zhang, Pee, and Cui 2021). They can contribute to social sustainability in order picking, as indicated by the 16 contributions. The advent of collaborative robots has introduced the concept of hybrid order picking, wherein both humans and autonomous robots collaborate in performing tasks. Winkelhaus et al. (2022) simulated a hybrid order-picking system, thereby demonstrating its cost advantages compared to purely manual or automated order-picking methods. They showed that hybrid order picking can improve ergonomics, motivation, and job satisfaction, thereby fostering social sustainability. Simulation results presented by Zhang, Winkelhaus, and Grosse (2021, 2023) showed that hybrid order picking can reduce human energy expenditure. Sgarbossa, Romsdal, et al. (2020) proposed a model for allocating items to human workers or robot pickers to minimise human workload and category similarity, thereby improving human well-being when human pickers handled lighter weights. The aforementioned studies highlight the potential of collaborative robots in facilitating a more human-centric approach to order picking, thereby leveraging the advancements in robotics technology.

Packing and shipping

A subset of 14 studies focused on the correlation between 4.0 technologies and packing or shipping processes. Among the investigated technologies, sensors garnered the most attention, with eight studies investigating their applications, followed by autonomous vehicles and cognitive assistance technologies such as AR and VR, each discussed in six studies. According to Cimini et al. (2020), collaborative robots that assist packing operations considerably impact operators and process efficiency. On the one hand, they help relieve humans from repetitive physical work, movements and load lifting (less fatigue and reduced risk of injury to operators), which simultaneously increases performance and safety. On the other hand, they speed up operations, exchange information and reduce operating costs.

Jost, Kirks, and Mattig (2017) examined various technologies encompassing the IoT, AI, big data analytics, and sensors within a production and logistics system, as illustrated using a case study. In the packaging sector, human workers receive step-by-step guidance from an integrated system comprising wearable devices, AI algorithms, and a purpose-built IoT platform. Aside from economic implications, study emphasises human-centric aspects, notably cognitive assistance provided to workers during the packaging.

Cross-docking

To date, there exists limited research on the effects of 4.0 technologies on cross-docking processes. In the sample, only three works study the aforementioned, thereby focusing on technologies such as sensors and cloud computing. Minashkina and Happonen (2020) found that 4.0 technologies enable the cross-docking of incoming goods by directing them to pick-up points, thereby conserving limited warehouse resources. Nantee and Sureeyatanapas (2021) noted improvements in productivity, accuracy, and warehouse space utilisation in cross-docking and sorting operations. However, they highlighted concerns as regards job displacement owing to autonomous operations, thereby raising social sustainability implications such as job insecurity among workers.

Production logistics

The review identified 14 studies that investigated the influence of these technologies on the sustainable performance of warehouses. A majority of these studies have investigated the energy consumption patterns of robots and AGVs. Yazdi, Azizi, and Hashemipour (2018) employed an agent-based algorithm as the control architecture to assess a sustainable and intelligent material-handling system and the overall equipment effectiveness. Their results indicated that energy consumption is affected by production and idle times, which can be addressed by reducing the idle time and increasing equipment effectiveness. Rubio, Llopis-Albert, and Valero (2021) developed a multi-objective optimisation algorithm to improve the productivity of autonomous industrial processes by reducing costs and energy consumption. They considered an assembly line with robotic cells and a material-handling system with AGVs. The kinematics and dynamics of these autonomously executed tasks were shown to reduce movement and travel times, thereby reducing energy consumption while maximising global business profits. Yao et al. (2020) proposed a combination of discrete event simulations and nonlinear mixed-integer programming using genetic algorithms to determine production schedules that prioritise just-in-time material delivery and energy efficiency in material transport. They modified AGVs and machine schedules within flexible manufacturing systems during production interruptions to enhance energy efficiency and resilience.

An additional area of investigation focuses on safety and ergonomics in mixed environments wherein humans collaborate with automated systems. Klumpp et al. (2019) introduced a framework for evaluating human–computer interaction efficiency in production logistics, which is based on an interdisciplinary analysis. Their research on traffic-control algorithms, considering human actors, revealed that hybrid approaches resulted in high travel distances evenly distributed among operators, with a low incidence of accidents and similar numbers of traffic collisions than human-centric approaches. Land et al. (2019) investigated the human-robot collaboration in the automotive industry, thereby showing that collaborative robots were useful in material handling, assembly, and quality control, which offers advantages in terms of ergonomics, efficiency, and quality. Cimini et al. (2020) examined the roles of various 4.0 technologies and discussed their impact on human labour in internal and external logistics. They concluded that the increase in the connectivity between operators and technology in logistics requires further understanding of human–computer and human-machine interfaces in the process control, including considerations related to ergonomics. Lagorio et al. (2021) investigated assistive technologies and proposed a taxonomy of technologies used in internal logistics processes. Their findings indicated that technologies are prevalent in order picking and material handling, which are tasks often associated with repetitive actions that pose higher safety risks to operators. They observed no considerable disparities between automation and support technology implementations, which are possibly owing to their simultaneous emergence.

Findings related to RQ2: What opportunities for improving the sustainability of warehouse processes arise from the evolution of 4.0 technologies?

Opportunities from a processual perspective

The analysis of warehousing processes has identified order picking as the most frequently considered activity. Order picking, also known for its time-consuming and costly nature, relies heavily on manual labour. Despite the growing interest in fully automating order-picking tasks (Jaghbeer, Hanson, and Johansson 2020), the predominant practice in companies remains manual order picking, with minimal or some support from assistive technologies (Grosse 2024; Winkelhaus, Grosse, and Morana 2021). Consequently, investigating 4.0 technologies that support workers and enhance the sustainability of the order picking process (e.g. through the integration of wearables or co-bots) is required. Future applications could explore batch and zone-picking strategies, wherein smart sensors assist workers to maintain safe distances to mitigate the spread of serious infections. Conversely, storage processes have received comparatively less attention, thereby presenting untapped opportunities for the future implementation of 4.0 technologies. We found no specific discussions linking storage to 4.0 technologies and their impact on sustainability despite the rapid technological advancements in the industry. For example, autonomous drones can capture images of warehouse inventory, which could be leveraged to enhance traceability and inventory record accuracy. AI can be used to improve space and assignment planning, while robots can efficiently move items between storage areas. Although these technological developments offer economic benefits, their environmental and social implications must be considered in detail. Furthermore, minimal attention has been paid to receiving, packing, and shipping processes. The importance of information exchange in real-time with other facilities, suppliers, and customers via digital platforms (Frank, Dalenogare, and Ayala 2019) highlights the necessity for digitally supported receiving and shipping processes within warehouses. This facilitates the optimisation and automation of the loading and unloading processes while streamlining the verification and tracking of deliveries. Blockchain technology can provide immutable, synchronised records and ensure the accuracy and security of shipment data (Pournader et al. 2020) to improve the efficiency and reliability of receiving and shipping processes. Future opportunities could also arise from smart packaging, often referred to as Packaging 4.0, and its impact on sustainability. Renewable packaging materials equipped with smart capabilities can protect items using less reusable or recyclable materials, monitor the condition of packaged items during transportation and storage, and improve traceability throughout the supply chain (Regattieri, Santarelli, and Piana 2019).

Opportunities from a technological perspective

The findings reveal a lack of clarity in the definition of 4.0 technologies for warehousing, with numerous studies focusing on broad concepts rather than specific applications. However, some studies have investigated specific technology applications such as automation (autonomous guided vehicles), traceability (identification and sensor technology), virtualisation (AI), assistance (AR/VR and exoskeletons) and collaboration technologies (collaborative robots). Technologies with potential for future research include blockchain, fifth-generation (5G) mobile networks, physical assistance systems, and cybersecurity. Blockchain technology offers considerable economic, environmental, and social advantages in warehousing, thereby ensuring reliable information flows across the supply chain, reducing the cost of errors and fraud, enhancing warehouse operational efficiency by streamlining paperwork and automating processes, increasing traceability, minimising waste, improving labour conditions, fostering trust (Pournader et al. 2020).

5G technology enhances data latency and capacity, thereby facilitating improved connectivity and increased automation. These advancements, coupled with impro ved information accessibility, lay the groundwork for smart warehouses, which improve operational efficiency and promote environmental sustainability. Further, innovative physical assistance systems can bolster the well-being and productivity of warehouse staff, thereby leveraging their skills and experience in a more sustainable manner (Sgarbossa, Groose, et al. 2020).

In addition to specific technologies, there is limited application and adoption of 4.0 technology frameworks (Frank, Dalenogare, and Ayala 2019; Pereira and Romero 2017) within warehouse operations. This is partly owing to ambiguity surrounding the definition of a 'warehouse 4.0' or 'smart warehouse' in terms of technology (Winkelhaus and Grosse 2022). While warehouse management systems (WMS) and AS/RS are often considered as 4.0 technologies, they may not necessarily meet the criteria that define Industry 4.0 base and front-end technologies. According to Winkelhaus and Grosse (2022), a smart warehouse is defined as 'a highly integrated facility that leverages advanced digital technologies and automation to efficiently conduct operations, thereby adapting to the dynamic business environment of the current economy.' One method for evaluating the 'smartness' of warehouse processes involves employing a well-established intralogistics 4.0 maturity model (Winkelhaus, Grosse, and Glock 2022), which offers a systematic approach for conducting comprehensive analyses. A holistic consideration of the capabilities provided by base- and front-end technologies through the lens of an integrative framework, also enables a more systematic approach to leveraging economic, environmental and social benefits in the transition to smart warehousing.

Opportunities from a measurement perspective

A common problem for effectively addressing sustainability concerns is the absence of global standards or a commonly accepted set of indicators or KPIs (Mura et al. 2018) thereby also posing a challenge for objectively measuring the sustainability impact of integrating 4.0 technologies into warehouse processes. For example, when examining the environmental sustainability of warehousing, the impact of buildings and floor space on the overall emissions remains vague due to the absence of specific data on infrastructure, resource consumption and emissions (Dobers et al. 2019; Shaw, Grant, and Mangan 2021). Thus, despite the considerable energy consumption in warehouses (Ries, Grosse, and Fichtinger 2017), the impact of technology remains unclear. While energy consumption for material handling could rise, other types like heating or lighting could decrease instead (Fichtinger et al. 2015). Similarly, social sustainability assessments in supply chains examining labour practices and working conditions, compliance with human rights or wider implications for consumers and society still lack information as well as appropriate quantitative social sustainability indicators (Popovic et al. 2018). In terms of warehousing activities, indicators tend to be rather generic (e.g. employee turnover) or focussed on a specific subset of social sustainability (e.g. safety and training) and less frequently adopted by industry as compared to environmental indicators (Bajec, Tuljak-Suban, and Bajor 2020).

Scholars and managers grapple with uncertain regarding which indicators must be utilised to evaluate sustainability across various dimensions, coupled with how to implement and monitor them. Numerous companies struggle with data collection, management, and control procedures, thereby hampering the development of suitable sustainability metrics and making benchmarking between different sites and competitors challenging (Perotti, Prataviera, and Melacini 2022). However, achieving sustainability goals requires establishing consistent measurement and reporting frameworks, backed by support from senior management and clear organisational structures to ensure accountability. These measures are crucial for overcoming potential resistance to new technology and fostering acceptance (Mukhuty, Upadhyay, and Rothwell 2022). Hence, quantifying the sustainability of warehouses is crucial for understanding implications in terms of resource utilisation and operational efficiency, as well as for mitigating negative environmental and social impacts. Such information can aid decision-makers in formulating strategies for carbon neutrality and promoting socially sustainable warehousing practices through 4.0 technologies. This increase in the demand for performance measurement using standardised indicators supported by reliable measurements and reporting frameworks corresponds with current international regulatory trends, as stated by recent guidelines for logistics and warehouses (ISO 14083 2023) or the EU corporate sustainability due diligence directive.

Opportunities from a sustainability perspective

Social sustainability is increasingly recognised as integral to the successful integration of 4.0 technologies in logistics, emphasising the pivotal role of operators in designing and implementing these advancements (Cimini et al. 2019). Here, technology is not considered as a substitute for human work, but rather a tool that assists operators in complex and repetitive tasks (Grosse 2024). This shift presents an opportunity for operators to actively participate in the transition to Logistics 4.0, with their roles evolving from a purely operational to more supervisory roles (Cimini et al. 2019; Neumann et al. 2021; Zhang, Grosse, and Glock 2023). Empowering operators with new skills and equipment is essential for practitioners to maximise the benefits of 4.0 technologies, moving beyond technical capabilities alone (Lagorio et al. 2021). At the same time, the integration of 4.0 technologies can provide tremendous opportunities for environmentally sustainable warehousing. Through its connectivity and intelligence solutions as well as its effect on the way smart warehouse processes are performed with the help of 4.0 technologies (Frank, Dalenogare, and Ayala 2019; Winkelhaus and Grosse 2022), can not only pave the way for increasing automation and energy-efficient warehouse operations, but also provides large amounts of real-time data to measuring and managing environmental sustainability.

However, in addition to the positive effects of 4.0 technologies on sustainability, there are also unintended negative effects (Grosse et al. 2023) which should not be disregarded. A significant concern is the replacement of human labour, which leaves the remaining employees to perform repetitive and unpleasant tasks (Neumann et al. 2021). Furthermore, 4.0 technologies could result in a loss of privacy and personal autonomy of employees (cloud computing, CPS, sensors) owing to monitoring capabilities (Niermann et al. 2023), unhealthy work–life balance owing to higher connectivity (Menti, Romero, and Jacobsen 2023), or even health problems derived utilising AR/VR in the workplace (Gruchmann et al. 2021; Lagorio et al. 2021). Hence, the implementation of 4.0 technologies must be designed and structured based on a human-centric perspective, thereby enabling gradual adaptation to the transition (Grosse et al. 2023). Similarly, the diffusion of 4.0 technologies in warehousing may also hamper environmental sustainability through its increasing demand for natural resources (e.g. rare earths) and energy and the consequent greenhouse gas emissions. For example, an increase in connectivity and data processing (implementation of AI, Cloud Computing, Blockchain and Big Data Analytics) may result in a high energy consumption, as cooling systems of data centres consume a large amount of energy (Menti, Romero, and Jacobsen 2023). This phenomenon is even more pronounced when unused, duplicate and/or low-value data are stored (digital waste). While 4.0 technologies provide significant opportunities for sustainable warehousing, their net effect requires a more detailed consideration.

Implications for management and research

Managerial implications

The perceptions of 4.0 technologies and their impact on warehouse sustainability among practitioners remain unclear (Hofmann and Rüsch 2017). Many companies still regard technologies designed to enhance warehouse performance and sustainability as a 'black box' (Winkelhaus, Grosse, and Glock 2022). Hence, holistic frameworks that identify key technologies in warehouse processes and elucidate their impact on different sustainability dimensions can offer invaluable guidance for the sustainable adoption of 4.0 technologies. As shown by the findings, comprehensive implementation advice considering synergistic effects across warehouse processes is still lacking and could provide valuable benchmarks for assessing the non-financial impact of investments in 4.0 technologies in warehouses. Practitioners must recognise that the benefits of 4.0 technologies are only realised through efficient integration into warehouse processes, with the effectiveness closely tied to the processes involved. Hence, adopting a process-oriented approach, as outlined in our framework, is crucial for implementing 4.0 technologies, thereby promoting an integrative perspective that maximises potential benefits. Moreover, to ensure the sustainable implementation of these technologies, warehouse managers must establish an appropriate organisational structure and implement effective change management strategies, such as digital transformation coaching (Bauer and Grosse 2024).

While environmental sustainability criteria generally seem to be of relevance to warehouse managers (Bajec, Tuljak-Suban, and Bajor 2020), the absence of global standards or commonly accepted KPIs (Mura et al. 2018) still poses a challenge for objectively measuring the sustainability impact of integrating 4.0 technologies into warehouse processes. Practitioners should seek to quantify the environmental impact of their logistics facilities in terms of CO2e emissions and SDGs to comply with current standards and regulations for logistics and warehouses (e.g. ISO 14083 2023). This could be done by establishing a comprehensive set of measurable indicators, thereby facilitating a systematic pursuit of longer-term sustainability objectives. Moreover, human centricity is crucial to achieving the desired benefits (Pasparakis, De Vries, and De Koster 2023). The implementation strategies must be designed to support the role of the operator, while considering possible negative impacts of 4.0 technologies on operators, and proactively developing countermeasures (Lagorio et al. 2021; Menti, Romero, and Jacobsen 2023). It is imperative that warehouse managers consider human factors and the diverse impacts of technology on their workforce to mitigate the risks of innovation pitfalls, technological resistance, and phantom profits (Grosse et al. 2023; Neumann et al. 2021).

Policymakers must assume a central role in promoting the development and dissemination of training programmes to equip workers with the skills for adopting 4.0 technologies, thereby addressing key cultural and educational barriers as outlined in the literature (Lagorio et al. 2021; Nantee and Sureeyatanapas 2021). Additionally, new regulations may be required to address safety issues related to human-robot interaction, privacy protection, and unhealthy work–life balance, which are considerable negative impacts of 4.0 technologies on social sustainability (Cantini, De Carlo, and Tucci 2020; Javed et al. 2021; Zhang, Pee, and Cui 2021). The risk of job displacement owing to autonomous operations is widely acknowledged in this literature (Nantee and Sureeyatanapas 2021). Hence, policymakers must consider implementing job market policies to support workers who could be replaced by 4.0 technologies. However, the increase in the demand for performance measurement through a reliable framework which corresponds with current international regulations necessitates policymakers to continue supporting practitioners with tools and documentation that assist companies to measure and effectively communicate their impact on sustainability.

Other relevant stakeholders, such as investors and company top management, must carefully consider the costs and potential return on investment before adopting 4.0 technologies, including their impact on sustainability in terms of SDGs (Aravindaraj and Chinna 2022). These goals demonstrate a commitment to sustainable practices, thereby improving the reputation, brand image, transparency, and accountability of the company in the long term. Consequently, stakeholders must increasingly favour investments in SDG-compliant companies as they are better positioned to adapt to future regulations and consumer preferences, thereby improving their long-term resilience.

Research implications

Our results highlight interesting insights and promising directions for future investigation. We see a noticeable gap in research addressing the theoretical aspects within this domain. Few studies refer to specific theories or theoretical frameworks, such as systems theory, contingency theory, social cognitive theory, and the technology organisational environment framework. While the literature does offer conceptual frameworks that aim to advance theories within the context of Logistics 4.0 and sustainability (Beltrami et al. 2021), there remains limited research on sustainable warehousing. Future research could explore environmentally sustainable warehouse operations using the theory of swift, even flow, thereby assessing the productive capability of 4.0 technologies (see Schmenner and Swink 1998). Scholars are encouraged to research on social sustainability in warehousing, thereby basing their approach on existing concepts and theories, such as socio-technical systems (Neumann et al. 2021) and the unified theory of acceptance and use of technology (UTAUT) (Jacob et al. 2023). These studies can expand knowledge in this area and mitigate side effects when implementing and using advanced technology, such as technology rejection, workarounds, workplace deviance and phantom profits (Neumann et al. 2021).

Our results demonstrated a diverse array of research methods employed, with conceptual and case studies being the most prevalent. While an increasing number of studies use empirical data, often through illustrative cases, there remains limited empirical evidence on the specific measurable impact of individual 4.0 technologies on the sustainability of distinct warehouse processes. This highlights the considerable potential for future research using intervention-based studies, data-driven multimethod approaches and empirical methods (single/multiple case study investigations, Delphi studies, data-driven simulation approaches). Such approaches are particularly relevant as practitioners continue to invest in new technologies. In this line of thought, future research could focus on workers and operators while assessing the impact of 4.0 technologies on sustainability, thereby prioritising empirically grounded studies. This will provide solid evidence in terms of the social consequences of using 4.0 technologies in assisting operators in their manual work. It will identify the principal human factors affected and enable a comparison with literature-based results. Such research methodologies could offer considerable advantages beyond merely validating existing theoretical frameworks. They would provide empirically tested data to practitioners and policymakers and relevant insights to support their decision-making processes as regards selecting and evaluating the 4.0 technologies. This would minimise implementation risks, foster innovations, and facilitate informed decision-making.

Finally, there is still need for a more comprehensive exploration of the negative effects of the 4.0 technologies on environmental and social sustainability, thereby providing empirical evidence from the industry, as highlighted by previous research (Bohnsack, Bidmon, and Pinkse 2022; Dieste et al. 2024; Ghobakhloo 2020; Singh and Bhanot 2020; Winkelhaus, Grosse, and Glock 2022). As indicated in the literature, 4.0 technologies generally impact the design (building infrastructure) and operations (storage and retrieval) of warehouses. However, defining and assessing the environmental impact of 4.0 technologies presents challenges due to its interlinked intermediate effects at the process level. Consequently, we advocate for researchers to adopt a process-oriented approach, as outlined in our framework, to foster a more integrative perspective, which is often touted as a benefit of the 4.0 technologies (Frank, Dalenogare, and Ayala 2019). This approach may further enable a more accurate evaluation of the sustainability implications (Fichtinger et al. 2015). Based on our finding of only 2 papers addressing Industry 5.0 and warehousing, future research on human centricity and environmental sustainability must consider the transition from Warehousing 4.0 to Warehousing 5.0 (Glock and Grosse 2024; Grosse et al. 2023).

Conclusions

This study presents a conceptual framework for sustainable warehousing using 4.0 technologies based on an SLR. Given the current challenges faced by companies such as customer demands, the availability of skilled labour, and the rise in energy costs, the concept of sustainable warehousing has garnered considerable attention. Unlike previous literature reviews on sustainable warehousing, this study adopts a comprehensive, process-based approach and proposes a conceptual framework that encompasses multiple performance dimensions grounded in the TBL approach and SDGs to assess the impact of 4.0 technologies on warehousing processes. Its findings highlight how 4.0 technologies can contribute to sustainable warehouse processes.

Regarding RQ1, the effect of 4.0 technologies on warehouse sustainability is often considered from a cross-sectional perspective without addressing the specific warehouse processes. When it comes to specific warehouse processes, order picking is the most frequently considered process was order picking, followed by storage, packing and shipping, receiving, production logistics and cross-docking. Base technologies such as sensors are widely used across processes, while autonomous vehicles and collaborative robots are primarily utilised in order picking and storage. In terms of sustainability, the environmental implications of 4.0 technologies gained more attention than social implications. Studies focusing on social sustainability often highlight safety, ergonomics, or human-machine collaboration. Conversely, the environmental perspective was more pronounced in cross-sectional studies on warehousing.

As regards RQ2, our study identified opportunities for improving the sustainability of warehouse processes by implementing 4.0 technologies based on four different perspectives: processual, technological, measurement and sustainability. From a processual perspective, although order picking received considerable attention, it may still provide further opportunities due to its time-consuming and costly nature. Conversely, storage as well as receiving, packing and shipping processes may benefit considerably from 4.0 technologies. From a technological perspective, blockchain, 5G and CPS hold considerable potential for future opportunities by laying the foundation for smart warehouses. From a measurement perspective, 4.0 technologies not only pave the way for human-machine collaboration and increasing warehouse efficiency but also provide large amounts of real-time data for measuring and managing sustainability. From a sustainability perspective, 4.0 technologies provide significant opportunities, but also potential pitfalls related to resource and energy consumption or health and privacy issues. Hence, a systematic consideration of the net sustainability effect is necessary to pave the way to Warehousig 5.0.

While this work contributes considerably to the field of sustainable warehousing, it is subject to several limitations. First, the definition of a 4.0 technology remains unclear, as it encompasses different front-end and base technologies. Consequently, some technologies facilitating sustainable warehousing may not have been considered. However, we mitigated this risk by adopting a deductive-inductive and technology-agnostic approach to identifying relevant studies. Technologies that are not encompassed within our sample, such as quantum computing, could emerge as pertinent to sustainable warehousing in the future. Moreover, despite using three categories of keywords, we may have omitted some keywords that would have identified other relevant studies. Lastly, our reliance on a single database (Scopus) posed a constraint. While Scopus is among the most comprehensive and widely utilised databases, it is likely that some important studies may have been omitted. Our cross-referencing strategy was designed to mitigate this risk to some extent.

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Data availability statement

Data is available on request from the authors.

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Appendix – 4.0 technologies considered for warehousing applications

Technology	Description	Main references
5G	The fifth generation of wireless networks promises to be a key enabler for smart factories. Key features are higher speed, excellent ability to work with a high number of IoT sensors, and high reliability of remote connection.	Koivisto et al. (2017); Rao and Prasad (2018); Choi et al. (2022)
Cyber-Physical System (e.g. Internet of Things, Digital Twin)	Complex, interdisciplinary systems that integrate computation, communication, and control of physical processes. These systems integrate computational processes with physical ones, which are monitored and controlled by embedded computers and networks and have the capacity to auto-organise, share information, data and resources, reacting and acting in face of situations and changes in the environment.	Madakam et al. (2015); Holweg et al. (2018)
Collaborative Robots	Robots that help operators perform manual activities and allow a safe interaction between humans with the aim to improve production systems performance and human work conditions.	Gualtieri, Rauch, and Vidoni (2021)
Autonomous Vehicles (e.g. AGV, drones)	Provide automated loading, transport, and unloading capabilities.	Bechtsis et al. (2017)
RFID/beacon tags and Identification	Automatic identification of objects, by storing data on tags and remotely retrieving these data via radio waves using RFID transponders within companies, supply chains or international supply networks.	Becker et al. (2010); Chanchaichujit, Balasubramanian, and Charmaine (2020)
Artificial Intelligence	Learning algorithms that improve based on past data and tasks. A system's ability to correctly interpret external data, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation.	Holweg et al. (2018); Kaplan and Haenlein (2019)
Blockchain	Distributed ledgers that record transactions in a trustless environment and are protected by cryptography. A finite set of transactions is placed on each block, which is protected by digital signatures and cryptographic hash functions.	Pournader et al. (2020)
Cloud Computing	Virtual computing and storage capacity provided across the Internet. Uses fast, high-bandwidth internet connections to deploy services that are centrally maintained, often by third parties, and thus minimise the cost and difficulty of IT administration and support for the organisations that consume those services.	Borenstein and Blake (2011); Holweg et al. (2018)
Big Data Analytics	Machine learning tools to identify patterns in large quantities of structured and unstructured data. The data sets and analytical techniques in applications are so large and complex that they require advanced and unique data storage, management, analysis, and visualisation technologies.	Chen, Chiang, and Storey (2012); Holweg et al. (2018)
Augmented and Virtual Reality (Cognitive Assistance)	Technology-enabled augmented content that combines with the real environment to develop an augmented real environment where people can have an augmented experience. VR is an advanced computer technology that can give users multiple intuitive sensations while simulating mechanisms in a physical or imaginary world.	Caboni and Hagberg (2019); Guo et al. (2020)
Exoskeletons (Physical Assistance)	Can be categorised as passive or active. The former generate forces/torques in response to deformation, using un-powered mechanisms including springs or spring-like elements. Active devices, in contrast, involve powered force/torque generating elements (e.g. motors) to amplify operator strength.	Nussbaum et al. (2019)
Sensors	Devices that can self-organise, learn, and maintain environmental information to analyse behaviours and abilities.	Kalsoom et al. (2020)