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Warehousing 5.0 for the Future of the Logistics Industry

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Abstract

This editorial introduces and contextualizes the *International Journal of Production Research* Special Issue on "Warehousing 5.0 for the Future of the Logistics Industry." Building on the principles of *Industry 5.0*, the concept of Warehousing 5.0 redefines warehouse operations as *human-centric, intelligent, sustainable, and resilient systems*. It emphasizes the integration of advanced automation and analytics with human well-being, environmental stewardship, and data responsibility—shifting the focus from efficiency alone to a balanced socio-technical paradigm. The Special Issue received 45 submissions, from which 13 papers were accepted after rigorous peer review. Together, these studies advance understanding across four interconnected themes: (T1) Human Factors and Human-Centric Design, (T2) Optimization and Efficiency in Robotics and Automation, (T3) Energy Efficiency and Sustainable Operations, and (T4) Data-Driven and AI-Enabled Warehousing. The contributions highlight innovations in ergonomic design, collaborative robotics, energy-aware scheduling, stochastic and multi-objective optimization, wearable sensing, and AI-enabled vision systems, demonstrating how operational efficiency can coexist with human welfare and environmental responsibility. Synthesizing across these themes, the editorial identifies key insights on human-technology symbiosis, sustainable digitalization, and cyber-physical-social integration in warehouses. It also outlines future research directions on adaptive human-robot collaboration, circular logistics, responsible AI, and integrative modelling. The practical and policy implications discussed provide a framework for managers and decision-makers to implement Warehousing 5.0 principles effectively. Collectively, the Special Issue contributes to shaping a new generation of resilient, sustainable, and human-aware warehouses, reinforcing *IJPR's* leadership in advancing innovative and responsible production and logistics systems.

Keywords: warehousing, digitalisation, warehousing 5.0, industry 5.0, human-centric, sustainability, resilience

1. Introduction

Since its founding in 1961, the *International Journal of Production Research (IJPR)* has been a cornerstone in advancing knowledge on production, logistics, and warehousing systems. Over the decades, IJPR has served as a platform for research on warehouse design, control, and operations, topics that have evolved in tandem with technological and societal change (de Koster et al., 2017). In recent years, the journal has been instrumental in expanding the boundaries of warehousing research, encouraging interdisciplinary work that integrates human-

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centric, sustainable, and digital dimensions. This special issue (SI) continues that tradition, offering a timely reflection on how Warehousing 5.0 is redefining research and practice.

Warehousing is undergoing a paradigm shift in response to emerging Industry 5.0 principles and the rapidly evolving logistics landscape. Industry 5.0, as introduced by the European Commission, extends the focus beyond the productivity and efficiency obsessions of Industry 4.0 to emphasize human-centricity, environmental sustainability, and resilience in industrial systems (European Commission, 2020). In the warehousing context, this shift calls for an approach that not only leverages robotics, automation, and artificial intelligence (AI) to enhance operational performance but also ensures that these technologies are implemented in ways that empower human workers, reduce environmental impact, and build systemic robustness against disruptions (Ivanov, 2023; Grosse et al., 2023).

The emerging concept of Warehousing 5.0 thus comprises the integration of advanced automation and digital technologies with human- and planet-oriented values. It repositions the warehouse as an intelligent, adaptive, and *socio-technical ecosystem* where technology, human well-being, and sustainability coexist as interdependent pillars of success (Glock et al., 2024). In practice, this means that warehouse managers are no longer tasked solely with maximising productivity or minimising costs, but with designing systems that are *human-friendly, energy-efficient, and resilient by design*.

The need for such a paradigm has been accelerated by transformative trends in logistics. The exponential growth of e-commerce, particularly in fast-moving sectors such as groceries and pharmaceuticals, and the rise of omnichannel retail have redefined customer expectations toward rapid fulfilment, shipping accuracy and seamless service (GroceryDive, 2023). As a result, warehouses have evolved from back-end storage spaces into *strategic hubs* of responsiveness and innovation (Boysen et al., 2019). Yet, the pursuit of operational speed and precision often places strain on both human workers and natural resources. Industry 5.0 principles consider that efficiency without empathy or environmental awareness is unsustainable. Warehouses of the future must therefore become *smarter, safer, and greener*, a vision that combines technological sophistication with care for people and the planet (Perotti et al., 2025). With this comes the understanding that there are trade-offs between technological advancement and societal wellness considerations in the design and operations of such systems.

The human-centric dimension of Warehousing 5.0 repositions workers as collaborative partners rather than passive operators. Technologies such as *collaborative robots (cobots)*, *wearables*, and *AI-assisted systems* are designed to augment human capabilities, improve safety, and reduce physical or cognitive strain. Several papers published in this SI demonstrate this trend. Examples include *exoskeletons* that mitigate fatigue during repetitive lifting (Ashta et al., 2025), *data glasses* that lower mental workload in order-picking (Tudisco et al., 2025), and *wearable sensors* that monitor fatigue in real time (Kazemi Kheiri et al., 2025). At the same time, the sustainability and resilience dimensions require that warehouses operate with reduced energy consumption and carbon footprint (Mao et al., 2025; Silva et al., 2025) while ensuring robustness against operational and cyber risks (Rodríguez-García et al., 2025). These converging priorities, human, technological, and ecological, are what distinguish Warehousing 5.0 from earlier paradigms.

From a theoretical standpoint, Warehousing 5.0 marks a decisive departure from technology-centric models toward *integrative, human-technology-environment frameworks*. It embraces

systems thinking, in which ergonomics, automation, data analytics, and sustainability are viewed as interconnected levers of performance. This holistic view opens new avenues for research that blend *industrial engineering, operations research, psychology, and data science*, a multidisciplinary approach that defines the contributions of this SI.

This SI brings together a diverse yet coherent collection of studies that advance understanding of Warehousing 5.0 through empirical, analytical, and conceptual approaches. Collectively, these papers illustrate how human factors, optimisation, sustainability, and digital intelligence converge to shape next-generation warehouse systems. To guide readers through this synthesis, the contributions are structured into four interrelated thematic categories:

- **(T1) Human Factors and Human-Centric Design**, focusing on worker well-being, ergonomics, and human–technology interaction;
- **(T2) Optimization and Efficiency in Robotics and Automation**, addressing analytical and algorithmic innovations for hybrid and automated systems;
- **(T3) Energy Efficiency and Sustainable Operations**, highlighting environmental performance, energy-aware scheduling, and system-level sustainability; and
- **(T4) Data-Driven and AI-Enabled Warehousing**, encompassing AI, IoT, and predictive analytics for intelligent, transparent, and resilient warehouse management.

2. Contributions in this Special Issue

This section presents the scholarly contributions featured in the SI on Warehousing 5.0, each offering a unique perspective on the evolving landscape of warehouse operations. To structure the discussion, the papers are grouped into four interrelated thematic categories reflecting the multidimensional nature of Warehousing 5.0. Each theme is introduced with an overview, followed by a synthesis of how the respective papers contribute in terms of research focus, methodological innovation, and practical or theoretical insights.

2.1 Overview

Overall, the SI attracted 45 submissions from around the world, with 13 papers ultimately accepted for publication after rigorous peer review and 3 submissions withdrawn by their authors. In addition, 7 manuscripts were rejected after full review, while 3 papers were withdrawn by their authors following review due to the extent of revisions required. A further 22 submissions were desk-rejected for not meeting the scientific or thematic requirements of the SI.

The submissions were both geographically and methodologically diverse. Research approaches ranged from industry case studies and human-subject experiments to advanced optimization models and simulation studies, highlighting the broad scope of Warehousing 5.0 scholarship. This breadth of perspectives is reflected in the accepted papers, which are discussed in the next sub-section and organized according to key thematic areas.

These figures highlight both the competitiveness of the review process and the high-quality benchmark upheld for inclusion. Figure 1 summarises the overall submission and review outcomes.

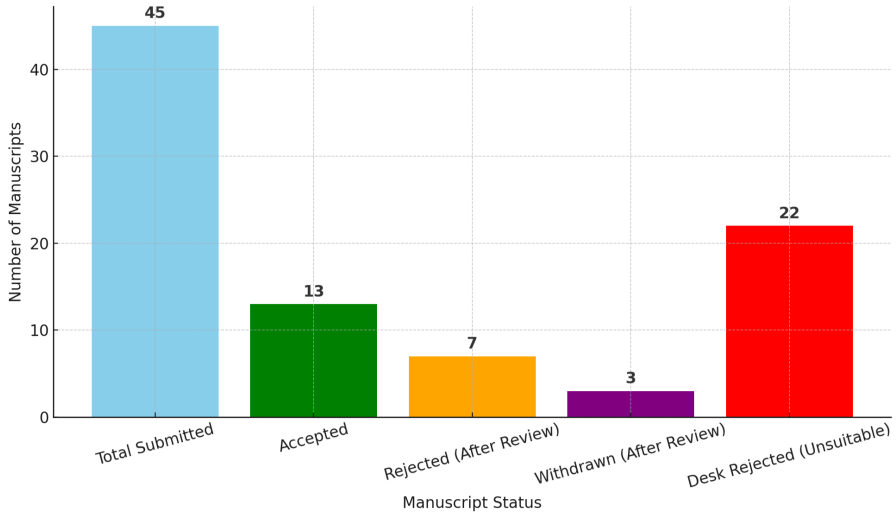

Figure 1: Manuscript Submissions to the SI

The contributions included in this SI comprise 13 carefully selected articles, reflecting multidisciplinary research that collectively emphasizes *human-centricity, technological innovation, analytical sophistication, sustainability,* and *data-driven intelligence*. Based on the conceptualization outlined in Section 1, these papers are organized into four distinct yet closely interrelated thematic categories: (T1) *Human Factors and Human-Centric Design*, (T2) *Optimization and Efficiency in Robotics and Automation*, (T3) *Energy Efficiency and Sustainable Operations*, and (T4) *Data-Driven and AI-Enabled Warehousing*. Table 1 presents the thematic alignment and specific contributions of each paper across these categories.

Table 1: Summary of Special Issue Contributions

		Theme			
		T1	**T2**	**T3**	**T4**
Author	**Contribution**	**Human Factors & Human-centric Design**	**Optimization & Efficiency**	**Energy & Sustainability**	**Data-driven & AI enabled Warehousing**
Hosseini et al. (2024)	Examines effects of workload and autonomy on boredom and performance in AGV-assisted warehouses.	✓			
Ghorashi Khalilabadi et al. (2024)	Uses IoT-based travel data for more accurate facility layout optimization with multiple I/O points.		✓		✓
Ma et al. (2024)	Develops a multi-objective RMFS model balancing travel distance and human fatigue.	✓	✓	✓	
Rodríguez-García et al. (2025)	Integrative review identifying technological risks and cyber vulnerabilities in automated warehouses.				✓

Cretskens et al. (2025)	Qualitative study exploring psychosocial factors influencing warehouse employee well-being.	✓			
Ashta et al. (2025)	DSS assessing ergonomic and operational benefits of passive exoskeletons in order picking.	✓		✓	
Mao et al. (2025)	MIP model optimizing electric vehicle scheduling under time-of-use electricity pricing.		✓	✓	
Flores-García et al. (2025)	Applies AI-enabled vision systems for human-centred order picking and ethical monitoring.	✓			✓
Wei et al. (2025)	MILP and heuristic optimization for buffer allocation in cooperative robot systems.		✓		
Silva et al. (2025, in press)	Multi-period stochastic optimization of RMFS integrating pod repositioning for sustainability.		✓	✓	
Wang et al. (2025, in press)	Bi-objective model synchronizing replenishment and storage for energy efficiency and blocking avoidance.		✓	✓	✓
Kazemi Kheiri et al. (2025, in press)	Hierarchical Bayesian model predicting worker fatigue via wearable sensors for proactive safety.	✓			✓
Tudisco et al. (2025, in press)	Experimental study comparing batch vs. single order-picking using neuroscience-based cognitive data.	✓			

Notably, most contributions intersect multiple themes, reflecting the cross-disciplinary essence of Warehousing 5.0. For instance, Ma et al. (2024) integrates human well-being (T1), robotic automation (T2), and sustainability (T3) through a multi-objective optimization framework for robotic mobile fulfilment systems, demonstrating a truly socio-technical approach. Similarly, Wang et al. (2025) advances the synergy between sustainable design (T3) and digital intelligence (T4) through a bi-objective optimization model (T2) that synchronizes replenishment and storage to enhance both energy efficiency and system flow. Flores-García et al. (2025) bridges human-centricity (T1) and AI-enabled warehousing (T4) by developing vision-based decision support systems that enhance transparency and worker well-being. In contrast, Kazemi Kheiri et al. (2025) demonstrate how wearable sensing and Bayesian modelling (T4) can predict and prevent fatigue (T1), translating data intelligence into proactive safety applications.

Further, Mao et al. (2024) and Silva et al. (2025) exemplify the growing intersection between optimization (T2) and sustainability (T3) through energy-aware electric vehicle scheduling and sustainable robotic fulfilment models. At the same time, studies such as Ghorashi Khalilabadi et al. (2024) and Wei et al. (2025) underscore the optimization-driven (T2) nature of next-generation logistics by enhancing layout design and order-processing efficiency through IoT data and heuristic modelling.

In the following sections, each of the four thematic areas is examined in detail. For each theme, the included papers are discussed in terms of their *central research focus, methodological contribution, and theoretical or practical insights* into the evolving Warehousing 5.0 landscape. This structure highlights both the unique contributions of individual studies and the synergistic relationships that emerge across themes, illustrating how human factors, technological automation, optimization, and sustainability are increasingly integrated within warehouse systems.

2.2 Human Factors and Human-Centric Design (T1)

The first theme, *Human Factors and Human-Centric Design (T1)*, captures the essence of Warehousing 5.0 by positioning human well-being, ergonomics, and cognition at the core of technological transformation. The contributions within this theme converge on a shared understanding: that the success of intelligent warehouses depends on how technology augments, rather than replaces, human capability.

Several studies directly address the interplay between automation and worker experience. Ma et al. (2024) combine robotic travel efficiency with operator fatigue reduction harmonising performance and ergonomics. Hosseini et al. (2024) empirically demonstrate that increased task autonomy in AGV-assisted operations alleviates boredom and enhances engagement, while excessive workload can counteract these gains, signalling the need for carefully balanced human–machine task allocation. Complementing this, Cretskens et al. (2025) adopt a qualitative lens to explore psychosocial influences such as leadership, social support, and perceived control, revealing that psychological well-being in warehouses extends far beyond physical ergonomics. Ashta et al. (2025) advance this conversation by introducing a decision-support system for passive exoskeleton selection, offering a practical framework that merges ergonomic and operational criteria to ensure wearable technologies enhance both comfort and productivity. From a cognitive perspective, Tudisco et al. (2025) use neuroscience-based measurements to show that while batch picking increases throughput, it also intensifies cognitive load, highlighting the importance of designing cognitively sustainable processes.

The integration of data intelligence into human well-being is also notable. Kazemi Kheiri et al. (2025) develop a hierarchical Bayesian model that uses wearable sensor data to predict worker fatigue, offering a proactive approach to safety management. Flores-García et al. (2025) similarly employ AI-enabled vision systems to monitor and support human-centred order picking, emphasizing ethical data use and transparency in automation. Together, these papers reveal that human factors in Warehousing 5.0 are no longer just after-thoughts but a strategic dimension of system design, where physical, psychological, and cognitive well-being become key indicators of sustainable performance.

2.3 Optimization and Efficiency in Robotics and Automation (T2)

The second theme, *Optimization and Efficiency in Robotics and Automation (T2)*, focuses on the analytical and computational backbone of modern warehouse operations. The studies in this category extend classical optimisation and operations-research techniques to address the complexities of hybrid, multi-robot, and data-driven systems—establishing automation as both a scientific and engineering challenge in the Warehousing 5.0 era.

At the system-design level, Ghorashi Khalilabadi et al. (2024) integrate IoT-based travel data into facility layout optimisation, developing a mixed-integer programming (MIP) model enhanced by a genetic algorithm to capture realistic multi-I/O travel sequences. Their data-informed approach significantly improves spatial efficiency compared to conventional flow models. Similarly, Wei et al. (2025) propose a hybrid MIP–heuristic approach for cooperative robot buffer allocation, demonstrating how algorithmic coordination enhances throughput and resource utilisation.

The integration of human and environmental considerations into optimisation is a hallmark of this theme. Ma et al. (2024) combine robotic travel efficiency with operator fatigue reduction in a multi-objective robotic mobile fulfilment system (RMFS) model, offering a socio-technical optimisation perspective that harmonises performance and ergonomics. Mao et al. (2025) optimise electric vehicle scheduling under time-of-use energy pricing, while Silva et al. (2025) address multi-period stochastic RMFS planning that incorporates pod repositioning and energy efficiency, both showing how *green automation* principles can drive long-term operational gains. Wang et al. (2025) extend this trajectory by developing a bi-objective replenishment and storage model that integrates AI-based demand forecasting (via long short-term memory - LSTM), reducing congestion and energy waste simultaneously.

Collectively, these papers exemplify the evolution of warehouse optimisation towards *adaptive, energy-aware, and AI-augmented optimisation frameworks*, providing analytical foundations for the intelligent, self-regulating warehouse of the future.

2.4 Energy Efficiency and Sustainable Operations (T3)

The third theme, *Energy Efficiency and Sustainable Operations (T3)*, underscores the commitment of Warehousing 5.0 to environmental sustainability and energy-aware performance management. The contributions within this category explore how sustainability objectives can be embedded directly into warehouse design, scheduling, and control models, linking operational performance with ecological and ergonomic responsibility.

Mao et al. (2025) and Silva et al. (2025) demonstrate how energy efficiency can be systematically optimised through model-based decision-making. Mao et al. (2025) introduce a mixed-integer programming approach for electric vehicle scheduling that adapts to time-of-use electricity tariffs, reducing both energy costs and carbon impact. Silva et al. (2025) advance this by developing a stochastic optimisation framework for robotic mobile fulfilment systems that integrates pod repositioning decisions to achieve lower energy use without sacrificing throughput. Similarly, Wang et al. (2025) present a bi-objective model synchronising replenishment and storage processes to minimise energy waste and congestion, enhanced through AI-based forecasting.

Together, these contributions reveal that *sustainability in Warehousing 5.0 is multidimensional*, spanning energy conservation, resource utilisation, and human endurance, all co-optimised to promote resilient and responsible operations.

2.5 Data-Driven and AI-Enabled Warehousing (T4)

The fourth theme, *Data-Driven and AI-Enabled Warehousing* (T4), represents the digital intelligence layer of Warehousing 5.0. These contributions focus on how data analytics, artificial intelligence, and cyber-physical integration enhance decision-making, transparency, and resilience in warehouse systems.

Rodríguez-García et al. (2025) provide a comprehensive integrative review of technological vulnerabilities in automated warehouses, identifying emerging risks such as cyber-attacks, data privacy breaches, and system interoperability issues. Their framework lays the groundwork for cyber-resilient warehousing, establishing digital security as a fundamental design principle. Wang et al. (2025) highlight the growing role of AI and data analytics in operational optimisation, using IoT data for dynamic layout planning and employing AI forecasting for flow synchronisation.

At the human–technology interface, Flores-García et al. (2025) explore the use of AI-enabled vision systems to support human-centred order picking, integrating ethical and privacy safeguards into system design. Similarly, Kazemi Kheiri et al. (2025) leverage wearable sensor data with hierarchical Bayesian modelling to predict fatigue in real time, offering AI-driven safety intelligence for worker well-being.

Collectively, these papers illustrate that data-driven warehousing is no longer confined to efficiency enhancement, it is a multidimensional enabler of transparency, trust, and resilience. By embedding AI and IoT technologies within ethically guided, human-aware frameworks, the T4 contributions redefine warehouses as intelligent, adaptive ecosystems where data empowers both performance and protection.

3. Emerging Insights from the Special Issue

The contributions in this SI collectively advance the conceptual and empirical foundations of Warehousing 5.0 as an integrated socio-technical paradigm. Beyond their individual research findings, the papers together portray a logistics environment where human-centric design, technological intelligence, and sustainability imperatives are no longer separate agendas but mutually reinforcing dimensions of performance. Three overarching insights emerge from this synthesis, each reflecting a structural transformation in how modern warehouses are conceived, modelled, and managed.

3.1 Human–Technology Symbiosis as the New Operational Logic

A first and striking insight concerns the evolution from automation for efficiency toward automation with empathy. The studies grouped under Theme 1 (Human Factors and Human-Centric Design) and Theme 2 (Optimization and Efficiency in Robotics and Automation) reveal that technological progress must operate in harmony with human variability and well-being. Hosseini et al. (2024) and Cretskens et al. (2025) show that psychological engagement, perceived autonomy, and social climate significantly influence performance, even in highly automated contexts. Complementary works such as Ma et al. (2024) and Ashta et al. (2025) integrate these insights into mathematical and decision-support models, balancing robot travel efficiency and human fatigue through multi-objective optimisation and ergonomic evaluation. Together, these studies demonstrate that human–machine collaboration, rather than substitution, will define the next generation of operational excellence. Warehouses are thus

emerging as symbiotic systems, where automation enhances human capability while preserving safety, satisfaction, and inclusion.

3.2 The Convergence of Optimization, Sustainability, and Digital Intelligence

A second insight is the clear convergence between analytical optimisation, energy efficiency, and AI-driven intelligence, which collectively underpin the sustainable transformation of warehouse operations. Across Themes 2 and 3, scholars such as Mao et al. (2025), Silva et al. (2025), and Wang et al. (2025) illustrate how multi-objective and stochastic optimisation models can jointly minimise travel distance, congestion, and energy consumption while maintaining service levels. Ghorashi Khalilabadi et al. (2024) and Wei et al. (2025) show that integrating IoT-generated data and heuristic algorithms enhances layout and buffer design, making system control adaptive and data-informed. Meanwhile, Kazemi Kheiri et al. (2025) and Flores-García et al. (2025) demonstrate how wearable and vision-based AI systems expand optimisation into the cognitive and physiological domains of work. Collectively, these contributions reveal a decisive methodological shift: warehouses are moving from static rule-based planning to context-aware, learning-based optimisation, where AI and sustainability considerations are embedded at every decision level.

3.3 Warehousing as a Cyber-Physical-Social Ecosystem

A third insight relates to the recognition of warehouses as cyber-physical-social ecosystems, integrating physical assets, digital infrastructures, and human actors into interconnected networks. This view is strongly reflected in Theme 4, where Rodríguez-García et al. (2025) provide an integrative framework for managing cyber vulnerabilities and technological risks. Their analysis underlines that as warehouses become more digitised, *cyber-resilience and data governance* are as crucial as physical robustness. In parallel, studies using AI-enabled monitoring and IoT-based optimisation highlight that data flows now shape not only operational efficiency but also ethical responsibilities. The inclusion of *ethical AI* and *responsible data design* principles, exemplified by Flores-García et al. (2025), marks an important evolution toward warehouses that are intelligent *and* trustworthy. This transformation reframes the warehouse as a living socio-technical organism: one that senses, learns, and adapts while maintaining transparency, privacy, and human dignity.

3.4 Towards an Integrative Warehousing 5.0 Framework

Synthesising across these themes, the SI underscores that the warehouse of the future cannot be understood through isolated technological or managerial lenses. Instead, integration of humans and machines, optimisation and sustainability, and data and ethics, is emerging as the defining capability of Warehousing 5.0. The contributions collectively call for interdisciplinary thinking that bridges operations research, human factors engineering, computer science, and sustainability management. Conceptually, they point toward an integrative Warehousing 5.0 framework in which:

- Human well-being forms the foundation of design and evaluation;
- Optimization and automation serve as the enabling mechanism for operational excellence;
- Sustainability functions as the strategic compass guiding long-term viability; and

- Data intelligence provides the connective tissue that links sensing, decision-making, and learning.

These insights collectively reaffirm that Warehousing 5.0 is not merely the next industrial revolution but a reorientation of purpose, one that aligns productivity with humanity and sustainability with innovation. The following section builds on these insights to identify future research directions that will further shape this transformative agenda.

4. Future Research Directions

Building on the collective insights from this SI, it is clear that Warehousing 5.0 represents not only a technological progression but a paradigm transformation toward *integrated, human-aware, and sustainable logistics ecosystems*. Yet, while the included papers significantly advance this frontier, they also expose key gaps and opportunities for further inquiry. Future research must continue to expand theoretical, empirical, and methodological horizons, linking human-centric design, automation, sustainability, and AI governance into coherent, multi-level frameworks. Four broad but interconnected research avenues emerge from the contributions to this SI.

4.1 Human-Centric Design and Neuro-Ergonomics

The evolution toward human-centric warehousing calls for a deeper understanding of how humans interact cognitively, emotionally, and physically with increasingly intelligent technologies. Future studies should extend beyond static ergonomic models to encompass dynamic and neuro-ergonomic approaches that capture real-time cognitive and physiological responses during warehouse tasks. Advances in wearable sensing, eye-tracking, and brain–computer interfaces offer promising opportunities to model mental workload, stress, and fatigue with unprecedented granularity. Longitudinal research could explore how these indicators evolve with technological adaptation, workforce diversity, and experience levels.

Equally important is the ethical dimension of human-data integration. As demonstrated, the collection of biometric or behavioural data must be guided by transparent consent mechanisms and privacy safeguards. Future work should therefore examine how trust, acceptance, and ethical governance shape the success of data-driven human-centred technologies. Such research would provide both theoretical refinement of human–machine interaction models and practical insights for developing inclusive, adaptive warehouse environments.

4.2 Hybrid Human–Robot Collaboration and Adaptive Optimization

While robotics and automation have long been studied in warehousing, the next frontier lies in adaptive human–robot collaboration, systems that dynamically adjust to human capabilities, preferences, and constraints. Future research should focus on developing bi-directional learning frameworks in which robots not only respond to human behaviour but also communicate and coordinate in intuitive ways. This requires integrating reinforcement learning, real-time scheduling, and multi-agent optimisation with behavioural and ergonomic data.

The methodological challenge lies in capturing the co-evolution between human skill acquisition and robot decision-making. Future extensions could incorporate feedback loops where robots adapt to operator fatigue, task complexity, or cognitive load. At a system level,

this implies a shift toward closed-loop optimisation, where decisions are continuously refined through sensor data and AI prediction, enabling truly responsive and resilient operations.

4.3 Sustainable Energy and Circular Warehouse Operations

Sustainability remains a defining ambition of Warehousing 5.0, but it requires expanding beyond operational energy efficiency to include holistic environmental performance and circular economy principles. Future research should develop integrated energy and material flow models that account for on-site renewable generation, battery storage, electric vehicle fleets, and resource reuse. The next step would be to embed life-cycle assessment (LCA) and carbon accounting directly into decision-support systems.

At a strategic level, future studies could explore network-level sustainability, linking warehouse operations to reverse logistics, waste valorisation, and green procurement. Integrating sustainability indicators into simulation and optimisation frameworks will enable managers to quantify trade-offs among cost, service, and environmental impact. Moreover, the interplay between human well-being and ecological sustainability remains underexplored, future interdisciplinary research could evaluate how energy-efficient design also enhances comfort, air quality, and occupational health.

4.4 Data Governance, Cyber-Resilience, and Responsible AI

As warehouses evolve into cyber-physical-social systems, the governance of data and algorithms becomes a pressing research frontier. Future work must move beyond technical security measures to propose multi-layered governance frameworks that embed accountability, explainability, and ethical oversight into AI-driven warehouse systems.

There is also a need for quantitative models of digital trust and resilience, combining insights from systems engineering, behavioural science, and operations management. Future studies could explore how AI-enabled decision systems perform under uncertainty, disruption, or adversarial attacks, and how human operators perceive and respond to these technologies. The development of auditable AI algorithms for warehouse scheduling, safety monitoring, and maintenance prediction represents an important step toward operationalising responsible AI in logistics.

4.5 Integrative Modelling and Interdisciplinary Methodologies

Across all four directions lies a meta-level research opportunity: the need for integrative modelling approaches that connect human, technological, and environmental subsystems. Hybrid methodologies combining operations research, human factors engineering, machine learning, and system dynamics are essential to capture the complex feedback loops that define Warehousing 5.0. Empirical validation through living labs, digital twins, and real-world pilot implementations will also be crucial to ensure that research outcomes are both scientifically robust and industrially actionable.

5. Managerial and Policy Implications

The evolution toward Warehousing 5.0 carries extensive implications for both industry practice and public policy. The insights presented across the papers in this SI highlight that achieving excellence in the next generation of warehousing will depend on integrating human, technological, and environmental considerations into every strategic and operational decision.

Rather than treating automation, sustainability, and well-being as separate agendas, managers and policymakers must recognise them as mutually reinforcing dimensions of long-term competitiveness and social responsibility.

5.1 Building Human-Centric Operations

For warehouse managers, the findings of this SI emphasise the importance of embedding human-centric design principles into all aspects of warehouse planning and management. Managers should therefore invest in participatory design processes where workers co-create and evaluate new technologies, workflows, and performance systems. Training programmes and organisational cultures that promote psychological safety and social cohesion will be vital for maintaining motivation in environments increasingly mediated by automation.

Furthermore, the deployment of assistive technologies such as exoskeletons and AI-supported vision systems should be guided by ergonomic evidence rather than technological novelty. Passive exoskeletons offer measurable benefits only under specific task conditions; thus, data-driven evaluation and personalised task allocation are essential for real performance gains. Ultimately, the managerial challenge in Warehousing 5.0 lies not in maximising automation, but in orchestrating human–machine complementarity to achieve both operational excellence and workforce well-being.

5.2 Operationalising Sustainable and Energy-Efficient Practices

From an environmental perspective, warehouse leaders must treat energy efficiency and sustainability as central metrics of operational success. Managers should incorporate energy-aware scheduling, on-site renewable energy use, and electrified vehicle fleets into their operations to reduce both costs and carbon footprints.

At the tactical level, sustainability can also be enhanced through smart inventory policies and modular warehouse layouts that reduce unnecessary movement and congestion. The convergence of human and environmental sustainability suggests that improvements in ergonomics often coincide with energy savings, a dual benefit that supports a holistic approach to performance management. By adopting sustainability-focused key performance indicators (KPIs) and integrating life-cycle considerations into procurement and design decisions, warehouses can contribute meaningfully to corporate sustainability objectives and national decarbonisation targets.

5.3 Governing Data, AI, and Ethical Automation

The increasing reliance on data and AI in warehouse operations calls for stronger governance mechanisms to ensure transparency, accountability, and ethical use. As seen, automation-driven efficiency gains can be undermined by vulnerabilities in cybersecurity, data privacy, and algorithmic bias. Managers should therefore implement responsible AI policies that define clear rules for data access, storage, and sharing, while also communicating these policies transparently to workers.

Technology providers have an equally important role in ensuring that AI and IoT solutions comply with ethical-by-design principles, embedding explainability, fairness, and human oversight into software and sensor systems. Routine audits of algorithmic decisions, risk assessment frameworks for data breaches, and AI literacy programmes for employees should become standard practice in digitally advanced warehouses. In this way, organisations can

foster both trust and resilience in cyber-physical environments, transforming AI from a source of uncertainty into a driver of informed, ethical decision-making.

5.4 Policy Frameworks for Inclusive and Sustainable Warehousing

At the policy level, governments and regulatory bodies must play an enabling role in guiding the transition toward Warehousing 5.0. This includes developing regulatory standards for human–robot collaboration, workplace ergonomics, and digital ethics. Policy instruments such as tax incentives for renewable energy adoption, funding schemes for human-centric automation, and certification systems for "green and responsible warehouses" can accelerate adoption across industries.

In addition, public–private partnerships and living lab initiatives can facilitate knowledge transfer between academia, industry, and policymakers, ensuring that innovations are tested in real-world environments before large-scale implementation. Workforce development programmes will also be essential, focusing on upskilling and re-skilling logistics workers for hybrid human-AI operations. By aligning industrial policy, social policy, and environmental objectives, policymakers can ensure that the transition to Warehousing 5.0 contributes to broader goals of sustainable growth, social inclusion, and technological sovereignty.

5.5 Toward Strategic Alignment Between Technology, People, and Policy

Ultimately, the managerial and policy implications of this SI converge on a single imperative: strategic alignment between technology, people, and governance. Managers must lead with empathy and evidence, leveraging analytics not only to optimise systems but also to enhance the well-being and autonomy of their workforce. Technology providers must innovate responsibly, ensuring that automation enhances human dignity and environmental stewardship. Policymakers must create enabling conditions for equitable digital transformation. The Warehousing 5.0 paradigm thus invites all stakeholders to collaborate in reimagining the warehouse as a human-centred, intelligent, and sustainable system, a cornerstone of the future industrial landscape.

6. Conclusion

The contributions gathered in this SI collectively mark a significant step forward in the evolution of warehousing research and practice. They reveal that the transformation toward Warehousing 5.0 is not merely technological, but deeply socio-technical, anchored in the synergy between humans, intelligent systems, and sustainable operations. The studies featured herein demonstrate that future warehouses will be defined by *collaboration* rather than substitution: humans and machines working together in ways that enhance both efficiency and well-being, guided by ethical, data-informed decision frameworks.

Across the four thematic areas, human-centric design, optimisation and efficiency, sustainable operations, and data-driven intelligence, a shared vision emerges. This vision positions the warehouse not as a mechanistic production unit, but as a *dynamic ecosystem* that senses, adapts, and learns while remaining attentive to human needs and planetary boundaries. By integrating advanced optimisation techniques, AI, ergonomic innovation, and sustainability strategies, these contributions establish a new foundation for understanding and managing the complexity of modern warehouse systems.

For researchers, the SI highlights the need for continued *interdisciplinary inquiry*, linking operations research, human factors, data science, and environmental management, to address the challenges and opportunities of this new era. For practitioners and policymakers, it offers a roadmap for aligning technological progress with social and environmental responsibility. Together, these perspectives affirm that the true promise of Warehousing 5.0 lies not only in smarter technologies, but in *wiser systems*, those designed to balance productivity with humanity, innovation with inclusion, and automation with sustainability.

In essence, this SI calls for a redefinition of excellence in warehousing: from efficiency-driven optimisation to *human- and planet-centred performance*. By embracing the principles of Industry 5.0, the warehousing community can lead the way toward a logistics future that is intelligent, resilient, and above all, humane.

References

Ashta, G., Finco, S., & Persona, A. (2025). Investigating the convenience of adopting passive exoskeletons in order picking. *International Journal of Production Research*, 1–25. https://doi.org/10.1080/00207543.2025.2487924.

Boysen, N., de Koster, R., & Weidinger, F. (2019). *Warehousing in the e-commerce era: A survey*. European Journal of Operational Research, 277(2), 396–411.

Cannava, L., & Perotti, S. (2025). *From warehouses to Net-Zero logistics facilities: A simulation-based roadmap to achieve carbon reduction and energy efficiency*. Computers & Industrial Engineering, 201, 110944. https://doi.org/10.1016/j.cie.2025.110944

Cretskens, I., Ramaekers, K., Van Laer, K., & Caris, A. (2025). Towards an increase in employee well-being in warehouses: insights from a qualitative study. *International Journal of Production Research*, 1–22. https://doi.org/10.1080/00207543.2025.2560528.

De Koster, R. B., Johnson, A. L., & Roy, D. (2017). Warehouse design and management. *International Journal of Production Research*, 55(21), 6327-6330.

Dhanda, M., Rogers, B. A., Hall, S., Dekoninck, E., & Dhokia, V. (2025). *Reviewing human-robot collaboration in manufacturing: Opportunities and challenges in the context of Industry 5.0*. Robotics and Computer-Integrated Manufacturing, 93, 102937. https://doi.org/10.1016/j.rcim.2024.102937

European Commission. (2020). *Industry 5.0* (Policy Brief). Retrieved from https://ec.europa.eu/info/research-and-innovation/research-area/industrial-research-and-innovation/industry-50_en

Flores-García, E., Ruiz Zúñiga, E., Jeong, Y., & Wiktorsson, M. (2025). AI-enabled vision systems for human-centered order picking – A design science research approach. *International Journal of Production Research*, 1–28. https://doi.org/10.1080/00207543.2025.2535515.

Ghobakhloo, M., Iranmanesh, M., Mubarak, M. F., Mubarik, M., Rejeb, A., & Nilashi, M. (2022). *Identifying Industry 5.0 contributions to sustainable development: A strategy*

roadmap for delivering sustainability values. Sustainable Production and Consumption, 33, 716–737.

Glock, C. H., Grosse, E. H., & Winkelhaus, S. (2024). Warehousing 5.0: Conceptual Background and Outline of the Book. In: Glock, C. H. and Grosse, E. H. (2024). Warehousing 5.0 - Managing the transition from techno-focused to human-value-centric intralogistics. Kindle Direct Publishing. ISBN: 979-8878899000

GroceryDive. (2023). *Online grocery sales will increase at 12% annual rate over 5 years, report says* (July 2023). Retrieved from https://www.grocerydive.com/news/online-grocery-sales-will-increase-at-12-annual-rate-over-5-years-report/641578/

Grosse, E. H. (2023). *Application of supportive and substitutive technologies in manual warehouse order picking: A content analysis*. International Journal of Production Research, 61(14), 4520–4539.

Grosse, E. H., Sgarbossa, F., Berlin, C., & Neumann, W. P. (2023). *Human-centric production and logistics system design and management: transitioning from Industry 4.0 to Industry 5.0*. International Journal of Production Research, 61(22), 7749–7759.

Hosseini, Z., Le Blanc, P., Demerouti, E., van Gool, P., & van den Tooren, M. (2024). *The impact of working with an automated guided vehicle on boredom and performance: An experimental study in a warehouse environment*. International Journal of Production Research, 62(4), 1298–1318. https://doi.org/10.1080/00207543.2023.2258747

Ivanov, D. (2023). *Supply chain resilience and the transition to Industry 5.0: Multi-dimensional value creation*. International Journal of Production Research, 61(22), 7721–7725.

Kazemi Kheiri, S., Sun, H., Megahed, F. M., & Cavuoto, L. A. (2025). *A hierarchical Bayesian modeling approach to predict upper extremities' fatigue in a dynamic order-picking task*. International Journal of Production Research, (in press).

Khalilabadi, S. M. G., Roy, D., & de Koster, R. (2024). Exploiting travel sequences to optimise facility layouts with multiple input/output points. *International Journal of Production Research*, 1–29. https://doi.org/10.1080/00207543.2024.2443798.

Ma, Z., de Koster, R., Roy, D., & Wu, G. (2025). Trading off travel distance and fatigue. The effect of storage, order batching, and pod selection in robotic mobile fulfillment systems. *International Journal of Production Research*, 1–28. https://doi.org/10.1080/00207543.2025.2472038.

Mao, Z., Zhao, Z., Song, M., & Huang, D. (2025). Electric vehicle scheduling problem considering time-of-use electricity price. *International Journal of Production Research*, 1–29. https://doi.org/10.1080/00207543.2025.2521047.

Panagou, E., Sarimveis, H., & Michalos, G. (2023). *The impact of human–robot collaborative order picking systems on warehouse workers*. International Journal of Production Research, 61(22), 7776–7790.

Perotti, S. & Dobers, K. (2024). Green Warehousing - Transitioning Towards Net-zero Logistics Sites. In: Glock, C. H. and Grosse, E. H. (2024). Warehousing 5.0 - Managing the transition from techno-focused to human-value-centric intralogistics. Kindle Direct Publishing. ISBN: 979-8878899000.

Perotti, S., Cannava, L., Ries, J. M., & Grosse, E. H. (2025). Reviewing and conceptualising the role of 4.0 technologies for sustainable warehousing. *International Journal of Production Research*, 63(6), 2305-2337.

Rodríguez-García, M., Kembro, J. H., Betts, K., & Ponce-Cueto, E. (2025). Managing technology-related disruptions and vulnerabilities in highly automated warehouse systems: an integrative review and research agenda. *International Journal of Production Research*, 1–33. https://doi.org/10.1080/00207543.2025.2552281.

Thylén, N., Wænström, C., & Hanson, R. (2023). *Challenges in introducing automated guided vehicles in a production facility – interactions between human, technology, and organisation*. International Journal of Production Research, 61(22), 7809–7829.

Tudisco, V., Tappia, E., Perotti, S., Meiser, A., & Klumpp, M. (2025). *Single order versus batch order-picking and Warehousing 5.0: Analyzing human factor impacts on picking performance with neuroscience methods*. International Journal of Production Research, (in press).

Wang, L., Zhang, N., Wang, S., Wang, X., & Yuan, Z. (2025). *Bi-objective optimization for synchronizing replenishment and storage assignment: Achieving energy efficiency and blocking avoidance in forward-reserve warehousing*. International Journal of Production Research, (in press).

Wei, J., Xu, X., Zou, B., Zhao, X., & Gong, Y. (2025). Order processing and buffer assignment in an order picking system with cooperative robots. *International Journal of Production Research*, 1–25. https://doi.org/10.1080/00207543.2025.2559140.

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