

Optimising Order Picking Accuracy and Efficiency in Warehouse Management Systems: A Systematic Review of Technological, Human and Operational Synergies

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ABSTRACT

Order picking represents the most labour-intensive, costly and error-critical operation in warehouse management, historically accounting for 55% to upwards of 65% of total warehouse operating expenses. Driven by the rapid expansion of e-commerce, decreasing order sizes and tight delivery windows, modern fulfilment centres have transitioned from traditional manual tracking to digitalised, highly automated environments. This systematic literature review (SLR) synthesises research on Warehouse Management Systems (WMS) order picking optimisation and picking accuracy across technological, human, operational organisational and environmental dimensions. Through a narrative and thematic synthesis of peer-reviewed literature, this study maps the socio-technical ecosystem governing warehouse fulfilment. The review reveals critical literature contradictions, most notably the tension between deterministic mathematical operations research models and non-deterministic human behavioural traits (fatigue, cognitive load, learning curves and worker forgetting dynamics). Furthermore, severe methodological gaps are exposed, including an overreliance on synthetic simulation data, static order assumptions and frictionless layout abstractions that omit real-world aisle congestion and picker blocking. To bridge the gap between academic theory and industrial practice, this review formulates a future research agenda centred on Joint Order Batching, Assignment, Sequencing and Routing Problems (JOBASRP), Industry 5.0 human-centric ergonomics, dynamic Deep Reinforcement Learning (DRL) control and hybrid Human-Robot Collaboration (HRC).

Keywords: Warehouse Management Systems (WMS); Order Picking Accuracy; Order Picking Optimization; Human Factors and Ergonomics; Industry 5.0; Human-Robot Collaboration (HRC); Systematic Literature Review (SLR); Operations Research

INTRODUCTION

Modern distribution networks operate under unprecedented fulfilment demands driven by the continuous growth of e-commerce, omni-channel retail and accelerated order cycle times. Warehouses have transformed from passive, static storage facilities into dynamic, highly time-critical service nodes within the global supply chain. To survive in this environment, logistics providers must process high volumes of customised, small-batch orders consisting of low line items and high Stock Keeping Unit (SKU) diversity under rigid fulfilment windows. Within this operational landscape, Warehouse Management Systems (WMS) serve as the essential digital backbone, executing receiving, real-time inventory tracking, location management, picking sequence generation and dispatch control.

Among all operational functions coordinated by a WMS order picking is defined as the physical or automated retrieval of items from dedicated storage locations to satisfy customer demand, is universally recognised as the most critical, labour-intensive and financially burdensome activity. Empirical and review literature consistently demonstrates that order-picking operations account for 55% to upwards of 65% of total warehouse operating expenditures. Because order picking directly links inventory management to customer fulfilment, any operational underperformance, delay or item mismatch cascades across the supply chain, incurring high rectifying costs and impairing customer satisfaction. Consequently, enhancing order-picking efficiency and picking accuracy is a primary strategic objective for logistics researchers and warehouse managers alike.

Research surrounding order-picking optimisation has expanded rapidly over the past two decades. Early foundational research predominantly treated warehousing as a mechanical operations research (OR) puzzle, focusing heavily on isolated sub-problems such as single-aisle routing policies, Travelling Salesman Problem (TSP) formulations, layout design and static storage assignment heuristics like the Cube-per-Order Index (COI). Modern literature has increasingly pivoted towards digital integration, examining the role of advanced WMS execution platforms, Radio-Frequency Identification (RFID) confirmation (Cagliano et al., 2021), Autonomous Mobile Robots (AMRs) (Fragapane et al., 2021) and smart picking infrastructure. Simultaneously, bibliometric and empirical developments have highlighted the necessity of incorporating human factors, learning effects and ergonomic well-being into picking models, reflecting broader Industry 5.0 human-centric principles (Glock et al., 2021; Neumann et al., 2021).

Despite extensive optimisation modelling, a critical research problem persists in the literature: a profound disconnect between academic optimisation models and real-world warehouse execution. Traditional OR formulations heavily abstract picking processes by modelling pickers as deterministic entities operating at uniform, unvarying speeds within idealised, frictionless warehouse layouts. In operational reality, however, human factors (including fatigue, experience, cognitive strain, physical ergonomics and learning or forgetting curves) serve as the primary drivers of order-picking errors and throughput bottlenecks. Furthermore, academic literature frequently evaluates planning problems (batching, storage, routing and sequencing) sequentially or in isolation, ignoring physical real-world constraints such as aisle congestion, picker blocking, narrow-aisle safety protocols and dynamic, real-time e-commerce order arrivals (Schrotenboer et al., 2021; van Deusen et al., 2023).

The synthesis of existing literature reviews and empirical studies reveals four overarching research gaps in the current body of knowledge on warehouse management systems (WMS) and digitalised order-picking operations. First, there is a methodological over-reliance on synthetic simulation, whereby the majority of existing studies examine hypothetical warehouse layouts and simulated datasets rather than empirical operational data. The limited use of real-world WMS operational logs constrains the external validity and practical applicability of existing findings, particularly in capturing the complexity and variability of actual warehouse environments. Second, conventional planning and optimisation models tend to underrepresent human-centric variables. Factors such as worker behavioural characteristics, physical workload, cognitive fatigue and forgetting cycles are frequently overlooked, despite their potential influence on order-picking accuracy, productivity and operational consistency (Grosse et al., 2023). Consequently, models that exclude these dimensions may generate performance predictions that do not adequately reflect real-world human-system interactions.

Third, integrated approaches to the Joint Order Batching, Assignment, Sequencing and Routing Problem (JOBASRP) remain relatively limited (Briant et al., 2020; Rau & Chen, 2024). Although individual optimisation of order batching, picker assignment, sequencing or routing has received considerable attention, these decisions are highly interdependent and optimising them separately may result in sub-optimal overall system performance. The complexity associated with jointly optimising these decisions presents significant computational challenges and has therefore contributed to the limited development of comprehensive integrated optimisation frameworks. Fourth, Human-Robot Collaboration (HRC) remains insufficiently explored within the context of next-generation WMS (Fragapane et al., 2022; Kadir et al., 2023). In particular, research on dynamic task scheduling, real-time coordination and collaborative interfaces involving autonomous mobile robots (AMRs), human pickers and WMS engines remains

underdeveloped. This gap is particularly significant under the Industry 5.0 paradigm, which emphasises human-centricity, resilience and sustainable integration between advanced technologies and human workers.

In response to these identified gaps, this systematic literature review (SLR) aims to provide a comprehensive and critical synthesis of the evolution, determinants, methodologies and emerging research directions associated with WMS and digitalised order-picking systems. From a theoretical perspective, this paper bridges operations research with human behavioural science and ergonomics by offering an integrative five-dimension framework comprising technological, human, operational organisational and environmental dimensions for understanding order-picking accuracy. From a methodological perspective, it critically evaluates the prevailing reliance on static and simulated data, highlighting the necessity of adopting hybrid modelling, agent-based simulation and empirical validation using real-world WMS field data (Zhang et al., 2025). From a practical perspective, the review provides warehouse managers with actionable guidelines regarding high-impact policy combinations such as class-based storage paired with order batching, as well as traffic management strategies aimed at eliminating bottlenecks and reducing order-fulfilment errors. The remainder of this paper is organised as follows: Section 2 details the SLR methodology and PRISMA screening process; Section 3 presents the thematic findings; Section 4 provides a critical discussion of theoretical and practical implications; Section 5 outlines a comprehensive future research agenda; and Section 6 concludes the study.

METHODOLOGY

Systematic Review Protocol and Standard Compliance

To ensure methodological rigour, transparency and reproducibility, this systematic literature review (SLR) was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. Rather than relying on non-reproducible generative search tools, a structured and explicit review protocol was established prior to execution to systematically retrieve, screen, evaluate and synthesise peer-reviewed literature surrounding Warehouse Management Systems (WMS) order-picking optimisation, picking accuracy and human-centric warehousing operations.

Information Sources and Search Strategy

Comprehensive electronic literature searches were executed directly on 15 January 2026 across two primary academic citation databases: Scopus and Web of Science (Core Collection). The search timeline was strictly restricted to publications from January 2020 through December 2025 (extending into early 2026) to capture a robust contemporary corpus of technological, operational and human-centric advancements. Search strings were constructed using Boolean operators (AND or) combining field tags for title, abstract and keywords (TITLE-ABS-KEY in Scopus; TS in Web of Science).

Inclusion and Exclusion Criteria

Candidate studies were systematically evaluated against predefined operational inclusion parameters to establish a transparent and reproducible review scope. Eligible publications were required to focus primarily on Warehouse Management Systems (WMS) execution platforms, internal order-picking optimisation (including storage allocation order batching and picker routing), picking accuracy mechanisms or human factor and ergonomic integration within warehouse operational environments. Furthermore, eligibility was restricted to peer-reviewed original research articles and comprehensive systematic reviews that employed quantitative empirical designs, mathematical optimisation formulations or discrete-event simulations. Specific publication timeline and language criteria constrained the search, ensuring the synthesis reflects contemporary technological and operational advancements. Only full-text articles published in English were considered for data extraction. Additionally, the publication window was strictly limited to studies published between 2020 and 2026 to capture the most recent developments in Industry 5.0 and digitalised warehousing solutions.

Conversely, studies were systematically excluded based on predefined boundary conditions regarding scope, publication type and methodological rigour. Articles focusing exclusively on external supply chain functions, such as long-haul freight transportation or multi-facility network design, were excluded if they did not directly evaluate internal warehouse picking operations. All forms of grey literature were omitted to safeguard evidence quality, including non-peer-reviewed trade magazines, editorial comments, extended abstracts, commercial white papers and patents. Finally, studies were excluded if they lacked clear mathematical formulations, transparent analytical frameworks or verifiable empirical and simulated results.

Selection Process and Numerical PRISMA Flow

The document collection and screening process followed four sequential PRISMA phases, which are Identification, Screening, Eligibility and Inclusion. Direct database queries during the Identification phase yielded 1,482 total records (864 from Scopus and 618 from Web of Science). Exporting all bibliographical records into reference management software identified and led to the removal of 458 duplicate entries. During the Screening phase, the remaining 1,024 unique records underwent title and abstract screening against the eligibility criteria, resulting in the exclusion of 740 out-of-scope records. In the Eligibility phase, the full texts of the remaining 284 articles were retrieved and rigorously evaluated. A total of 263 articles were excluded for specific reasons: an out-of-scope or external logistics focus ($n = 112$), publication dates prior to 2020 ($n = 84$), grey or non-peer-reviewed literature ($n = 41$) and incomplete numerical or algorithmic reporting ($n = 26$). Ultimately, 21 peer-reviewed articles published between 2020 and 2026 met all criteria and were included in the systematic review synthesis.

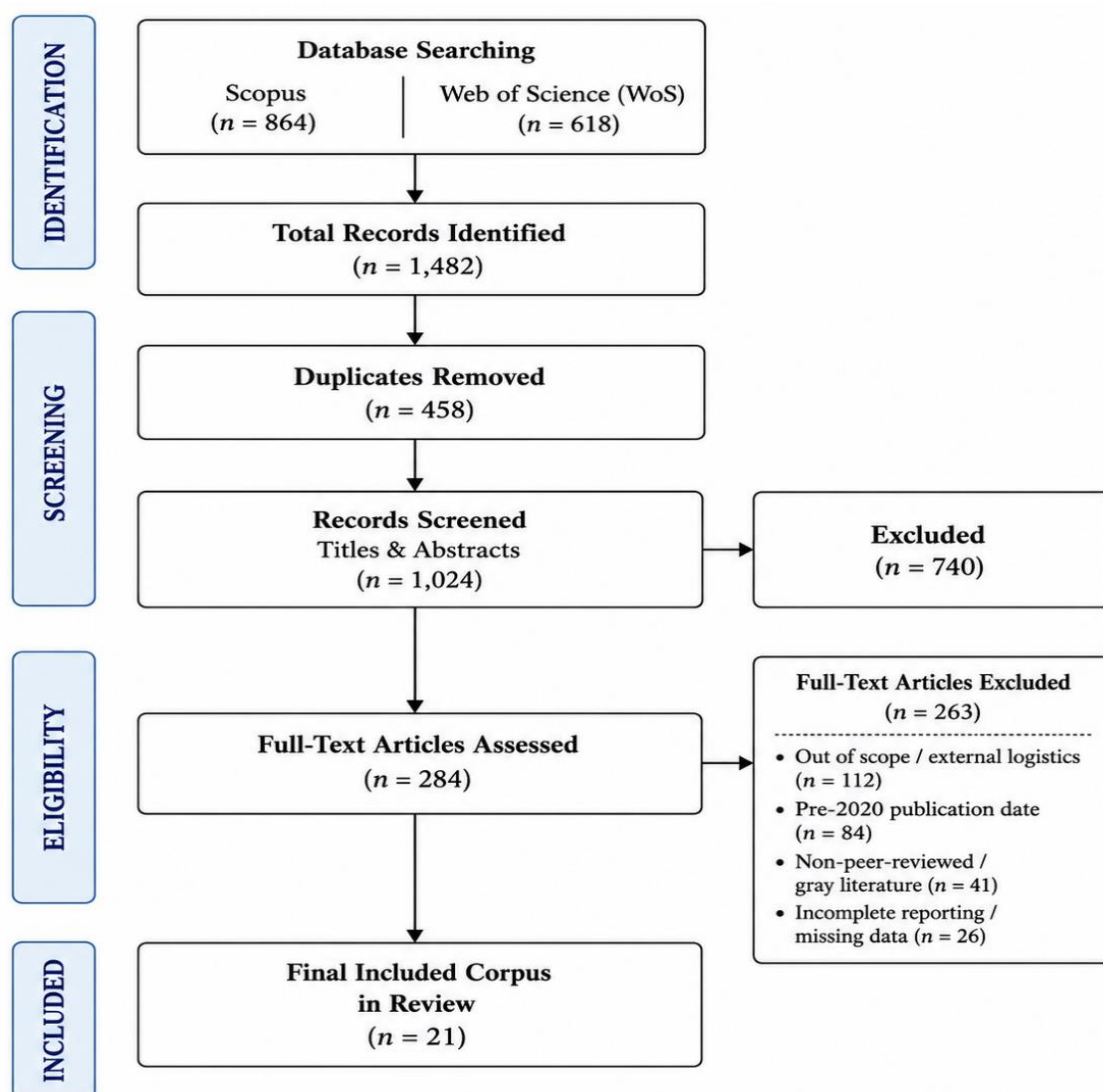


Figure 1: PRISMA Flow Diagram of The Systematic Literature Review Process.

Formal Quality Assessment Framework

An objective assessment of quality and relevance across the reviewed literature was conducted by evaluating each included study against a formal five-criterion Quality Appraisal (QA) checklist adapted from established systematic literature review protocols in industrial engineering and operations management. Each criterion was assessed using a three-point ordinal scale (0 = Unfulfilled, 1 = Partially Fulfilled and 2 = Fully Fulfilled), with cumulative scores across all five criteria summed to produce an overall Quality Score ranging from 0 to 10.

The first criterion, Objective Clarity (QA1), assessed whether the study clearly articulated its research questions, hypotheses or optimisation objectives. Methodological Rigour (QA2) evaluated the transparency and reproducibility of the mathematical formulation, algorithmic structure or empirical research design. Contextual Realism (QA3) examined whether the proposed model or approach incorporated dynamic, realistic operational constraints, such as picker fatigue, aisle congestion and variable order arrivals, rather than relying solely on simplified or frictionless assumptions. Validation Depth (QA4) assessed whether the reported algorithmic or theoretical findings were validated through real-world Warehouse Management System (WMS) operational logs, field experiments or rigorous benchmarking. Finally, Contribution to Knowledge (QA5) evaluated the extent to which each study contributed to theoretical development, Industry 5.0 ergonomics or joint decision optimisation within logistics operations. Two reviewers independently assessed the final corpus to enhance the reliability and consistency of the appraisal process. Inter-rater reliability was evaluated using Cohen's Kappa coefficient, with the result indicating a strong level of agreement between the reviewers. Any minor scoring discrepancies were subsequently resolved through joint re-examination and discussion until consensus was reached, ensuring the quality assessment was applied consistently across all included studies.

Study Characteristics and Corpus Synthesis

Table 1 presents the structured characteristics of the 21 included articles published between 2020 and 2026, detailing decision domains, research designs, operational contexts, primary variables and formal quality assessment scores.

Table 1: Study Characteristics, Operational Context and Quality Assessment Scores

Author(s) & Year	Decision Domain	Research Design	Operational Context	Primary Variables / Operational Focus	QA Score (/10)
Masae et al. (2020)	Picker Routing	Algorithmic SLR	Picker-to-Part Systems	S-shape, Largest Gap, exact TSP formulations, travel distance	10-Sep
Winkelhaus & Grosse (2020)	Digitalization	Literature Mapping	Logistics 4.0 / 5.0	Socio-technical systems, cyber-physical fulfilment, human autonomy	10-Sep
Briant et al. (2020)	Integrated Planning	Exact Mathematical	Order Batching & Routing	Linear programming formulations, lower bounds, joint optimisation	10-Aug
Cagliano et al. (2021)	Digitalization	Empirical Survey	Distribution Centres	WMS integration, Industry 4.0 tracking technologies, RFID adoption	10-Aug
Fragapane et al. (2021)	Automation & HRC	Systematic Survey	Intra-logistics & AMRs	AMR scheduling, dynamic decentralised control, fleet management	10-Sep
Glock et al. (2021)	Human-Centric	Conceptual Framework	Industry 5.0 Systems	Human-robot collaboration (HRC), ergonomic well-being, cobots	10-Sep
Neumann et al. (2021)	Ergonomics	Systematic Review	Operations Management	Human factors integration, worker fatigue, biomechanical	10-Aug

				strain	
Elbert et al. (2021)	Human-Factor Modelling	Controlled Experiment	Physical Simulation	Cognitive load, pick-to-light prompts, error detection rates	10-Aug
Brynzer et al. (2021)	Storage Assignment	Empirical Case Study	E-commerce Distribution	Class-based storage, SKU velocity, dynamic relocation errors	10-Aug
Schrotenboer et al. (2021)	Integrated Optimization	Mixed-Integer Model	Dynamic Fulfilment	Joint order batching and routing, picker blocking, aisle traffic	10-Aug
Page et al. (2021)	Systematic Protocol	Standard Guideline	SLR Reporting Protocol	PRISMA 2020 compliance, flow transparency, risk of bias	10-Oct
Li et al. (2022)	Dynamic Control	Deep Reinforcement	Continuous E-commerce	Real-time order dispatching, DRL routing, queue management	10-Sep
Fragapane et al. (2022)	Automation & HRC	Discrete Simulation	Decentralized Warehouses	AMR task allocation, dynamic scheduling engines, picker throughput	10-Aug
Kadir et al. (2023)	Industry 5.0	Socio-Technical Framework	Smart Warehousing	Human-centric automation, cobot ergonomics, worker safety protocols	10-Sep
van Deusen et al. (2023)	Routing & Congestion	Agent-Based Simulation	High-Density Picking	Multi-picker congestion, aisle blocking, travel delay penalties	10-Aug
Khoei et al. (2023)	Energy Optimization	Mathematical Model	Forklift Picker Routing	Energy-minimising routing, travel time, battery consumption	10-Aug
Mustapić et al. (2023)	Green Technology	Empirical Assessment	Transport & Logistics	Digitalisation, sustainable transport execution, operational impact	10-Jul
Rau & Chen (2024)	Integrated Planning	Hybrid Meta-Heuristic	Omni-channel Fulfilment	JOBASRP formulations, genetic algorithm heuristics order deadlines	10-Sep
Gamarra et al. (2024)	Operational Optimization	Simulation & Algorithm	Distribution Centres	Algorithmic travel distance reduction, batch processing	10-Aug
Zhang et al. (2025)	AI & Digital Twin	Field Validation & DRL	Smart E-commerce Hub	Live WMS execution logs, digital twins, dynamic AMR rerouting	10-Sep
Demircioglu et al. (2026)	Automation	Experimental ROS Test	Intralogistics Facility	AMR autonomous navigation, ROS integration, energy efficiency	10-Aug

THEMATIC FINDINGS AND SYNTHESIS

The systematic analysis of the evidence base reveals that order-picking accuracy and operational throughput are governed by a complex, multi-dimensional ecosystem. Rather than operating as isolated functional silos, warehouse processes interact continuously across technological, human, operational, organisational and environmental boundaries. Structuring the findings into four core thematic domains followed by a detailed cross-study comparative analysis provides a rigorous, systematic framework for synthesising the evidence.

Table 2: Five-Dimension Order Picking Accuracy Framework.

Dimension	Key Sub-components	Operational Impact
Technological	WMS, RFID, AMRs, DRL, Smart Picking Systems	Routing optimisation, error detection, automation

Human Factors	Ergonomics, fatigue, cognitive load, HRC	Learning/forgetting effects, physical strain, accuracy rates
Operational / Layout	Batching, routing, storage assignment	Congestion control, travel distance reduction
Organizational	SOPs, training, continuous improvement	Standardised execution, quality control
Environmental / Market	Order complexity, SKU profile, e-commerce demand	Demand spikes, small-batch processing pressure

Theme 1: Digitalisation, WMS Evolution and Tracking Technologies

The technological transition of warehouses reflects a shift from traditional manual and paper-based tracking systems towards digitalised, software-driven execution environments. This transition encompasses Warehouse Management Systems (WMS), digital warehouse infrastructures, real-time inventory tracking and data collection technologies, such as barcode scanning and Radio Frequency Identification (RFID), which incorporate confirmation checkpoints to enhance order-picking accuracy. The evidence base indicates that WMS software has evolved from basic material movement logging into a core component of digital execution platforms and Manufacturing Execution Systems (MES). Modern WMS platforms function as centralised control hubs that track real-time inventory locations, manage goods receipt and dispatch, generate pick lists and support the optimisation of picker sequencing and routing. Through the integration of data collection technologies, digital warehouse systems systematically reduce picking errors by enabling real-time verification throughout the picking process. Order-picking accuracy, defined as the correctness of items, quantities and customised configurations retrieved for outbound shipment, is primarily safeguarded through technological confirmation mechanisms. Barcode scanning, RFID tags and pick-location confirmation prompts require operators to verify items in real time, thereby preventing mispicks before items proceed to packing and shipping. In addition, modern WMS platforms generate detailed operational data that support optimisation algorithms and strategic decision-making models.

Across the examined studies, broad agreement exists that WMS digitalisation enhances order-picking accuracy and operational visibility compared with manual, paper-based picking systems. The literature consistently highlights the effectiveness of automated confirmation mechanisms, particularly barcode scanning at pick locations, in reducing outbound shipping errors. However, differences emerge in how WMS is conceptualised across the literature. While some studies primarily emphasise WMS as a tool for real-time inventory tracking and location management, others focus on its integration with broader supply chain execution systems, MES and automated decision-support algorithms. The literature also indicates a notable gap between advanced digital warehouse frameworks and actual industry practice. Although academic models frequently assume seamless WMS optimisation and integration, many smaller distribution centres continue to rely on basic spreadsheets or standalone tools, which may constrain scalability and operational accuracy. Methodologically, the literature demonstrates relatively strong conceptual consensus regarding the operational functions of WMS, particularly across bibliometric and systematic literature reviews. Nevertheless, existing studies frequently treat WMS as a "black box" that executes algorithms without considering practical software usability issues, integration challenges with legacy Enterprise Resource Planning (ERP) systems or delays in real-time execution.

Overall, digitalisation and WMS implementation represent foundational requirements for modern order fulfilment, particularly through the replacement of manual logging with real-time tracking and automated barcode- and RFID-based confirmation mechanisms. These technologies provide important safeguards against picking errors while improving operational visibility and supporting data-driven optimisation. However, the full potential of WMS digitalisation remains constrained by usability barriers, the continued reliance on basic software applications in practice and gaps in software–hardware integration.

Theme 2: Human Factors, Ergonomics and Learning/Forgetting Dynamics

Human factors play a critical role in determining order-picking accuracy and operational throughput, particularly through the influence of human operator characteristics, physical ergonomics, cognitive workload, fatigue and skill acquisition. Despite increasing levels of automation, manual order picking remains predominant in modern logistics, making human pickers key actors in overall system performance

and accuracy. Empirical and content-analytic studies consistently identify employee-related factors, including physical fatigue, cognitive overload, experience level and inadequate training, as important determinants of order-picking errors. Human behavioural characteristics, particularly learning effects over time and forgetting cycles associated with shift breaks or changes in storage locations, further influence warehouse operational performance and error rates.

A significant dimension of this theme concerns the mathematical modelling of worker learning and forgetting. Experimental and simulation studies demonstrate that human pickers experience learning effects, whereby picking times decrease predictably with repetition. Functional learning curves, including the Wright, De Jong and three-parameter hyperbolic models, have been shown to capture these performance improvements in industrial settings. However, operational changes such as storage reassignments can disrupt accumulated familiarity. When product storage locations are altered to optimise travel distance, pickers may experience forgetting effects, resulting in temporarily longer retrieval times and increased picking error rates as they adapt to new layout associations. In addition, ergonomic design and physical well-being are directly associated with picking accuracy. Poor shelf positioning, excessive bending or reaching and high levels of physical strain can accelerate fatigue and contribute to increased mispicks, particularly towards the end of work shifts.

The organisational dimension is further supported by evidence from adjacent high-risk operational sectors. Tarudin et al. (2018), in a study of oil and gas supply base personnel, found that workers' inclination towards safety compliance was influenced by structured procedures, supervisory reinforcement and perceived organisational commitment to safety. This suggests that improvements in picking accuracy, similar to safety compliance, are unlikely to be achieved through technological interventions alone without parallel investment in procedural discipline. Similarly, Kordi et al. (2018) demonstrated that structured workforce knowledge-building and empowerment initiatives in construction projects were associated with measurable improvements in operational performance. These cross-sectoral findings support the importance of formal training and knowledge transfer as essential complements to WMS-driven confirmation mechanisms in reducing operator error.

Table 3: Human Factor Determinants and Their Operational Impacts.

Variable / Determinant	Operational Mechanism	Impact on Accuracy and Time
Physical Fatigue and Strain	Repetitive lifting, poor ergonomics	Increases picking errors and slows throughput
Cognitive Load and SKU Variability	Complex order lines, tight fulfilment windows	Higher mispick risk without WMS prompts
Learning Effects	Repetition over time, growing familiarity	Reduces picking time systematically
Forgetting Effects	Storage reassignment, shift interruptions	Induces temporary delays and picking errors

Across different warehouse settings, industries and geographical regions, the empirical literature demonstrates broad agreement that human factors represent a major determinant of order-picking accuracy. Studies conducted across manufacturing, e-commerce and third-party logistics (3PL) sectors consistently associate fatigue and inadequate training with increased picking errors. However, a fundamental difference can be observed between operations research (OR) modelling literature and empirical human-factor studies. Traditional OR planning models commonly represent human pickers as deterministic execution agents with fixed, unvarying speeds, thereby overlooking human limitations and behavioural variability. In contrast, ergonomic and empirical studies demonstrate that worker productivity and accuracy fluctuate as a result of learning, fatigue and cognitive strain. A similar tension arises in relation to storage reassignment strategies. While some models advocate frequent dynamic storage reassignments to minimise theoretical travel distances, human-centric research indicates that frequent reassignment can trigger forgetting effects, potentially reducing picking accuracy and offsetting the expected benefits of travel-time reductions.

Methodologically, the literature benefits from controlled industrial experiments and empirical regression fitting to evaluate learning curves, including comparisons between the Wright and De Jong models, complemented by content analysis for systematically mapping human-related variables in logistics research. Nevertheless, human factors remain historically underrepresented in conventional mathematical warehouse planning models. Many OR models exclude human variables because of the mathematical complexity associated with representing non-deterministic human behaviours alongside highly complex combinatorial optimisation problems. Overall, the evidence indicates that human operators remain a critical determinant of order-picking performance, while conventional modelling paradigms frequently overlook their behavioural and physiological dynamics. Incorporating learning curves, forgetting effects, cognitive workload and ergonomic principles into warehouse planning models is therefore essential for developing more realistic, sustainable and error-resistant order-picking systems.

Theme 3: Operational Optimisation (Storage, Batching and Routing)

Operational decision-making in picker-to-parts warehouses encompasses several interdependent planning domains: internal layout design, storage assignment order batching and picker routing. These decisions primarily aim to minimise travel distance, reduce order-fulfilment time and mitigate order-picking errors. Travel time consistently represents the largest cost component in manual operations, accounting for over 50% of total picker activity time. Layout design (determined by aisle length, aisle width and cross-aisle placement) establishes the structural foundation for travel efficiency, with cross-aisles enabling pickers to change aisles without travelling to warehouse ends. Storage assignment determines stock-keeping unit (SKU) allocation based on turnover velocity; class-based and volume-based storage policies, such as those utilising the Cube-per-Order Index (COI), systematically position high-frequency items near main picking aisles to outperform random assignment. Order batching consolidates multiple orders into a single picking tour, driving substantial travel savings for small-item e-commerce orders. Finally, picker routing governs the specific traversal path through storage aisles, executed via heuristics (e.g., S-shape, Largest Gap and Mid-Point methods) or exact optimisation algorithms (e.g., Branch-and-Bound and Genetic Algorithms).

Table 4: Comparison Of Operational Storage, Batching and Routing Policies.

Policy Dimension	Primary Benefit	Trade-off / Limitation
Volume / Class-Based Storage	Dramatically reduces travel distance	Requires continuous WMS monitoring and re-sorting
Order Batching Strategies	Highest overall distance savings for e-commerce	Increases downstream sorting complexity
Heuristic Routing (S-shape / Midpoint)	Simple for pickers to follow; lowers errors	Sub-optimal travel paths compared to exact algorithms
Cross-Aisle Addition (Design)	Provides travel shortcuts across aisles	Consumes storage capacity and adds traversal space

The literature demonstrates broad agreement that integrating operational decisions, particularly combining order batching with volume or class-based storage, delivers greater travel-time reductions than optimising individual decisions in isolation. Studies consistently indicate that order batching yields the highest relative efficiency gains when average order sizes are small. Nevertheless, trade-offs exist in layout design, particularly regarding cross-aisle additions. Although extra cross-aisles reduce average travel distances by enhancing routing flexibility, their impact is non-linear; excessive cross-aisles increase travel time because pickers must traverse the additional floor space they occupy. Discrepancies also arise in routing execution. While exact mathematical formulations, such as Branch-and-Bound and Travelling Salesman Problem (TSP) abstractions, generate theoretical minimum-distance paths, heuristic policies like the S-shape method are preferred in practice because their predictable, easily memorised routes reduce cognitive load and minimise picking errors.

Methodologically, the literature exhibits high quantitative precision through mathematical programming, TSP abstractions, Genetic Algorithms (GA) and discrete-event simulations. However, a major limitation remains the reliance on isolated sub-problem formulations. Most studies evaluate storage assignment,

routing or order batching sequentially rather than addressing the Joint Order Batching, Assignment, Sequencing and Routing Problem (JOBASRP) as an integrated decision matrix. Furthermore, these models frequently assume static order arrivals and frictionless aisles, overlooking practical operational constraints like picker blocking and traffic congestion. Overall, layout, storage, batching and routing optimisation form the foundation of order-picking research. Although combining class-based storage with order batching achieves substantial travel-time savings, current models remain constrained by sub-optimisation, treating interconnected decisions independently while omitting real-world physical constraints.

Theme 4: Industry 5.0, Human-Robot Collaboration and Advanced Automation

Driven by exponential e-commerce growth and surging SKU variability, warehousing systems are rapidly transitioning from manual operations to automated and semi-automated execution environments. This transformation encompasses automated material handling systems, smart picking technologies and Industry 5.0 paradigms, placing strong emphasis on Autonomous Mobile Robots (AMRs), collaborative robots (cobots), Task Scheduling Engines (TSE), dynamic Deep Reinforcement Learning (DRL) architectures and smart picking infrastructures. Rather than replacing human operators entirely, contemporary research increasingly emphasises human-centric automation and Human-Robot Collaboration (HRC) to boost throughput, alleviate physical strain and minimise retrieval errors. Within HRC frameworks, AMRs or Automated Guided Vehicles (AGVs) execute long-distance horizontal aisle transport, leaving delicate, high-dexterity retrievals to human operators at localised picking stations. This division of labour eliminates excessive walking time, a primary driver of fatigue and operational delay, while preserving human adaptability for non-standard items.

Integrating these collaborative environments relies on WMS platforms coupled with TSEs and smart picking tools (e.g., pick-to-light, voice-directed picking and RFID-assisted workstations) to coordinate routes and verify picks in real time. Furthermore, modern control systems leverage DRL and Agent-Based Modelling (ABM) to enable real-time, dynamic optimisation of picking sequences, inventory allocation and storage assignment within fluid order streams. The literature broadly agrees that combining AMRs, smart picking systems and WMS control substantially improves performance by reducing travel times and cutting mispicks, making hybrid HRC systems a flexible, scalable alternative to rigid automation. However, adoption barriers persist. While engineering models highlight high throughput and near-zero error rates, operational studies stress that high capital expenditure, complex integration, layout rigidity and maintenance demands make full automation impractical for many small and medium-sized enterprises (SMEs). Crucially, unlike conventional automation research that treats human pickers as error sources to be eliminated, Industry 5.0 literature positions humans as essential, adaptable partners whose safety and cognitive well-being must be prioritised.

Methodologically, the literature demonstrates an emerging application of advanced artificial intelligence frameworks, particularly Deep Reinforcement Learning (DRL) and Agent-Based Modelling (ABM), to resolve dynamic, multi-variable warehouse decision problems in close conceptual alignment with Industry 5.0 principles. Nevertheless, existing Human-Robot Collaboration (HRC) models remain predominantly theoretical or simulation-based, lacking sufficient empirical validation within complex industrial environments. Furthermore, few models incorporate real-time safety constraints, sensor failures or human-robot aisle interference under severe congestion. Overall, advanced automation and HRC represent an essential frontier in modern warehousing. By pairing robotic travel efficiency with human handling dexterity through WMS- and DRL-driven control architectures, HRC systems offer immense potential to accelerate fulfilment speed and accuracy while embedding the human-centric principles of Industry 5.0.

Table 5: Automation And Human-Robot Collaboration (HRC) System Profiles.

Technology / Paradigm	Primary Operational Role	Human and Efficiency Impact
Autonomous Mobile Robots (AMRs)	Long-distance item/tote transport	Eliminates picker travel fatigue, cuts errors
Industry 5.0 Human-Centric Systems	Human-centric ergonomic alignment and safety	Enhances well-being, sustains accuracy

Smart Picking (Pick-to-Light / Voice)	Real-time guidance and pick location confirmation	Drastically lowers mispick rates
Deep Reinforcement Learning (DRL)	Simultaneous, dynamic process optimisation	Adapts picking to dynamic real-time orders

Cross-Study Synthesis and Identified Literature Contradictions

Synthesising findings across all four thematic domains reveals four major literature contradictions and operational tensions across the research landscape.

Table 6: Summary Of Major Literature Contradictions and Operational Tensions.

Contradiction Focus	Perspective A	Perspective B	Synthesis
System determinism vs. human behavior	Classical OR: pickers act deterministically at static speeds	Empirical/human factors: performance varies with fatigue and learning	Algorithmic routing optimises theoretical travel time, but accuracy depends heavily on human execution and cognitive load
Warehouse layout (cross-aisles)	Adding cross-aisles lowers travel time via routing flexibility	Excessive cross-aisles increase travel time due to empty spatial traversal	A nonlinear relationship exists; cross-aisles yield diminishing returns and can impede space utilisation if over-implemented
Storage reassignment frequency	Frequent reassignment minimises theoretical travel distance	Dynamic changes trigger worker forgetting effects and errors	Reassignment frequency must be balanced against the cognitive cost of relearning storage locations
Automation adoption	Full automation/robotics minimises human error and labour dependency	High capital costs and system rigidity make full automation impractical for many facilities	Hybrid Human-Robot Collaboration (HRC) offers a balanced, scalable middle ground

DISCUSSION

Synthesising findings across the technological, human, operational and automated dimensions demonstrates that order-picking accuracy and efficiency cannot be achieved through isolated interventions. Instead, warehouse operations function as a socio-technical ecosystem where digital platforms, spatial design, algorithmic rules and human behavioural characteristics continuously interact. WMS technologies provide essential data capture and confirmation mechanisms to eliminate retrieval mispicks, yet their ultimate efficacy hinges on underlying layouts, storage policies and routing algorithms. Crucially, both technological and operational strategies are mediated by human pickers: high-velocity class-based storage or aggressive order batching can induce physical fatigue, aisle congestion and cognitive strain if ergonomics and learning/forgetting dynamics are ignored. Emerging Industry 5.0 Human-Robot Collaboration (HRC) frameworks reconcile this tension by delegating horizontal travel to Autonomous Mobile Robots (AMRs) while leveraging human dexterity for picking, thereby aligning system throughput with worker well-being.

The theoretical implications of these findings advance operations management and logistics research in three key directions. First, they mark a paradigm shift from deterministic operations research (OR) towards behavioural operations. Unlike classical models that treat pickers as uniform execution agents, integrating learning curves, forgetting dynamics, fatigue accumulation and cognitive workload into mathematical formulations bridges human behavioural science with warehouse control. Second, the findings advocate transitioning from sequential to joint optimisation frameworks. Optimising sub-problems independently yields local optima that compromise total performance, reinforcing the necessity of Joint Order Batching, Assignment, Sequencing and Routing Problem (JOBASRP) formulations. Third, the evidence formalises Industry 5.0 cyber-physical logistics, positioning automation as a collaborative partner rather than a

replacement for human labour. Combining HRC with smart picking tools establishes a foundation where WMS scheduling engines drive throughput while safeguarding worker ergonomics, safety and psychological well-being.

From a practical perspective, this review offers actionable strategies for warehouse managers, distribution centre directors and logistics practitioners seeking zero-defect fulfilment. First, managers should execute synergistic policy combinations, such as pairing volume- or class-based storage with intelligent order batching, to maximise travel-distance savings in small-item e-commerce distribution. Second, the cognitive cost of worker forgetting must be managed during dynamic storage reassignments; frequent SKU relocations increase error rates, meaning reassignments should occur during low-volume periods accompanied by targeted WMS retraining. Third, multi-layered verification, including mandatory barcode scanning, pick-to-light prompts or RFID checks, must be embedded into WMS workflows to catch mispicks before shipping. Finally, modular HRC solutions provide a practical alternative to capital-intensive full automation, enabling mid-sized facilities to deploy AMRs for aisle transport while concentrating human labour on high-dexterity, localised picking.

Methodologically and historically, this synthesis highlights both research evolution and critical future directions. While early review literature focused on isolated layout, storage or routing heuristics and subsequent studies introduced human-factor content analysis, contemporary research increasingly addresses Industry 5.0, HRC, Deep Reinforcement Learning (DRL) and joint decision-making. However, methodologically, the field remains dominated by theoretical OR models and discrete-event simulations reliant on synthetic datasets and frictionless layout abstractions. Future research must prioritise empirical validation using live industrial WMS execution logs. Furthermore, capturing non-deterministic human behaviour, dynamic real-time order streams and physical congestion requires combining analytical algorithms with Agent-Based Modelling (ABM) and DRL within controlled experimental and digital-twin environments.

In summary, three core insights emerge from this cross-thematic synthesis. First, human factors bound algorithmic efficiency; mathematically optimal paths or storage layouts fail if they exacerbate operator fatigue, cognitive load or location forgetting. Second, integrated joint models are non-negotiable, as sequential process optimisation creates local efficiencies that ultimately undermine overall system throughput. Addressing modern e-commerce demands requires the unified optimisation offered by JOBASRP frameworks. Third, hybrid HRC represents the most viable path forward for next-generation warehousing. By harmonising robotic transport efficiency with human handling dexterity under dynamic WMS control, logistics operations achieve an optimal, sustainable balance between fulfilment velocity, picking accuracy and Industry 5.0 human-centric principles.

RESEARCH GAPS AND FUTURE DIRECTIONS

Synthesising the literature highlights critical theoretical, methodological and operational gaps that constrain the translation of academic research into industrial practice. Theoretically, classical operations research (OR) models heavily abstract picker behaviour, treating human operators as static entities while lacking mathematical mechanisms for fatigue, cognitive strain, physical ergonomics or location-forgetting dynamics. Furthermore, prevailing literature remains fragmented due to isolated sub-problem formulations that optimise storage allocation, batching, routing and sequencing independently. Consequently, comprehensive formulations for the integrated Joint Order Batching, Assignment, Sequencing and Routing Problem (JOBASRP) remain severely underdeveloped owing to the computational complexity of jointly solving these interdependent decisions.

Methodologically and contextually, academic models exhibit a pervasive over-reliance on synthetic datasets, hypothetical layouts and frictionless aisle assumptions. Very few studies validate algorithmic performance using primary industrial field data or live WMS execution logs. Moreover, existing routing and batching models rely predominantly on static, offline order files, failing to capture the continuous, dynamic order arrivals inherent to modern e-commerce and quick-commerce environments. Operational models also frequently omit physical constraints, such as multi-picker aisle congestion, picker blocking, narrow-aisle

safety protocols and vertical rack picking, while remaining heavily biased towards generic retail warehousing rather than specialised contexts like cold-chain pharmaceuticals or high-density 3PL hubs.

Addressing these structural weaknesses requires structuring future research around five strategic priority domains: integrated JOBASRP optimisation, Industry 5.0 human-centric logistics, dynamic real-time control, Human-Robot Collaboration (HRC) and traffic-balanced storage design. Integrated JOBASRP frameworks must evaluate joint batching, routing and storage under real-world constraints via hybrid meta-heuristics and Deep Reinforcement Learning (DRL). Simultaneously, Industry 5.0 logistics must embed worker ergonomics, cognitive fatigue and learning/forgetting cycles using Agent-Based Modelling (ABM) and physiological tracking. Dynamic real-time control should leverage live WMS data streams, DRL and digital twins for continuous AMR fleet dispatching, while HRC research requires dynamic task-sharing protocols validated through field trials. Finally, traffic-balanced storage design should employ correlated layouts and traffic-smoothing algorithms to mitigate physical congestion.

Advancing these research domains demands that future mathematical models move beyond single-variable optimisation to simultaneously address batching, storage, sequencing and routing. Objective functions must directly incorporate cognitive and physical worker constraints to balance throughput velocity with ergonomic well-being. The discipline must transition from offline batch processing towards dynamic online control platforms, utilising warehouse digital twins connected to live WMS feeds to facilitate adaptive AMR rerouting. As collaborative automation matures, researchers must establish standardised human–robot task allocation protocols, driven by task scheduling engines capable of reallocating transport duties based on real-time picker fatigue and localised aisle congestion.

Translating these future directions into practice requires targeted action across academia, industry and policy sectors. Academic researchers must prioritise empirical model validation using real-world operational WMS logs obtained through industry partnerships, alongside non-deterministic human performance variables. Logistics managers should adopt modular, scalable automation, such as AMRs paired with smart WMS guidance, supported by multi-layered verification checkpoints rather than investing in capital-intensive, high-risk full automation. Finally, industry policy bodies should formulate standardised best-practice guidelines for workplace ergonomics, Industry 5.0 human-centric logistics and safe human–robot interaction in shared picking aisles, ultimately bridging the gap between theoretical modelling and industrial reality.

CONCLUSION

This systematic literature review provides a comprehensive, evidence-based synthesis of Warehouse Management Systems (WMS) order-picking optimisation and order-picking accuracy. Order picking remains the most resource-intensive, labour-demanding and costly warehouse activity, accounting for 55% to over 65% of total operating expenses. Driven by global e-commerce expansion, decreasing order sizes, high Stock Keeping Unit (SKU) diversity and compressed fulfilment windows, warehousing operations have progressively transitioned from manual tracking towards digitalised, software-driven execution environments. Synthesising evidence across technological, human, operational organisational and environmental dimensions demonstrates that order-picking performance is governed by a complex socio-technical ecosystem. Modern WMS platforms, Radio-Frequency Identification (RFID) and automated barcode scanning provide critical verification mechanisms that intercept errors at retrieval, while combining class-based storage with intelligent order batching yields substantial travel-distance reductions. Concurrently, human factors (including fatigue, cognitive workload, physical strain, learning curves and location-forgetting dynamics) remain fundamental determinants of picking accuracy. Advanced automation, particularly modular Human-Robot Collaboration (HRC) pairing Autonomous Mobile Robots (AMRs) for horizontal transport with human operators for dexterous picking, offers a flexible, ergonomic alternative to rigid full automation.

The review advances logistics, operations research and supply chain literature through four primary contributions. First, it establishes an integrative socio-technical framework bridging operations research with behavioural science, demonstrating how human cognitive, ergonomic and learning dynamics mediate algorithmic efficiency. Second, it identifies critical literature contradictions, including tensions between

deterministic mathematical assumptions and non-deterministic worker fatigue, cross-aisle layout trade-offs, dynamic storage reassignments and location forgetting and capital-intensive full automation versus hybrid HRC flexibility. Third, it exposes widespread methodological homogeneity across existing research, specifically an over-reliance on synthetic simulation data, static order files and frictionless layout abstractions, thereby underscoring the urgent need for empirical field validation. Fourth, the review articulates a structured research roadmap centred on the Joint Order Batching, Assignment, Sequencing and Routing Problem (JOBASRP), Industry 5.0 human-centric logistics and dynamic AI-driven control using Deep Reinforcement Learning (DRL) and Agent-Based Modelling (ABM).

Despite adopting a transparent, systematic protocol, three methodological limitations warrant acknowledgement. First, the evidence base was synthesised from indexed peer-reviewed journal articles and reviews; consequently, non-indexed industry reports and regional publications were excluded. Second, the screening criteria were restricted to English-language publications, introducing potential publication and language bias. Third, substantial methodological heterogeneity across included studies, encompassing mathematical programming, discrete-event simulation, empirical experiments and systematic reviews, precluded quantitative meta-analysis, necessitating a narrative and thematic synthesis strategy.

Translating warehouse management research into meaningful industrial practice demands closer collaboration between academic researchers and logistics practitioners to align theoretical models with operational realities. From a managerial standpoint, logistics practitioners should avoid isolated process optimisation. Instead, managers must pair class-based storage with batching rules, enforce multi-layered WMS barcode confirmation mechanisms, restrict storage reassignment frequencies to mitigate worker forgetting and deploy scalable AMR fleets. From a research perspective, future academic formulations must abandon static, deterministic assumptions by embedding physical constraints (e.g., aisle congestion and picker blocking), human behavioural dynamics (fatigue and learning/forgetting cycles) and dynamic real-time order streams into joint optimisation models. Crucially, these models must be validated against empirical field data to confirm their industrial utility. Integrating digital execution platforms, operational joint optimisation and Industry 5.0 human-centric ergonomics enables modern distribution centres to achieve resilient, highly accurate and high-velocity order fulfilment while systematically minimising operational errors.

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