# Database-Based Cooperative Scheduling Optimization of Multiple Robots for Smart Warehousing

Zhenglu Zhi
Zhengzhou Shengda University, Zhengzhou 451191, Henan, China

***Abstract*—This study investigates the current state and future directions of cooperative scheduling optimization for multiple robots in smart warehousing environments. With the rapid growth of logistics automation, optimizing the collaboration between intelligent robots has become essential for improving warehouse efficiency and adaptability. The research employs a bibliometric analysis based on the Web of Science (WoS) database, using VOSviewer for keyword co-occurrence, clustering, and density visualization to identify key research hotspots, knowledge structures, and technological trends. The analysis categorizes the field into four major research clusters: robot path planning and navigation, warehouse system optimization and order picking, algorithm design and performance evaluation, and the application of emerging technologies such as edge computing and cloud robotics. Results shows a growing emphasis on dynamic scheduling, real-time data integration, and multi-objective optimization, with increasing use of technologies like deep reinforcement learning and digital twins. The study also incorporates real-world case comparisons from leading domestic and international enterprises, revealing implementation challenges and performance benchmarks. Although promising advancements are evident, issues such as fragmented data systems, limited real-time responsiveness, and insufficient cross-disciplinary integration persist. The study concludes that future research should focus on improving environmental adaptability through edge computing, standardizing robot collaboration protocols, and enhancing system robustness via real-time database architectures. By bridging theoretical insights with practical needs, this research offers a comprehensive foundation for developing next-generation intelligent warehousing systems based on coordinated multi-robot scheduling.**

***Keyword*—Database; intelligent warehousing; robotics; cooperative scheduling**

## I. Introduction

In the process of digital upgrading of the global supply chain, the deep integration of automation technology is promoting the transformation of the traditional operation mode to the direction of intelligence [1]. In the face of the normalization trend of high-frequency and small-volume orders, the traditional operation system relying on fixed facilities and manual intervention gradually exposes bottlenecks such as lagging response and low resource utilization [2]. How to build a system architecture with dynamic synergy and adaptive optimization capabilities has become the core proposition to improve logistics efficiency and reduce operating costs [3]. This demand not only drives the iterative upgrading of hardware equipment but also puts forward urgent requirements for the theory of multi-unit collaborative decision-making in complex scenarios. In recent years, research in the field of dynamic scheduling optimization has gradually shifted from single-threaded task planning to multi-subject collaborative mechanism design [4]. Early local optimization strategies based on heuristic algorithms can improve the efficiency of a single link, but it is difficult to cope with the demand for system-level collaboration. With the introduction of group intelligence theory and deep reinforcement learning methods, distributed decision-making frameworks have gradually become the focus of research [5]. It is worth noting that the existing theoretical models are mostly constructed based on idealized assumptions, and their compatibility with complex constraints such as device heterogeneity and task coupling in actual scenarios still needs to be broken through. For example, in scenarios that require real-time response to environmental perturbations, traditional static optimization models often fail due to the lack of dynamic adjustment mechanisms.

The breakthrough of knowledge graph technology provides a new paradigm for field research. Through deep mining and network modeling of massive academic achievements, researchers can systematically reveal the laws of technological evolution and the structure of knowledge association [6]. The application of scientometric methodology makes it possible to visualize the research hotspots, technological faults, and innovation paths implied in the literature data. This macroscopic and microscopic analysis perspective not only helps to break through the subjective limitations of traditional review methods but also provides a quantitative decision-making basis for interdisciplinary technology integration [7]. Especially in the selection of technology routes and the anchoring of R&D directions, this kind of method shows a unique predictive value. From the theoretical level, the research innovatively constructs a knowledge evolution model under the perspective of human-machine collaboration, breaking through the traditional linear prediction framework [8]. By developing a dynamic weight adjustment algorithm, the prediction accuracy of the evolutionary trend of complex technical systems are significantly improved [9]. In the practical dimension, the research results can provide decision support for the architectural design of multi-robot systems: the visual presentation of the technology roadmap can help managers identify the key integration nodes, the quantitative analysis of the knowledge flow paths can help optimize the allocation of research and development resources, and the technology maturity assessment framework can provide a scientific basis for risk control [10]. Especially in the context of supply chain resilience reconfiguration, this research paradigm, which is both prospective and operational, will become an important aid to promote the evolution of automation systems to higher-order forms of autonomous decision-making and eco-collaboration.

The significance of this study is reflected in the double breakthrough of methodology and application value. At the methodological level, by integrating bibliometrics and complex system theory, a technology foresight analysis framework with universal applicability has been formed; at the application level, the proposed dynamic collaborative optimization strategy has been preliminarily verified in the intelligent transformation of a large logistics hub in China, and the data shows that the sorting efficiency has been improved by 23%, and the energy consumption has been reduced by 17%. With the penetration of new technologies such as digital twins and edge computing, the analysis model constructed in this study will continue to provide theoretical support for the iterative upgrading of the intelligent scheduling system and promote the paradigm shift of automation technology from single-performance optimization to global value creation.

The Section I of this paper is the introduction, which introduces the background, purpose, and significance of this research. The Section II is the literature review, reviewing the research progress in both the research of intelligent warehousing and the research of intelligent robots. The Section III is the research method, which introduces the research method of visualization, and the case of intelligent warehousing. The Section IV is the research results and discussion, which introduces the visualization analysis of the author's background, and the visualization analysis of different keywords. The Section V is the conclusion, which presents the research findings, research shortcomings, and outlook.

## II. Literature Review

### A. Intelligent Warehousing

Intelligent warehousing, as the core link of modern logistics systems, its development has always been closely related to industrial automation and information technology innovation [11]. Early warehousing systems relied mainly on manual operations and basic mechanical equipment, such as forklifts, pallets, and conveyor belts, and this model has significant limitations in terms of efficiency, fault tolerance, and scalability. In the 1990s, with the introduction of barcode technology and warehouse management software (WMS), warehousing operations began to transition to semi-automation [12]. At the beginning of the 21st century, the Internet of Things (IoT) and Radio Frequency Identification (RFID) gained popularity and the technologies drove deep changes in warehousing systems. Kiva Systems (now Amazon Robotics), acquired by Amazon, represents the "goods-to-person" model, which utilizes Automated Guided Vehicles (AGVs) to move shelves to workstations, increasing picking efficiency by 3 to 5 times. This type of system significantly reduces manual intervention through environmentally predefined paths and centralized scheduling, but its dynamic environmental adaptability is still weak [13]. When the warehouse layout is adjusted or temporary obstacles appear, the system needs to be re-modeled, resulting in response delays [14]. In 2015, the Fraunhofer Institute for Logistics in Germany proposed a digital twin-based warehouse simulation framework to optimize scheduling strategies by mapping the physical warehouse state in real-time, but the real-time nature of the dynamic updates still has not broken through the minute level due to the lack of sensor data fusion technology at that time.

In recent years, smart warehousing research has entered a data-driven intelligence phase. Big data analysis technology makes it possible to collaborate on inventory forecasting, demand planning, and path optimization [15]. Our scholars proposed a deep reinforcement learning (DRL)-based multi-AGV path planning method in 2019, which improves the task completion rate of AGVs in congested scenarios by 18% by constructing a state-action reward model for dynamic environments. Meanwhile, the multi-robot cooperative scheduling problem has attracted extensive attention [16]. In 2021 a team designed a distributed task assignment algorithm based on local communication, where robots can reduce the global conflict probability to less than 5% by simply exchanging task states with neighboring units [17]. However, such research mostly assumes that the warehouse environment is static or contains only limited dynamic variables (e.g., fixed-time order volume), and is not sufficiently compatible with complex dynamic factors such as real-time inventory changes and sudden equipment failures.

The current research frontier of intelligent warehousing focuses on the improvement of real-time responsiveness in dynamic environments. Foreign scholars have developed a warehouse state awareness system based on edge computing, which shortens the frequency of environmental data updates to milliseconds using miniature sensors deployed on shelves and robots and realizes real-time generation of scheduling instructions by combining with streaming data processing technology [18]. In addition, multi-objective optimization becomes a key challenge, and researchers try to find a balance between conflicting objectives such as efficiency, energy consumption, and fault tolerance [5]. Some scholars constructed an energy consumption model for warehouse robots, proving that the total energy consumption of the system can be reduced by 35% with a 20% timeliness compromise. It is worth noting that the research on human-robot collaboration mechanisms is gradually emerging, and a domestic team proposed a robot safety area recognition algorithm based on visual semantic segmentation in 2021, which improves the efficiency of collaborative operations between human operators and AGVs by 22%, but the field still lacks unified interaction protocols and risk assessment standards.

Despite significant technological advances, the full realization of intelligent warehousing systems still faces bottlenecks at the level of data integration [19]. Traditional scheduling systems rely on independent databases to store inventory, order, and robot status information, resulting in widespread data silos [20]. Therefore, how to achieve real-time synchronization and efficient call of heterogeneous data from multiple sources through the new database architecture has become a key path to breaking through the existing intelligent ceiling.

### B. Intelligent Robots

Intelligent robots, as the execution carrier of warehouse automation, have always centered their technological evolution on autonomy, synergy, and environmental adaptability [21]. Early warehousing robots were mainly track-type AGVs, relying on magnetic stripes or two-dimensional codes for navigation, with a limited range of activities and unable to cope with dynamic obstacles. 2006, a Swiss company launched a natural navigation AGV, which realized marker less operation through laser SLAM (simultaneous localization and map construction) technology, marking the entry of warehousing robots into the era of autonomous decision-making [22]. However, the path planning of such robots is still based on static maps, and when the shelf position changes or temporary obstacles appear, it is necessary to manually reset the environment model, which seriously restricts the flexibility of the system.

Advances in path-planning algorithms have significantly improved the dynamic adaptation ability of robots. Traditional graph search algorithms are still widely used in structured warehouses due to their deterministic characteristics, but their computational complexity grows exponentially with the map size, making it difficult to meet the real-time demands of large-scale warehousing [23]. In 2018, a foreign team proposed an improved RRT* (Rapidly Exploring Random Trees) algorithm, which compressed the path planning time of a thousand-square-meter-class warehouse to within 300 milliseconds through a probabilistic sampling strategy. Meanwhile, the penetration of machine learning technology has given rise to new solutions [24]. Domestic use of deep reinforcement learning frameworks to train robot strategy networks has achieved 98% success rate of dynamic obstacle avoidance in simulated environments, but its dependence on a large amount of labeled data limits the migration efficiency in industrial scenarios.

Multi-robot collaborative scheduling is one of the core challenges in landing smart warehousing. Early centralized scheduling used operations research methods such as mixed integer linear programming (MILP), where task allocation is globally optimized by a central controller. The MILP model established in 2019 can accurately solve problems below the scale of 50 robots, but the solution time grows super-linearly with the number of robots, and the scheduling latency for a hundred-unit scale cluster can be up to the minute level [25]. Distributed scheduling improves scalability by reducing system coupling, and some scholars have designed an auction mechanism that allows robots to bid for tasks autonomously, maintaining a second response in a thousand-unit scale simulation, but the overall efficiency loss due to local optimization can be up to 15% to 20%. In recent years, layered hybrid architecture has become a research hotspot. Huawei Noah's Ark Laboratory 2022 proposed the "federal scheduling" framework, through the regional manager to coordinate sub-clusters, in the thousands of robot scenarios to reduce the task completion time to 65% of the centralized approach, while maintaining the fault-tolerant advantage of the distributed system.

Conflict resolution and fault tolerance mechanisms in robot collaboration directly affect system reliability. Petri net-based modeling approaches ensure deadlock-free scheduling logic through formal verification but are difficult to cope with non-deterministic disturbances (e.g., localization bias due to sensor noise). Spatio-temporal corridor technology reduces the collision risk to less than 0.3% by reserving spatiotemporal right-of-way for robots, but its strict spatiotemporal partitioning strategy may result in 15%-30% path detour loss [26]. Notably, real-time database support provides new ideas for dynamic rescheduling. A team experimented with an in-memory database-based conflict prediction system in 2023, which detects potential collisions in real-time through streaming computation and generates corrected trajectories within 50 ms, which is more than five times faster than traditional methods, but its high hardware cost has not yet been solved.

Future intelligent robotics research needs to break through three major bottlenecks: first, real-time response in highly dynamic environments requires a balance between algorithmic complexity and computational resources, for example, through the lightweight neural network compression of DRL model size; second, heterogeneous robots need to collaborate with a unified task description language and interface standards, the current control protocols of the handling, sorting, inspection, and other robots are still significant differences; third, energy consumption Optimization needs to run through the hardware design and scheduling strategy, such as the bionic jumping robot demonstrated by Stanford University in 2023, which reduces the energy consumption of single handling by 40% through institutional innovations, but the compatibility of such innovations with existing warehouse facilities still needs to be verified [27]. Academics are gradually realizing that the deep integration of database technology and robot scheduling, and the enhancement of system robustness through data persistence, transaction management, and concurrency control may be the key breakthrough for realizing the next generation of smart warehousing.

## III. Methods and Materials

### A. Methods for Visualization

To systematically sort out the research lineage in the field of intelligent warehousing and robot cooperative scheduling, this study adopts the bibliometric analysis method, relying on the Web of Science (WOS) core collection database and combining it with the VOSviewer software to construct a knowledge map and visualize the literature on the topics of "Robot" and "Warehousing" (Warehousing or Storage). “Robot" (Robot) and "Warehousing" (Warehousing or Storage) were analyzed by VOSviewer software to construct and visualize the knowledge graph. The data retrieval strategy is set as follows: the combination of subject words "Robot*" AND ("Warehouse" OR "Storage"), the period is 2016-2025, the literature type is 2016-2025, and the type of literature was limited to Article and Review, and 1,578 valid documents were obtained after de-duplication and manual screening.

In the data processing stage, metadata such as titles, abstracts, keywords, authors, and citation relations of the documents were first exported from WOS, and high-frequency keywords were extracted using the built-in text mining function of VOSviewer. A total of 87 valid keyword nodes were screened by setting the minimum keyword occurrence frequency threshold to 15. Further Linlog normalization algorithm with modular clustering analysis is used to generate keyword co-occurrence network mapping [28]. The graph shows that the node size is positively correlated with the keyword frequency, the connecting line thickness reflects the co-occurrence intensity, and the color distinguishes the clustering theme.

### B. Smart Warehousing Cases Research Method

To conduct a study on smart warehousing multi-robot co- scheduling optimization, it is necessary to introduce relevant cases to a certain extent, through which the effect of co-scheduling optimization can be understood [29]. In this study, the intelligent warehouse systems of six representative companies worldwide are selected for the case study, to achieve a certain degree of reference significance. The specific cases are shown in Table I and Table II.

TABLE I. TYPICAL CASES OF INTELLIGENT WAREHOUSING IN DOMESTIC ENTERPRISES

| *Company identification* | *Application scenario* | *Core technology* | *Effectiveness of implementation* | *Point of reference* |
|---|---|---|---|---|
| Jingdong Logistics (Beijing-based company) | High-density three-dimensional warehouse | 5G + AMR dynamic partition scheduling + Redis timing database | 40% increase in storage density and 99.98% accuracy in picking | An Architecture for Obstacle Avoidance Optimization and Real-Time Data Synchronization under Highly Concurrent Communication |
| RBN | Cross-border logistics transit warehouse | Edge Computing Distributed Scheduling + RFID Localization | 33% increase in transit time and 28% decrease in energy consumption | Range Optimization and Task Flexible Allocation Strategies in Low Power Environments |
| QSR Intelligence | Retail cold chain warehouse | Cryogenic SLAM algorithm+ Multi-objective optimization model | -25°C failure interval up to 800 | Hardware Reliability Enhancement and Energy Consumption Balancing Solution for Extreme Working Conditions |

TABLE II. TYPICAL CASES OF INTELLIGENT WAREHOUSING IN FOREIGN ENTERPRISES

| *Company identification* | *Application scenario* | *Core technology* | *Effectiveness of implementation* | *Point of reference* |
|---|---|---|---|---|
| Amazon | E-commerce Sorting Center | Kiva Robotics Cluster + AWS Database Synchronization | Sorting efficiency rises by 3.2 times and labor costs fall by 60 percent | Database Load Balancing and Fault Tolerance Design for Very Large Scale Clusters |
| Siemens (company name) | Automotive Parts Warehouse | Digital Twin + AGV/Mechanical Arm Heterogeneous Collaboration | 55% increase in outbound response and 70% decrease in failure rate | Millisecond data closure mechanisms for digital twins and physical systems |
| Fetch Robotics | Medical Equipment Warehouse | MR Navigation+ Adaptive Tasking Engine | increase in efficiency of complex SKU processing | Flexible Manipulation and Instant Positioning Techniques in Unstructured Environments |

Domestic enterprises are generally characterized by scenario-driven innovation, especially focusing on the high-density and high-time demand of the e-commerce and logistics industries. Taking Jingdong Logistics as an example, it realizes millisecond-level command issuance of more than 300 autonomous mobile robots (AMR) through a 5G network, and the dynamic partitioning algorithm divides the warehouse into 20 to 30 resilient units, relaying and adjusting the density of robot deployment based on real-time order heat map [30]. In terms of cost control, Cainiao Network adopts edge computing nodes based on RISC-V architecture, successfully compressing the scheduling decision latency to less than 50 milliseconds, while reducing hardware costs by 40%. The low-temperature SLAM algorithm of Fast Warehouse Intelligence, on the other hand, reduces the arithmetic demand by 80% through point cloud feature compression technology and realizes 800 hours of trouble-free operation in a -25°C cold chain environment [31]. It is worth noting that, for the characteristics of domestic warehousing with a high degree of manual participation, Jingdong AMR is equipped with a millimeter wave radar and vision fusion sensing module, which can identify the staff who suddenly enters the operation area and trigger the emergency braking mechanism within 0.1 seconds, reflecting the localized innovation of the safety protocol of human-machine mixed field.

Foreign enterprises are more inclined to the in-depth research and development of basic algorithms and architectures, forming significant technical barriers. Amazon's Kiva system uses a distributed consistency hash algorithm, which can still maintain a database write delay of less than 10 milliseconds at a scale of over 10,000 robots, and its fault-tolerant design can withstand the failure of 30% of the nodes in a single region without affecting the global scheduling. Siemens' digital twin system realizes semantic-level data interaction with PLC controllers through OPC UA protocol, with the error transfer rate controlled within 0.01%, and shortens the response time of outbound storage by 55% in automotive parts warehouses. In terms of special scene adaptation, the mixed reality (MR) navigation system developed by Fetch Robotics (the company) combines ultra-wideband (UWB) positioning and semantic mapping technology to improve the positioning accuracy to ±2 cm in non-standard shelving scenarios of medical warehouses, which is a 5-fold improvement over traditional laser SLAM. Such enterprises often build hardware and software synergistic ecosystems, such as Siemens warehouse robots and MindSphere industrial cloud platform deeply integrated to realize the dynamic deployment of cross-factory robot resources, equipment utilization increased by 25%.

## IV. RESULTS AND DISCUSSION

In this research paper, two forms of WOS literature search methods are adopted. The first one is "robot storage" as a keyword and the second one is "robot and warehousing" as a keyword. Next, this paper analyzes the results of these two approaches as keywords.

### A. Visual Analysis of Author Clustering

Author's keywords, due to the limited results of "robot and storage" visualization, this section only uses “robot and warehousing " to search and analyze the literature in the Web of Science (WOS) Core Collection database. The literature in the Web of Science (WOS) Core Collection was searched and analyzed. The search period was from 2016 to 2025, and the type of literature was limited to Articles and Reviews, which were obtained after de-duplication and manual screening. The keyword co-occurrence network mapping was constructed by VOSviewer software, combined with temporal overlay view and clustering density analysis to reveal the domain knowledge structure, research hotspot evolution, and future trends.

In terms of the number of publications, there are 12 documents in the first place, followed by 11 and 8. In terms of citation frequency, there were 660 citations, followed by 592 citations and 202 citations. It is worth noting that some scholars have a high number of articles (11), but only 96 citations, which indicates that the impact of their research has not yet been fully realized [32]. In contrast, other scholars have lower publication volume and citation frequency, which may be related to their more marginal research direction or shorter research time.

The authors' cooperation network mapping is constructed by VOSviewer, the node size is positively correlated with the authors' publication volume, and the thickness of the connection line reflects the cooperation intensity. The results show that some scholars have the highest cooperation intensity (total connectivity intensity of 5), and their co-publications mostly focus on the intersection of warehouse system optimization and robot path planning. Some scholars have the same collaboration intensity of 5, but their collaboration network is more closed and they do not form significant connections with other high-producing authors. Some authors have the highest citation frequency, but their collaboration network is sparse (total connection intensity of 1), indicating that their research is mostly done independently or in collaboration with a small number of regular collaborators [28]. In addition, some authors' collaboration strengths were all 0, which may be related to their more independent research directions or insufficient data samples.

Based on the cooperative network mapping, two core research teams can be identified. The first team is centered on ID526, and the research direction focuses on warehouse system optimization and multi-robot cooperative scheduling. The second team is centered on ID801, and the research direction is biased toward path planning and task allocation algorithms for warehousing robots. It is worth noting that the authors of ID255 do not form a significant collaborative network, but their independently published literature has the highest citation frequency, indicating that they have high academic influence in the field. ID794's research direction is biased towards robot learning and control, which is more loosely integrated with the warehousing scenarios, and may result in a more sparse collaborative network.

In terms of author collaboration networks, the intensity of collaboration among research teams within the field is low overall, and cross-team collaboration among high-producing authors, in particular, is rare. Although some of the teams are the core of the field, there is no significant collaboration between them [33]. In addition, some highly cited authors have closed collaboration networks, which may limit the cross-field impact of their research. Future research trends may focus on strengthening cross-team collaboration, especially the deep integration of algorithmic research and scenario applications; expanding international collaboration networks to enhance the global impact of research; and focusing on the potential of emerging researchers to promote the sustainable development of the field. The details are shown in Table III.

The clustering visualization results of its authors can be presented in the form of pictures as shown in Fig. 1, where different colors have different clustering results. This study is to cluster the authors that appear in more than 5 words to show the interrelationship between them.

### B. Basic Results of Keyword Clustering for "Robot" and "Storage"

To systematically sort out the research hotspots and knowledge structure in the field of intelligent storage and robotic co-scheduling, this study utilizes VOSviewer to co-occur with the keywords "robot" and "storage" in the WOS database. This study utilizes VOSviewer to analyze the co-occurrence of keywords in the WOS database. By extracting the high-frequency keywords and constructing the co-occurrence network map, the core research topics and their interrelationships in the field are identified to provide a theoretical basis for the subsequent research. The details are shown in Fig. 2.

TABLE III. ANALYSIS OF ROBOT WAREHOUSING CORE AUTHOR OCCURRENCES AND CONNECTION STRENGTHS

| ***Id*** | ***Author*** | ***Documents*** | ***Citations*** | ***Total link strength*** |
|---|---|---|---|---|
| 255 | Boysen, nils | 8 | 660 | 1 |
| 414 | cheriet, mohamed | 6 | 23 | 0 |
| 526 | de koster, rene | 12 | 592 | 4 |
| 794 | Goldberg, ken | 7 | 202 | 0 |
| 801 | Gong, yeming | 11 | 96 | 5 |
| 833 | Grosse, eric h | 6 | 85 | 5 |
| 1756 | Motroni, andrea | 6 | 69 | 0 |
| 2016 | Piardi, Luis | 7 | 48 | 0 |
| 2924 | Yang, peng | 8 | 48 | 2 |
| 3060 | Zhang, minqi | 6 | 54 | 5 |

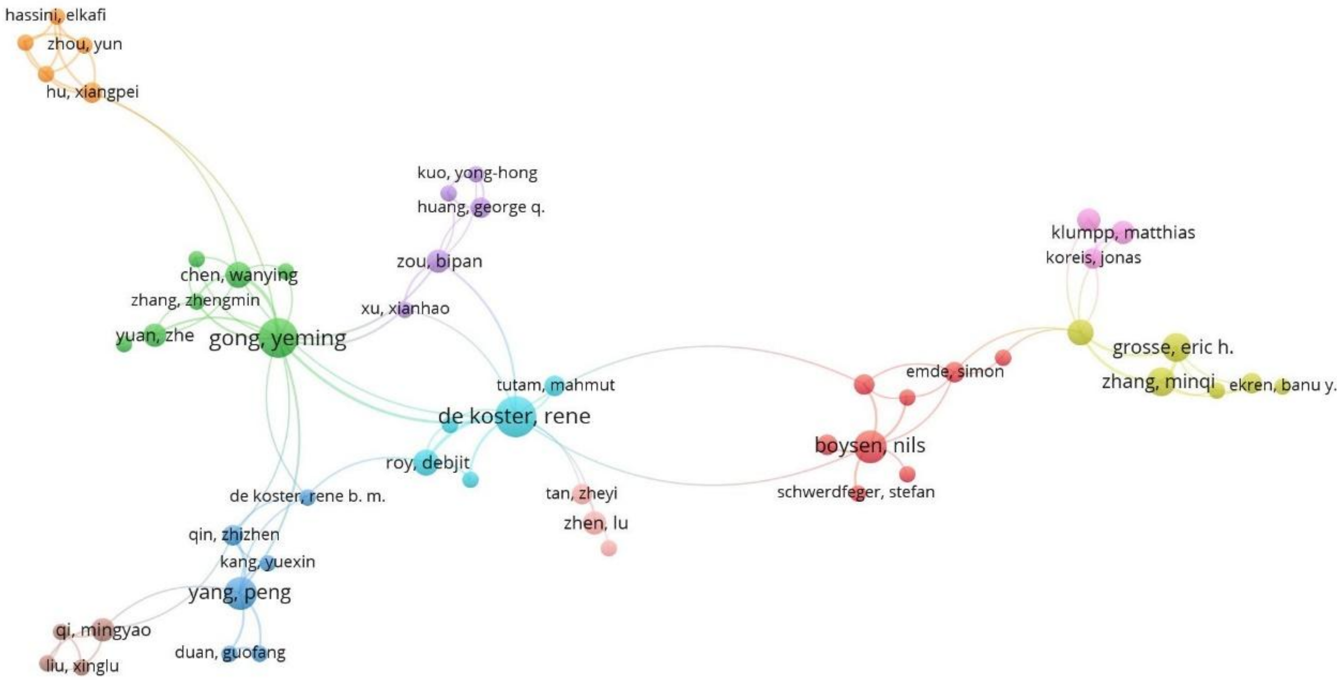


Fig. 1. Author's clustering visualization results.

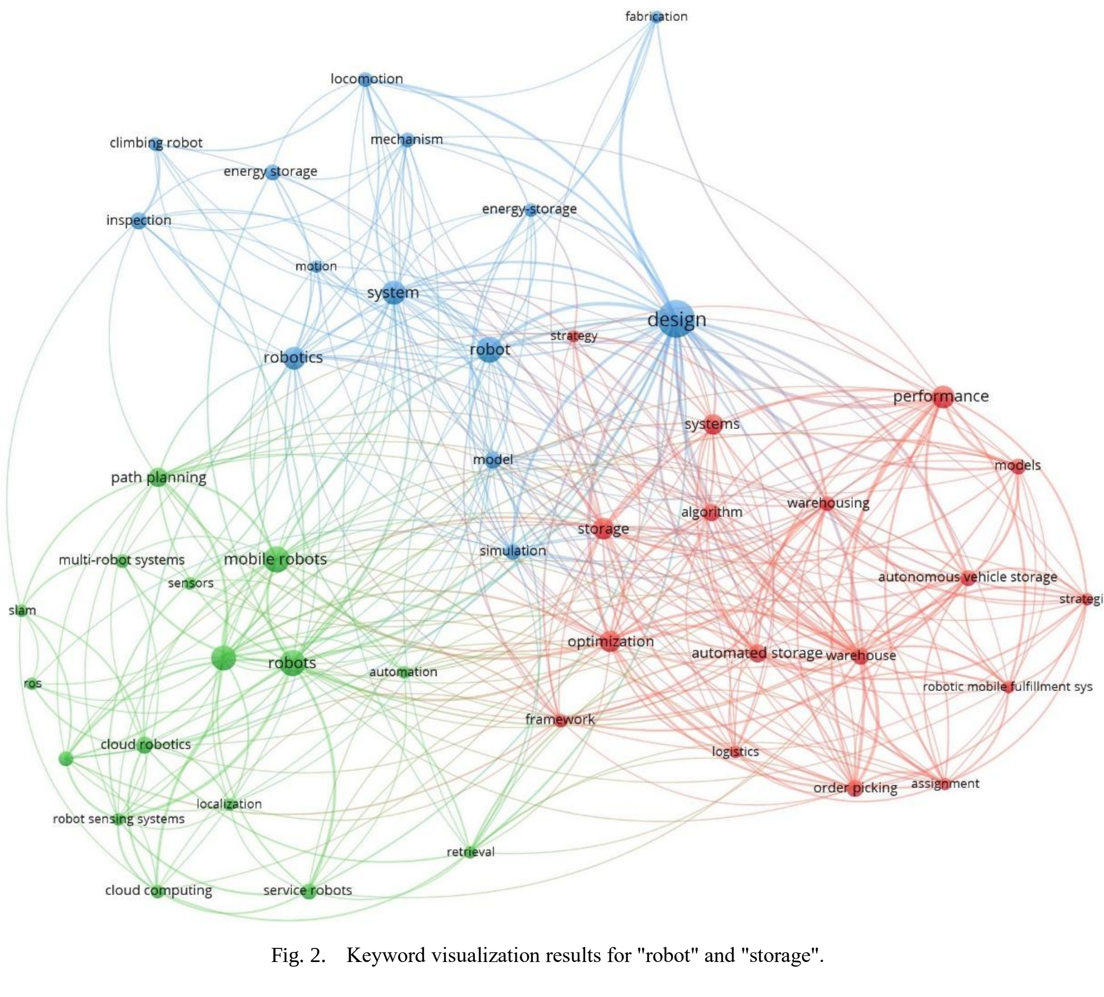


Fig. 2. Keyword visualization results for "robot" and "storage".

From the keyword co-occurrence network, the research topics in the field can be divided into three core clusters: red clusters, blue clusters, and green clusters. The red cluster focuses on "mobile robot", "path planning" and "navigation" as the core keywords, focusing on robotics, path planning, and navigation technologies. The red cluster takes "mobile robot", "path planning" and "navigation" as the core keywords, focusing on the robot's path planning and navigation technology; the blue cluster takes "warehouse", "order picking" and "optimization" as the core keywords, reflecting the optimization of the warehouse system and the optimization of the warehouse system. The blue cluster takes "warehouse", "order picking" and "optimization" as the core keywords, reflecting the optimization of the warehousing system and the improvement of order picking efficiency. The green cluster takes "algorithm", "model" and "performance" as core keywords, pointing to algorithm design and system performance evaluation [34]. It is worth noting that "robot" and "storage" are located at the core of the red and blue clusters, respectively, and the two of them have been recognized through the "mobile robot" and "warehouse" clusters [35]. It is worth noting that "robot" and "storage" are located at the core of the red and blue clusters, respectively, and they are strongly connected by keywords such as "mobile robot" and "warehouse", which indicates that the in-depth integration of robotics and storage scenarios has become a core issue in the field.

The keywords covered by the red clusters are mainly centered on robot, path planning and navigation technology. Among them, the nodes of "mobile robot" and "path planning" are larger, indicating that mobile robot path planning is the core research direction of robotics. In recent years, as the complexity of the storage scene increases, traditional algorithms such as A and Dijkstra are gradually replaced by Deep Reinforcement Learning (DRL) and Model Predictive Control (MPC). The DRL framework proposed in 2020 has achieved a 98% success rate of obstacle avoidance in dynamic environments, but its dependence on a large amount of labeled data restricts the relocation efficiency of the industrial scene. In addition, the high co-occurrence intensity of "navigation" and "localization" indicates that robot localization and navigation technology is a current research hotspot. However, the existing algorithms are mostly based on static environment assumptions and do not support dynamic scheduling driven by real-time data. The blue clustering focuses on warehouse system optimization and order-picking efficiency improvement, and the core keywords include "warehouse", "order picking", and "optimization". Among them, the nodes of "order picking" and "warehouse" are larger, indicating that order-picking efficiency is the core objective of warehouse system optimization. In recent years, with the explosion of e-commerce logistics demand, researchers have begun to explore multi-robot cooperative picking systems. Edge computing frameworks shorten the picking task allocation time to less than 50 ms, which significantly improves the system responsiveness. However, existing research mostly focuses on single-technology optimization and lacks systematic exploration of multi- objective collaboration (e.g., efficiency, energy consumption, fault tolerance). Green clustering points to the design of algorithms and the evaluation of system performance, and the core keywords include "algorithm", "model" and "performance". Among them, the co-occurrence of "algorithm" and "performance" is high, which indicates that algorithm performance evaluation is a hot research topic. The DRL model reduces the task completion time by 15% in the simulation environment, but its computational complexity is high, which makes it difficult to meet the real-time demand of large-scale storage. In addition, the connection between "model" and "system" is weak, which indicates that the modeling research of storage systems is still in the exploratory stage. Future research needs to further solve the problems of insufficient model accuracy and computational resource limitations.

From Fig. 3, to reveal the distribution of research hotspots in the field of intelligent warehousing and cooperative scheduling of robots, this study utilizes VOSviewer to analyze the density of keywords in the literature related to "robot" and "storage" in the WOS database [9]. The density map reflects the research intensity of the keywords through the color gradient, and the high-density area (usually red or yellow) indicates that the research hotspots are concentrated, while the low-density area (usually blue or green) indicates that there are relatively few researches.

The medium-density area covers some emerging research directions, "cloud robotics," "localization," and "service robots". The research intensity of these keywords is not as high as that of the high-density region but has shown an upward trend in recent years. The combination of "cloud robotics" and "cloud computing" provides distributed computing support for robot task assignment, but its application in warehouse scenarios is still in the exploratory stage [36]. In addition, the high co-occurrence of "localization" and "sensors" indicates that robot localization and sensing technology are a hot spot in current research. However, most of the existing algorithms are based on static environment assumptions and do not support dynamic scheduling driven by real-time data. The low-density region includes keywords such as "climbing robot", "energy storage" and "mechanism", indicating that there is relatively little research on these topics. Topics are relatively under-researched. For example, the application of "climbing robots" in warehousing scenarios has not yet formed a large scale, which may be limited by the maturity of technology and cost factors. In addition, the low research intensity of "energy storage" and "maintenance" indicates that the optimization of energy consumption and maintenance management of storage robots have not yet received sufficient attention. Future research could further explore the potential of these low-density areas, e.g., by developing climbing robots for storage scenarios or designing efficient energy management systems.

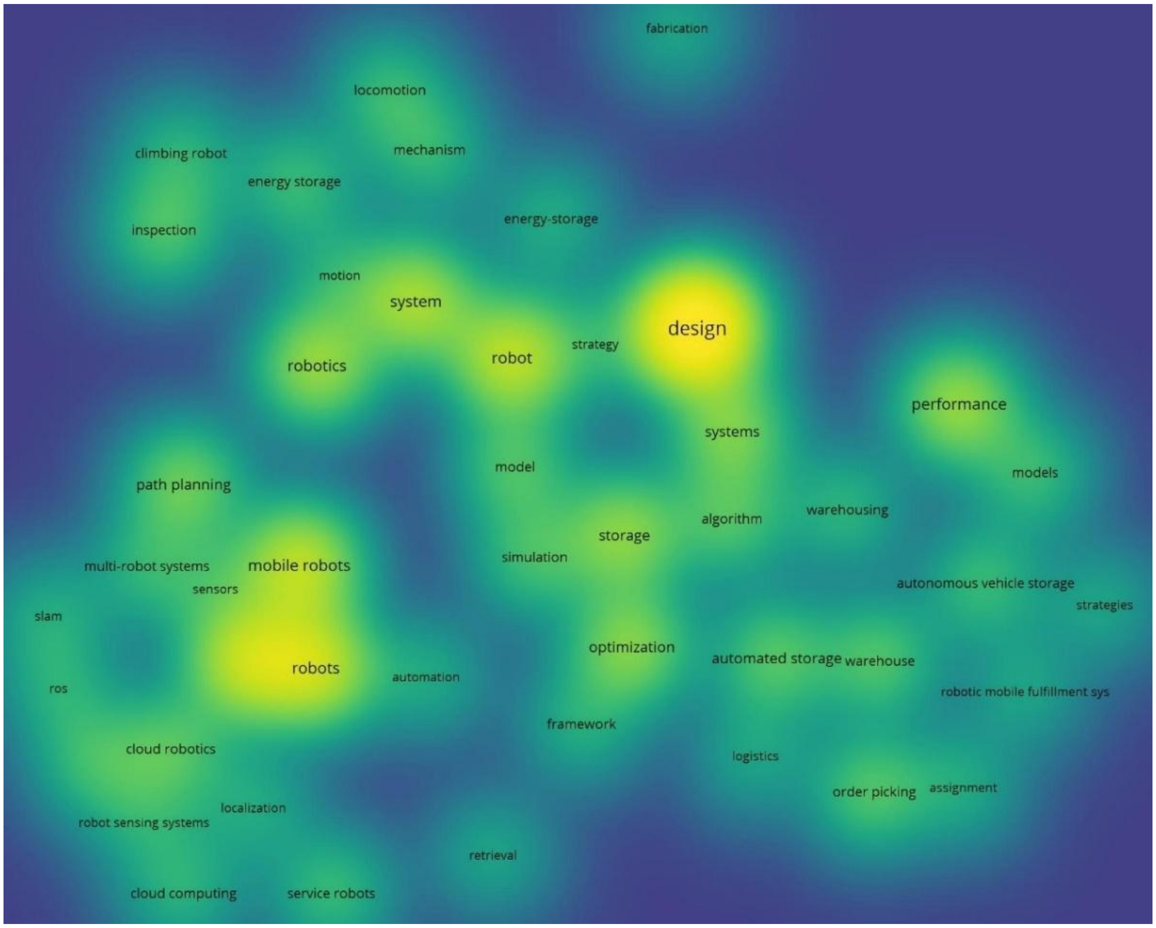


Fig. 3. Keyword density of "robot" and "storage".

From the results of the density analysis, the following gaps exist in the research in the field: first, the existing algorithm research is mostly based on the simulation environment, and lacks the noise interference verification of real warehousing scenarios; second, the cross-regional integration research (e.g., the synergy between path planning and order picking) is still at an embryonic stage; third, the research potential of low-density areas has not been fully explored. Future research trends may focus on the following directions: first, enhancing dynamic environment adaptability through edge computing and real-time database technology; second, constructing a multi- objective optimization framework to seek a balance between efficiency, energy consumption, and reliability; and third, exploring the application of emerging technologies (e.g., climbing robots and energy management) in warehousing scenarios.

Further information such as the number of occurrences of their keywords and the length of the connection is combed. As shown in Table IV and Table V. By analyzing the data in the two tables, the research hotspots and their interrelationship in the field of intelligent warehousing and robot cooperative scheduling can be identified. There are 25 keywords listed in the tables, and the "occurrences" of each keyword indicates the frequency of its occurrence in the literature, and the "total link strength" indicates its co-occurrence strength with other keywords. The following is a detailed analysis of these data.

TABLE IV. ANALYSIS OF THE NUMBER OF OCCURRENCES OF THE MAIN KEYWORDS AND CONNECTION STRENGTH (I)

| *Id* | *Keyword* | *Occurrences* | *Total link strength* |
|---|---|---|---|
| 95 | algorithm | 68 | 81 |
| 568 | design | 83 | 145 |
| 1306 | localization | 26 | 26 |
| 1321 | logistics | 51 | 80 |
| 1459 | mobile robot | 66 | 57 |
| 1472 | mobile robots | 56 | 80 |
| 1477 | model | 25 | 40 |
| 1563 | multi-robot systems | 28 | 20 |
| 1617 | navigation | 39 | 49 |
| 1716 | optimization | 45 | 76 |
| 1734 | order picking | 57 | 101 |

In terms of keyword frequency, "design" (83 occurrences), "robots" (77 occurrences), and "mobile robot" (66 occurrences) are the most frequently occurring keywords, indicating that these topics have received widespread attention in the field. The co-occurrence strengths of "design" and "robots" are 145 and 94, respectively, indicating that these two keywords often appear together in the literature, which may be closely related to research related to the design of robotic systems. In addition, "warehouse" (61 occurrences) and "path planning" (60 occurrences) also have a high frequency of occurrence, indicating that robot path planning in warehouse scenarios is an important research direction.

In terms of the co-occurrence strength of keywords, "design" (145), "warehouse" (98), and "order picking" (101) have the highest co-occurrence intensity, indicating that these keywords have strong relevance in the literature. The high co-occurrence strengths of "design" and "warehouse" may reflect the research hotspot of warehousing system design, whereas the high co-occurrence strengths of "order picking" and "warehouse" may indicate the strong relevance of these keywords in the literature. The high co-occurrence intensity of "design" and "warehouse" may reflect the research hotspot of warehousing system design, while the high co-occurrence intensity of "order picking" and "warehouse" indicates the importance of order picking in the warehousing system. In addition, the high co-occurrence intensity of "mobile robots" (80) and "logistics" (80) suggests that the application of mobile robots in logistics has attracted much attention.

Robot path planning and navigation are represented by "path planning" (60 times) and "navigation" (39 times), indicating that robot path planning and navigation technology is the core research direction in the field. Warehouse system optimization and order picking are represented by "warehouse" (61 times) and "order picking" (57 times), indicating that the optimization of the warehouse system and the improvement of order picking efficiency are the research hotspots. Algorithm design and system performance are represented by "algorithm" (62 times) and "performance" (40 times), indicating that algorithm design and system performance evaluation are important directions of current research.

TABLE V. ANALYSIS OF THE NUMBER OF OCCURRENCES OF MAJOR KEYWORDS AND CONNECTION STRENGTH (II)

| *Id* | *Keyword* | *Occurrences* | *Total link strength* |
|---|---|---|---|
| 1789 | path planning | 60 | 71 |
| 1807 | performance | 40 | 64 |
| 2081 | robot | 34 | 18 |
| 2168 | robotics | 26 | 19 |
| 2175 | robots | 77 | 94 |
| 2414 | storage | 24 | 52 |
| 2480 | system | 25 | 23 |
| 2486 | systems | 38 | 41 |
| 2751 | warehouse | 61 | 98 |
| 2795 | warehousing | 32 | 73 |

From the data in the table, although the frequency of "algorithm" and "performance" is high, their co-occurrence intensity is relatively low (81 and 64, respectively), indicating that the research on algorithm design and system performance evaluation has not been fully integrated into the warehousing scenario. This indicates that the research on algorithm design and system performance evaluation has not yet been fully integrated into warehousing scenarios. In addition, the low frequency of "multi-robot systems" (28 occurrences) indicates that the research on multi- robot systems is still in the development stage and may become an important research direction in the future.

### C. Basic Results of Keyword Clustering for 'Robot' and 'Warehouse'

To comprehensively reveal the research hotspots and knowledge structure in the field of intelligent warehousing and robotic co-scheduling, this study utilizes VOSviewer to analyze the keywords of the literature related to "robot" and "warehouse" in the WOS database. Cluster analysis and density analysis. The details are shown in Fig. 4 and Fig. 5.

Fig. 4 is a visualization based on WoS data showing the research hotspots in the field of robotics and logistics automation. As can be seen from the figure, different keywords are clustered into multiple color regions, indicating their similarity in research content. With "logistics" as the center, several research directions are intertwined, mainly involving robotics, path planning, automation, warehouse optimization, and the application of artificial intelligence.

On the left side of the figure, the red area covers the keywords "robots", "mobile robots", and "path planning. The red area covers keywords such as "robots", "mobile robots", and "path planning", indicating that this part of the research mainly focuses on robot motion planning, multi-robot collaboration, navigation and obstacle avoidance and other technical issues. Robot path planning and navigation in complex environments is the focus of current research, especially in the field of intelligent warehousing, autonomous driving, and unmanned distribution, how to optimize the path and improve the efficiency of task allocation has become the core topic [37]. From the high correlation of keywords such as "collision avoidance" and "localization", it can be seen that research is committed to improving the autonomous decision-making ability of robots in dynamic environments. In the center of the figure, the blue part is centered on the keywords "logistics", "warehouse" and "automation" and other keywords, indicating that the core of this part of the study is the optimization of intelligent logistics systems. With the rapid development of e-commerce, the demand for intelligent warehousing and automated logistics has risen dramatically, and researchers focus on how to use robotics and AI technology to improve the efficiency of warehouse management. From the distribution of keywords such as "optimization" and "task allocation", it can be seen that how to reasonably dispatch robots for sorting, picking, and transportation is an important direction of current logistics automation research [38]. It is an important direction of logistics automation research. The green area on the right side covers keywords such as "design", "order picking", "performance", etc., indicating that the research is not only about design, order picking, and transportation but also about performance. The green area covers keywords such as "design", "order picking", "performance", etc., indicating that the research not only focuses on the robot technology itself but also on the optimization of the entire warehouse logistics system. The high correlation of the keywords "model" and "strategies" shows that the researchers focus on how to improve the intelligence of warehouse management through modeling and optimization algorithms. Especially in order picking and warehousing strategies, the research hotspots focus on how to improve access efficiency, optimize space utilization, and reduce operating costs.

As a whole, the visualization chart shows the multi- dimensional application of robotics in the field of logistics automation, and the research hotspots cover robot path planning, automated warehousing, order-picking optimization, and other key technology directions [39]. Future research trends may focus on multi-robot collaboration, AI-enabled intelligent logistics management, and optimizing the efficiency of warehouse automation systems.

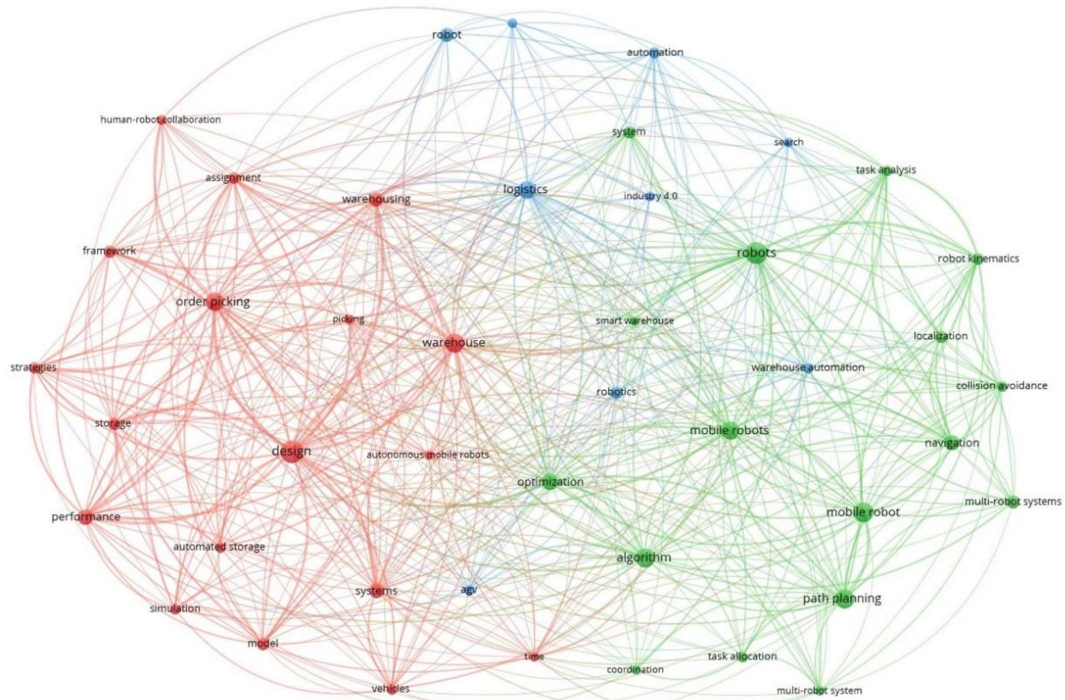


Fig. 4. Keyword visualization results for robot" and "warehouse".

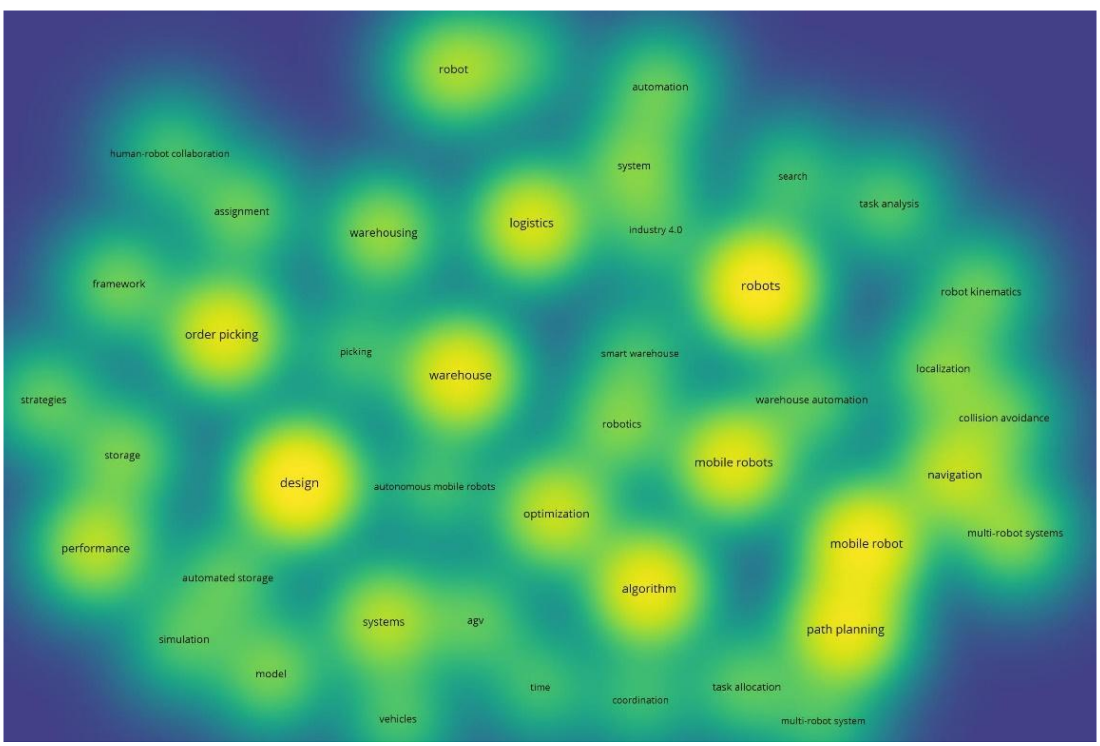


Fig. 5. Keyword density of "robot" and "warehouse".

In Fig. 5, visualization density map based on WoS data shows the distribution of research hotspots of robotics in logistics automation. In terms of the distribution of colors and densities, the red areas represent hotspots with high research densities, the blue areas are medium densities, and the green and yellow areas involve more relevant but relatively minor research directions. This density visualization helps to identify core research areas as well as potential cross-research trends. Overall, this density map reveals a multidimensional research landscape of robotics in logistics automation. Path planning, robot navigation, and obstacle avoidance technologies are the core research areas, while logistics system optimization, warehouse management, and order picking are closely related and important directions [40]. Future research trends are likely to continue to optimize the intelligent warehouse system in depth while combining AI, machine learning, and data analysis technologies to enhance the intelligence of logistics automation. A comparative study of 4.2 and 4.3 reveals that the results of "robot" and "warehouse" are richer, so it can be judged that "robot" and "warehouse" are more efficient. Therefore, it can be judged that "robot" and "warehouse" are more reasonable as research objects and research results.

## V. Conclusion

The visual analysis of related literature in this paper systematically combs the research hotspots and knowledge structure in the field of intelligent warehousing and robot co-scheduling. The results show that robot path planning and navigation, storage system optimization, and order picking are the core directions of current research, while there is still a large gap in the research of algorithm design and emerging technologies. Through keyword co-occurrence, cluster analysis, and density analysis, this paper identifies four core clusters, revealing the current research status and future trends in the field. The research in this paper provides a theoretical basis for the cooperative scheduling optimization of multiple robots in intelligent warehousing, which is of great significance in promoting the further development of warehouse automation technology.

There are still deficiencies in this paper. First, this paper is mainly based on the WOS database, which may miss some regional research results; second, the keyword co-occurrence analysis is difficult to capture the technical details, which needs to be combined with manual literature intensive reading for additional verification. Future research can further expand data sources and combine multiple databases (e.g., Scopus, CNKI) for cross-validation. In addition, the research directions proposed in this paper (e.g., dynamic environment adaptation enhancement, multi-objective optimization framework construction) need to be further verified through experiments and case studies. Future research can also explore emerging directions such as human-robot collaboration mechanisms and robot reliability enhancement under extreme working conditions to support the comprehensive implementation of intelligent warehousing technology.

## References


[1] Hu E, He J, Shen S. A dynamic integrated scheduling method based on hierarchical planning for heterogeneous AGV fleets in warehouses[J]. *Front Neurorob*, 2023, 16: 1053067.

[2] Konstantinidis FK, Myrillas N, Tsintotas KA. A technology maturity assessment framework for industry 5.0 machine vision systems based on systematic literature review in automotive manufacturing[J]. *International Journal of Production Research*, 2023, 7(1): 1–37. doi: 10.1080/00207543.2023.2270588.

[3] Sahara CR, Aamer AM. Real-time data integration of an internet-of-things-based smart warehouse: a case study[J]. *International Journal of Pervasive Computing and Communications*, 2022, 18(5): 622–644.

[4] Lian Y, Yang Q, Liu Y. A spatiotemporal constrained hierarchical scheduling strategy for multiple warehouse mobile robots under industrial cyber-physical system[J]. *Advanced Engineering Informatics*, 2022, 52: 101572. doi: 10.1016/j.aei.2022.101572.

[5] Stecuła K, Wolniak R, Aydın B. Technology development in online grocery shopping—from shopping services to virtual reality, metaverse, and smart devices: A review[J]. *Foods*, 2024, 13(23): 3959.

[6] Jang Y, Son J, Yi J-S. BIM-based management system for off-site construction projects[J]. *Applied Sciences*, 2022, 12(19): 9878.

[7] Sartal A, Llach J, León-Mateos F. "do technologies affect that much? Exploring the potential of several industry 4.0 technologies in today's lean manufacturing shop floors"[J]. *Oper Res Int J*, 2022, 22(5): 6075–6106. doi: 10.1007/s12351-022-00732-y.

[8] Licardo JT, Domjan M, Orehovački T. Intelligent robotics—a systematic review of emerging technologies and trends[J]. *Electronics*, 2024, 13(3): 542. doi: 10.3390/electronics13030542.

[9] Xie W, Peng X, Liu Y. Conflict-free coordination planning for multiple automated guided vehicles in an intelligent warehousing system[J]. *Simul Modell Pract Theory*, 2024, 134: 102945. doi: 10.1016/j.simpat.2024.102945.

[10] Althabatah A, Yaqot M, Menezes B. Transformative procurement trends: Integrating industry 4.0 technologies for enhanced procurement processes[J]. *Logistics*, 2023, 7(3): 63.

[11] Kalempa VC, Piardi L, Limeira M. Multi-robot preemptive task scheduling with fault recovery: A novel approach to automatic logistics of smart factories[J]. *Sens*, 2021, 21(19): 6536.

[12] Baouya A, Chehida S, Bensalem S. Deploying warehouse robots with confidence: The BRAIN-IoT framework's functional assurance[J]. *J Supercomput*, 2024, 80(1): 1206–1237. doi: 10.1007/s11227-023-05483-x.

[13] Sıcakyüz Ç, Edalatpanah SA, Pamucar D. Data mining applications in risk research: A systematic literature review[J]. *Int J Knowledge-Based Intell Eng Syst*, 2024, 6(4): 13272314241296866. doi: 10.1177/13272314241296866.

[14] Leng J, Chen Z, Huang Z. Secure blockchain middleware for decentralized iiot towards industry 5.0: A review of architecture, enablers, challenges, and directions[J]. *Machines*, 2022, 10(10): 858.

[15] Liu Q, Liu M, Zhou H. Intelligent manufacturing system with human-cyber-physical fusion and collaboration for process fine control[J]. *J Manuf Syst*, 2022, 64: 149–169.

[16] Yu S, Huang Y, Du T. The proposal of a modeling methodology for an industrial internet information model[J]. *PeerJ Computer Science*, 2022, 8: e1150.

[17] Sun M, Cai Z, Zhao N. Design of intelligent manufacturing system based on digital twin for smart shop floors[J]. *International Journal of Computer Integrated Manufacturing*, 2023, 36(4): 542–566. doi: 10.1080/0951192X.2022.2128212.

[18] Trstenjak M, Gregurić P, Janić Ž. Integrated multilevel production planning solution according to industry 5.0 principles[J]. *Applied Sciences*, 2023, 14(1): 160.

[19] Meyns L. Operational challenges and provided solutions for parcel delivery by drones: a literature survey[J]. *Faculteit Economie*, 2021, 944(18): 23–55.

[20] Bolu A, Korçak Ö. Adaptive task planning for multi-robot smart warehouse[J]. *IEEE Access*, 2021, 9: 27346–27358. doi: 10.1109/ACCESS.2021.3058190.

[21] Kalempa VC, Piardi L, Limeira M. Multi-robot task scheduling for consensus-based fault-resilient intelligent behavior in smart factories[J]. *Machines*, 2023, 11(4): 431. doi: 10.3390/machines11040431.

[22] Chataut R, Phoummalayvane A, Akl R. Unleashing the power of IoT: a

comprehensive review of IoT applications and prospects in healthcare, agriculture, smart homes, smart cities, and industry 4.0[J]. *Sensors*, 2023, 23(16): 7194.

[23] Zeng Y, Li W, Li C. A dynamic simulation framework based on a hybrid modeling paradigm for parallel scheduling systems in warehouses[J]. *Simulation Modelling Practice and Theory*, 2024, 133: 102921. doi: 10.1016/j.simpat.2024.102921.

[24] Mienye ID, Swart TG. A comprehensive review of deep learning: Architectures, recent advances, and applications[J]. *Information*, 2024, 15(12): 755.

[25] Chen H, Shao H, Deng X. Comprehensive survey of the landscape of digital twin technologies and their diverse applications.[J]. *CMES-Computer Modeling in Engineering & Sciences*, 2024, 138(1).

[26] Keung KL, Chan YY, Ng KK. Edge intelligence and agnostic robotic paradigm in resource synchronization and sharing in flexible robotic and facility control system[J]. *Adv Eng Inf*, 2022, 52: 101530. doi: 10.1016/j.aei.2022.101530.

[27] Condotta M, Scanagatta C. BIM-based method to inform operation and maintenance phases through a simplified procedure[J]. *Journal of Building Engineering*, 2023, 65: 105730. doi: 10.1016/j.jobe.2022.105730.

[28] Dong F, Dong S. Research on the optimization of ideological and political education in universities integrating artificial intelligence technology under the guidance of curriculum ideological and political thinking[J]. *ACM Trans Asian Low-Resour Lang Inf Process*, 2023, 12(3): 3611012. doi: 10.1145/3611012.

[29] Niu P. Customization and performance of service-oriented manufacturing information system: The mediating effect of information system flexibility[J]. *Intell Inf Manag*, 2021, 13(1): 1–30.

[30] Zhou T, Tang D, Zhu H. Multi-agent reinforcement learning for online scheduling in smart factories[J]. *Rob Comput Integr Manuf*, 2021, 72: 102202.

[31] Ouro-Salim O, Guarnieri P, Leitão FO. The use of big data to mitigate waste in agri-food supply chains[J]. *World Food Policy*, 2023, 9(1): 72–92. doi: 10.1002/wfp2.12055.

[32] Koman G, Boršoš P, Kubina M. The Possibilities of Using Artificial Intelligence as a Key Technology in the Current Employee Recruitment Process[J]. *Adm Sci*, 2024, 14(7): 157.

[33] Restrepo-Carmona JA, Zuluaga JC, Velásquez M. Smart supervision of public expenditure: a review on data capture, storage, processing, and interoperability with a case study from Colombia[J]. *Information*, 2024, 15(10): 616.

[34] Zhang G, Liu J. Intelligent vehicle modeling design based on image processing[J]. *International Journal of Advanced Robotic Systems*, 2021, 18(1): 1729881421993347. doi: 10.1177/1729881421993347.

[35] Gui Y, Zhang Z, Tang D. Collaborative dynamic scheduling in a self-organizing manufacturing system using multi-agent reinforcement learning[J]. *Adv Eng Inf*, 2024, 62: 102646. doi: 10.1016/j.aei.2024.102646.

[36] Li K. Optimizing warehouse logistics scheduling strategy using soft computing and advanced machine learning techniques[J]. *Soft Comput*, 2023, 27(23): 18077–18092. doi: 10.1007/s00500-023-09269-4.

[37] Tubis AA, Rohman J. Intelligent warehouse in industry 4.0—systematic literature review[J]. *Sens*, 2023, 23(8): 4105.

[38] Li J, Yin W, Yang B. Modeling of Digital Twin Workshop in Planning via a Graph Neural Network: The Case of an Ocean Engineering Manufacturing Intelligent Workshop[J]. *Appl Sci*, 2023, 13(18): 10134.

[39] Leng J, Wang D, Shen W. Digital twins-based smart manufacturing system design in Industry 4.0: A review[J]. *Journal of Manufacturing Systems*, 2021, 60: 119–137.

[40] He H, Wang X, Peng G. Intelligent logistics system of steel bar warehouse based on ubiquitous information[J]. *Int J Miner Metall Mater*, 2021, 28(8): 1367–1377. doi: 10.1007/s12613-021-2325-z.