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Review

Order-Picking Efficiency in E-Commerce Warehouses: A Literature Review

Yi Li [1,2], Ruining Zhang [3] and Dandan Jiang [4,*]

[1] Network Social Development Research Center, Chongqing University of Posts and Telecommunications, Chongqing 400065, China
[2] School of Economics and Management, Chongqing University of Posts and Telecommunications, Chongqing 400065, China
[3] School of Modern Posts, Chongqing University of Posts and Telecommunications, Chongqing 400065, China
[4] School of Economics and Management, West Anhui University, Lu'an City 237012, China
* Correspondence: 10000083@wxc.edu.cn

Abstract: With the vigorous development of e-commerce, efficient order picking in e-commerce warehouses has attracted the attention of many scholars. To analyze the issues about order-picking efficiency currently being studied by relevant scholars in e-commerce warehouses, this paper reviews the literature on the application of order-picking strategy and efficiency optimization direction from 2020 to 2022. That mainly falls into two categories of picking systems: "picker-to-parts" and "parts-to-picker". In the "picker-to-parts" picking system, more attention is paid to the picking strategies of storage assignment and order batching and the integration of multiple picking strategies. In contrast, in the "parts-to-picker" picking system, the main attention is on the man-machine cooperation in the Mobile Robot Fulfillment System (RMFS) and the Automated Storage and Retrieval System (AS/RS), as well as the coordination of the picking station. Further, this paper proposes future research directions for two categories of picking systems: further studying the order splitting strategy and order delivery issues; considering the dynamic uncertainties; combining the automated picking system with different picking strategies, and so on.

Keywords: e-commerce; automated warehouse; order picking; picking efficiency; RMFS; AS/RS

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1. Introduction

The main functions of the warehouse are receiving, storage, order picking, and shipping [1]. Warehouses provide a place to store a buffer against unreliable demand or price increases [2]. In the e-commerce environment, the demand for and price of goods are more unpredictable, which shows that the e-commerce warehouse is a very important node in the e-commerce supply chain. In e-commerce promotion activities (such as Christmas and Black Friday), a large number of e-commerce orders will be generated. E-commerce mainly includes B2B (Business to Business), B2C (Business to Customer) and other subdivided fields. Boysen et al. [3] summarized the following four characteristics of e-commerce orders.

Small orders: In e-commerce retail platforms, the number of merchants is increasing, which also means that consumers have a wider range of choices. A user may not order many goods from a single merchant at the same time, resulting in the goods coming from all over the country. Finally, there may be a few items for the order received in the same warehouse. After investigating a large distribution center, Weidinger and Boysen [4] found that there is an average number of two items per order. During promotion activities, the warehouse may receive many similar small orders in the same period. Efficiently handling these orders from all over the world is a complex process for e-commerce warehouses.

Large assortment: In order to save costs and facilitate order picking, a warehouse will accumulate many types of products for Internet dealers so that they can provide more product types than physical retailers [5]. For example, JD.com self-run stores in China have a wide range of goods, from a single part to large household appliances.

Tight delivery schedules: With the development of e-commerce, people have higher and higher requirements for delivery services. In addition to door-to-door delivery, delivery time is required to be increasingly quick [6]. In order to better meet the needs of consumers, the delivery time requirements for e-commerce requirements have been increasingly shortened to same-day or next-day delivery [7]. Additional services, such as furniture installation, may also be provided. Such requirements necessitate the close cooperation of each link in the warehouse to ensure the delivery of goods within the time required by customers.

Varying workloads: The items stored in each warehouse may change with seasons, batch production and transportation [1]. For example, short T-shirts are more popular in summer, while down coats are more popular in winter, which requires the warehouse to be variable [3]. The warehouse must adjust its storage and picking methods according to seasonal changes.

These are the order characteristics of B2C, but there may be some differences in B2B and other subdivisions. E-commerce warehouses in any field should be able to achieve fast delivery of orders. They have higher requirements than before for multiple links involved in the warehouse, especially for improving order-picking efficiency.

Order picking typically accounts for about 55% of warehouse operating costs. The time spent in the whole picking process is mainly divided into the time traveling, searching, extracting, paperwork and other activities. The mobile time accounts for the highest proportion, about 55%. Therefore, the growth of e-commerce orders creates strict requirements for order picking in e-commerce warehouses to be faster and for less time to be spent on non-productive work [2].

To address laborious and expensive order picking, warehouse systems and processes are rapidly developing towards automation [8]. In 2006, a unit loading warehouse was set up in Germany to start warehouse automation, and AS/RS was able to store bulk stock on unit loads (pallets or totes (miniload system)). In addition, there are mobile robots combined with mobile shelves. In this way, the pickers do not need to enter the storage area to pick with manual pick stations in a “parts-to-picker” picking system, and the processed goods can enter the packaging process faster.

From 2020 to 2022, some scholars further studied the application of order-picking strategy and the optimization objectives; few scholars summarized the research contents of these articles. To supplement the research on these issues, we collated the relevant literature in the past three years. This paper summarized the research content from the perspective of “picker-to-parts” and “parts-to-picker” picking systems in particular.

The specific literature review is arranged as follows. In Section 2, the related literature was collected and screened. Section 3 introduces the classification of order-picking systems, order-picking strategies, order-picking optimization indicators and research framework. Section 4 summarizes 37 related papers from the perspective of “picker-to-parts” and “parts-to-picker” picking systems. Section 5 presents the conclusion, and Section 6 offers recommendations for future research.

2. Methodology

2.1. Literature Collection

This paper aims to explore the research status of order-picking efficiency in e-commerce warehouses. The process of filtering and retention is as follows.

First, this paper is based on the English periodical literature in the Web of Science core journal database and used the keyword phrase “order picking and e-commerce” to search for relevant studies in the literature. The search excluded newspapers, books, popular science, conferences and other non-journal articles. Literature based on business economics and operations research management science disciplines were targeted. A total of 172 articles were retained.

Second, the publication years from 2020 to 2022 were considered. Based on these criteria, 78 eligible studies were identified.

Third, manually checking whether the title, keywords, abstract and text refer to "e-commerce", "order picking", "warehouse", and "models, algorithms, case research ", a total of 37 eligible literature publications were selected. Detailed manual screening criteria are as follows.

The literature retrieval process is shown in Figure 1.

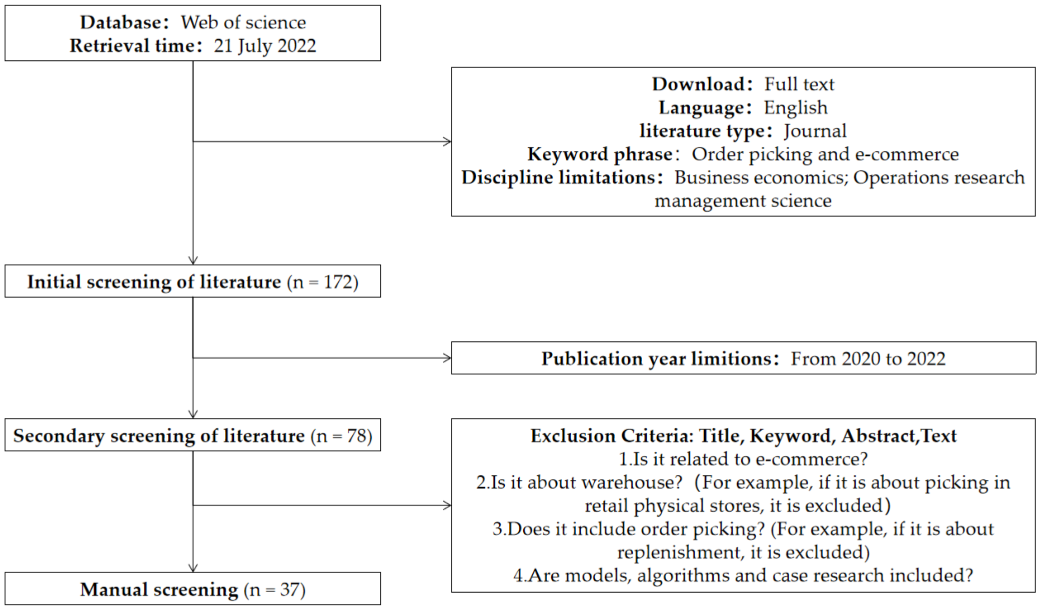

Figure 1. The process of database retrieval and literature screening.

2.2. Screening Criteria

In addition to searching in the literature database, after reading the literature review on the same topic, the year was selected, then manual screening was conducted. Articles selected manually mainly include "e-commerce", "order picking", "warehouse", and "models, algorithms, case research". For example, some articles mentioned e-commerce in the abstract but were not closely related to e-commerce when they were written. Some articles were excluded because their main content is physical retail stores, distribution center location, part locker location optimization and so on. Some articles did not study warehouses, focused on other research subjects, or did not include models or algorithms or case studies. The criteria for database retrieval and literature screening are shown in Table 1.

Table 1. The criteria of database retrieval and literature screening.

Stage	Number	Type	Inclusion Criteria	Exclusion Criteria	Judgment Method
Screen in the database	1	Download	Full text	Full text is not available in the current database	System discrimination
	2	Language	English studies	Non-English studies	
	3	Literature type	Journal	Non-journal	
	4	Keyword phrase	Order picking and e-commerce	Except for two keywords	
	5	Discipline	Business economics, operations research management science	Except for two disciplines	

Table 1. *Cont.*

Stage	Number	Type	Inclusion Criteria	Exclusion Criteria	Judgment Method
Secondary screening (Screen after reading relevant reviews)	6	Publication year	From 2020 to 2022	Before 2020	Excel screen
Manual screening	7	Title, abstract, and keywords	Including e-commerce	Non-e-commerce	Subjective judgment
	8	Title, abstract, and keywords	Including order picking	Picking in physical retail stores, only delivery problem, location of distribution center, carton set optimization, parcel locker location optimization, the last kilometer problem, etc.	
	9	Title, abstract, keywords and text	Warehouse related	Retail physical stores, flower auction centers, physical internet-enabled customized furniture delivery systems, intelligent vegetable greenhouses, etc.	
	10	Title, abstract, keywords and text	Models, algorithms, case research	Empirical research, etc.	

2.3. Analysis of Journals and Year of Publication

Table 2 summarizes the published journals based on these 37 articles. We can see that the main articles are from the *International Journal of Production Research*, *European Journal of Operational Research*, and *Transportation Research Part E-Logistics and Transportation Review*. In addition, some articles were also published in "Industry", "Management" and "Computer"-related journals. Before 21 July 2022, the published articles from 2020 to 2022 are distributed in Figure 2.

Table 2. Summary of the journals of the analyzed literature.

Journal of the Analyzed Literature	Number of Papers
International Journal of Production Research	6
European Journal of Operational Research	3
Transportation Research Part E-Logistics and Transportation Review	3
Computers & Industrial Engineering	2
Flexible Services and Manufacturing Journal	2
Naval Research Logistics	2
Computers & Operations Research	2
Informs Journal on Applied Analytics	2
IISE Transactions	1
Central European Journal of Operations Research	1
IEEE Transactions on Visualization and Computer Graphics	1
Advanced Engineering Informatics	1
Computers in Industry	1
Journal of Intelligent & Fuzzy Systems	1
Annals of Operations Research	1
Informs Journal on Computing	1
Journal Of Theoretical and Applied Electronic Commerce Research	1
International Transactions in Operational Research	1
Production and Operations Management	1

Table 2. *Cont.*

Journal of the Analyzed Literature	Number of Papers
International Journal of Production Economics	1
Enterprise Information Systems	1
Complexity	1
E & M Ekonomie a Management	1

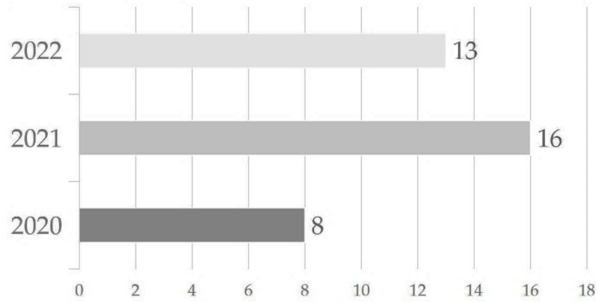

Figure 2. Distribution of publications from 2020 to 2021.

2.4. Difference between This Review and Related Reviews

To understand the current literature review of order picking, the following comparative analysis is made on the eight literature reviews about order picking and e-commerce retrieved from the Web of Science core journal database. The year of publication is mainly 2019 and 2020. Five of the eight literature reviews focus on the automated system in the warehouse, while there are few reviews related to manual order-picking, order-picking strategy and optimization objectives. Since 2020, there have also been scholars who have conducted modeling and simulation research on order-picking strategy and optimization under e-commerce scenarios. Therefore, this paper reviews the e-commerce-related literature from 2020 to 2022 from the perspective of "picker-to-parts" and "parts-to-picker" picking systems. The comparison of relevant literature reviews is shown in Table 3.

Table 3. Summary of literature reviews related to order picking in e-commerce warehouses.

Author	Research Object	Main Content	Research Method	Number of Papers	Timespan
[9]	Omni-channel logistics warehouse	Ten themes in omnichannel logistics were identified and grouped into value proposition and channel management and the logistics network design.	Induction and generalization	64	N/A
[3]	Warehousing in the e-commerce era	The applicability of mixed-shelves storage, dynamic order processing, batching, zoning and sorting systems, and automated storage system (e.g., automated picking workstations, robots, and AGV-assisted order-picking systems) in the B2C segment of e-commerce is summarized according to the degree of automation.	Induction and generalization	N/A	N/A
[10]	Automated sortation conveyors system	This paper describes the layout of typical automatic sorting systems in warehouse cross docks, the postal industry, airports and other fields, and identifies the basic decision-making problems to be solved.	Induction and generalization, bibliometric analysis	70	N/A
[8]	Automated warehouse systems	This paper reviews new categories of automated and robotic handling systems, such as shuttle-based AS/RS, shuttle-based compact storage systems, and RMFS.	Induction and generalization	55	2002–2019
[11]	Automated order-picking systems	This paper summarizes the performance throughput, lead time, human factors, quality, flexibility, operational efficiency and cost of the automation system from the perspective of "parts-to-picker", "robots-to-parts", "parts-to-robots", and "picker-less" systems.	Induction and generalization, bibliometric analysis	74	1979–2020

Table 3. *Cont.*

Author	Research Object	Main Content	Research Method	Number of Papers	Timespan
[12]	Flexible automated warehouse	This paper outlines the automation equipment, data collection technology and management solutions in the flexible automated warehouse and constructs a flexible automated warehouse framework based on the overview paper that can adapt to dynamic market changes.	Induction and generalization, bibliometric analysis	113	2008–2018
[13]	Decision support in warehousing and distribution	Studies are categorized by warehouse type, decision support target, operational task and problem type, research literature methodology, architecture and technology in this paper to assist operational decision-makers to manage and complete the daily volume of work through the warehouse.	Induction and generalization	63	2009–2019
[14]	Smart warehouse operations management	This paper provides a framework to review smart warehouse operations management based on the characteristics of smart warehouses, including the perspectives of information interconnection, equipment automation, process integration, and environmental sustainability.	Induction and generalization, bibliometric analysis	N/A	2010–2022
This paper	Order picking system in e-commence warehouse	In this paper, order-picking strategies, optimization methods and objectives are studied from the perspective of two order-picking systems, "picker-to-parts", and "parts-to-picker" in e-commence warehouse.	Induction and generalization	37	2020–2022

3. Construct the Research Framework

3.1. Order Picking System Classification

There are many kinds of order picking in the warehouse. To classify the order-picking system more clearly, Dallari et al. [15] proposed the picking systems of "picker-to-parts", "pick-to-box", "pick and sort", and "parts-to-picker". These categories are defined by who picks the goods, who moves in the picking area, uses a conveyor to connect picking zones and picking policy. This paper focuses on the "picker-to-parts" and the "parts-to-picker" picking systems. In the "picker-to-parts" picking system, the picker completes a single or batch order formed by multiple orders along the channel or using vehicles. In the "parts-to-picker" picking system, goods are moved from the storage area to the picking station by automatic equipment, where the picker completes the picking according to the order. In addition to AS/RS, which has a long history, RMFS also belongs to the "parts-to-picker" picking system. In RMFS, the robot can lift the shelf and move it to the picking station [3]. Based on the "picker-to-parts" picking system and "parts-to-picker" picking system, van den Berg [16] also identified a new category—a "picker-less" picking system. In this process, mechanical automation is used to complete picking. This paper classifies the picking system in the warehouse, as shown in Figure 3.

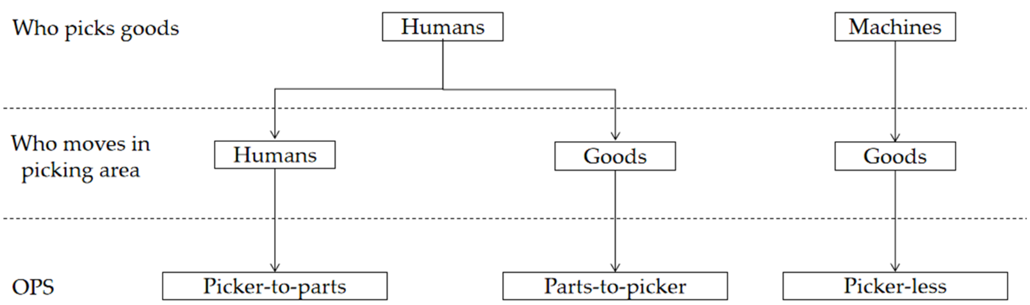

Figure 3. Order picking system classification [8,11,12].

3.2. Order Picking Strategies

In the order-picking process, some order-picking strategies can be used to save some operation steps or reduce the number of pickers. Order-picking strategies include layout design, storage assignment, routing method, order batching and zoning [17]. The relevant order-picking policies defined by de Koster et al. [18] and specific applications in the "picker-to-parts" picking system are as follows.

Layout design: In the picking environment, the layout design concerns two sub-problems, including the layout of the facility containing the order-picking system and the layout within the order-picking system (internal layout design or aisle configuration problem). The effective use of warehouse space can be achieved, which can lower labor costs and handling costs and increase picking efficiency. This can be done by accurately calculating and researching the number of channels in the picking area, the length and width of channels, and the layout and distance of the basic equipment involved in the picking process.

Storage assignment: A storage assignment method is a set of rules that can assign products to storage locations [18]. There are five frequently used types of storage assignment: random storage, closest open location storage, dedicated storage, full turnover storage and class-based storage. Random storage needs computer assistance, which is convenient for people who store goods. The space utilization rate is high, but it is not conducive to picking by the picker. The closest open location storage will lead to uneven utilization of storage space. Dedicated storage can store goods reasonably. The picker will be very familiar with the location of goods, but the space utilization rate is low. Full turnover storage is due to dynamic data, so it is necessary to predict the turnover rate of the next cycle. Class-based storage is applicable to those with large difference in turnover rate and size of goods (specific classification standards), which is convenient for reasonable storage of goods, but the space utilization rate is low.

Routing method: The objective of routing policies is to sequence the items on the pick list to ensure a good route through the warehouse [18] and reduce unnecessary turn-backs with reasonable planning the route of picking.

Order batching: This means integrating multiple orders into an order batch. Completing the batch picking in one picking process can increase the picking density in each order-picking process [3]. Integrating orders according to certain standards can shorten the average walking distance and time during picking.

Zoning: Each order picker only needs to complete part of the order picking in the region where the order is located. Two classifications of the zoning are the "parallel zoning" and the "pick-and-pass". The picker can be very familiar with the placement position and the moving distance of goods. In a short time, the pickers in multiple areas can pick orders together. However, attention should be paid to work balance.

The specific implementation in the warehouse is shown in Figure 4.

3.3. Order Picking-Related Optimization Indicators

Regarding warehouse design and optimization, de Koster et al. [18] summarized the optimization objectives, including minimizing the throughput time of an order, minimizing the overall throughput time (e.g., to complete a batch of orders), maximizing the use of space, maximizing the use of equipment, maximizing the use of labor, and maximizing the accessibility to all items. Staudt et al. [19] divided the performance indicators in the warehouse into four dimensions: time, quality, cost, and productivity. The relevant evaluation indicators under each dimension involve order picking. Jaghbeer et al. [11] concluded that the derived performance categories are throughput, lead time, human factors, quality, flexibility, operational efficiency, and costs, according to previous literature. According to the summary of the above two scholars, this paper mainly uses the time, cost, efficiency and other. There are four dimensions of the optimization objectives in all.

3.4. Research Framework

According to the relevant literature review, most reviews focused on automation, while few papers summarized the literature published from 2020 to 2022 from the perspective of "picker-to-parts" and "parts-to-picker" picking systems. In addition, few scholars have summarized the order-picking strategy and the optimization objectives in the past three years. Thus, it is difficult to explore the issues currently being studied by relevant scholars about the two picking systems in e-commerce warehouses. However, this paper analyzes and categorizes the papers from the past three years to understand the research content from the perspective of the two picking systems. It aims to evaluate and analyze the proposed strategies and optimization objectives from different indicators. This is conducive to understanding the research direction in e-commerce warehouses in recent three years. The specific research framework is shown in Figure 5.

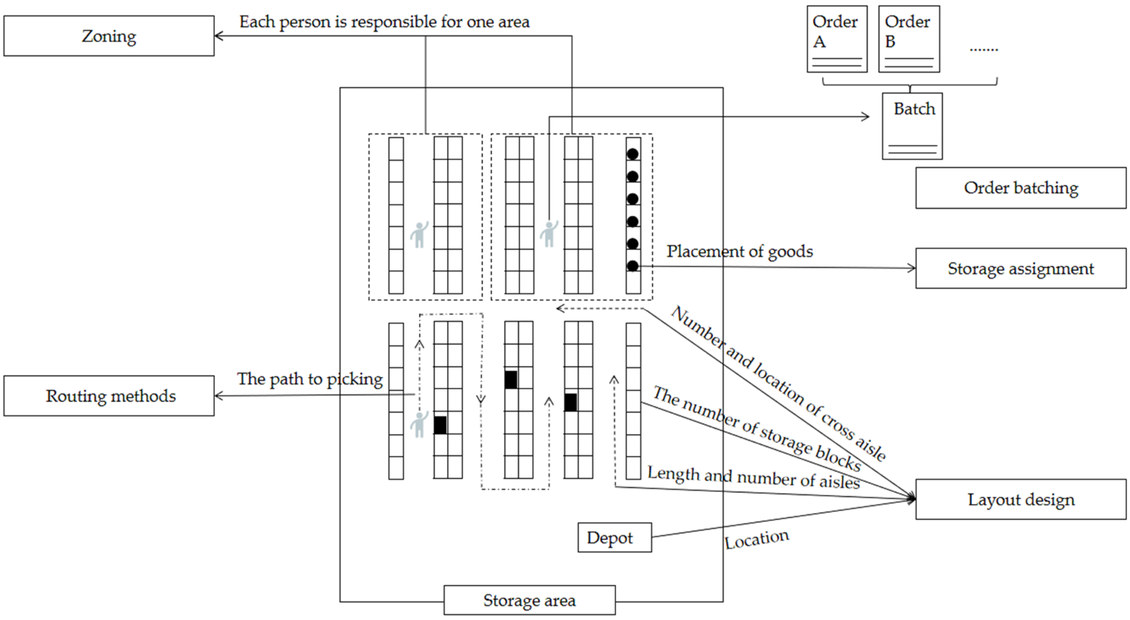

Figure 4. Function diagram of order-picking strategy (Taking the "picker-to-parts" picking system as an example [18]).

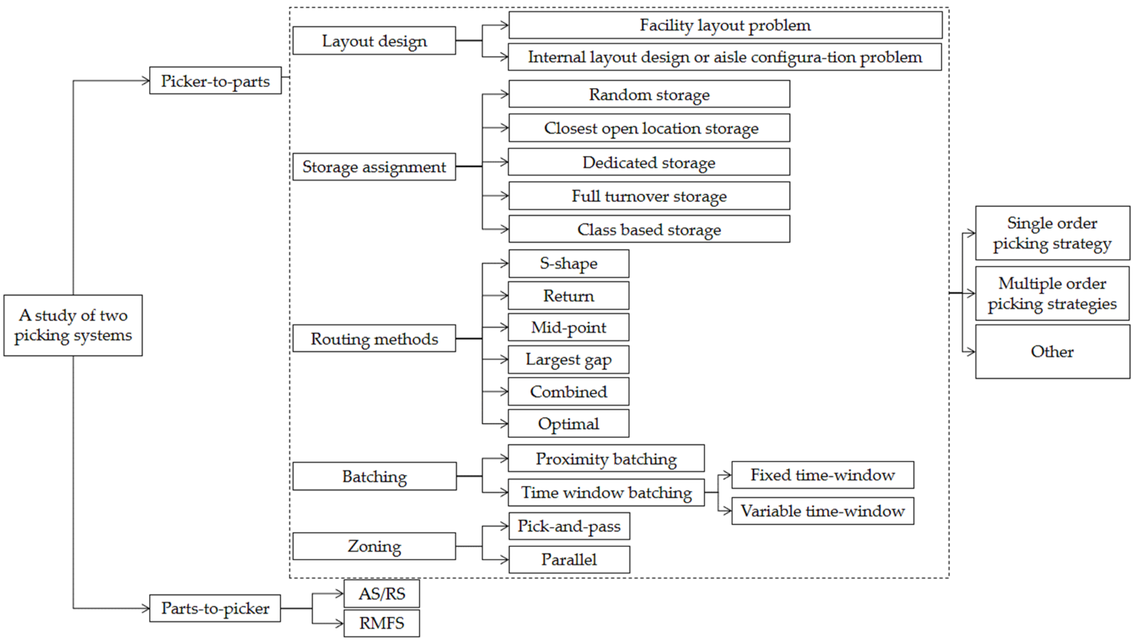

Figure 5. Research framework.

4. Literature Review

4.1. "Picker-to-Parts" Picking System

In the "picker-to-parts" picking system, the order-picking strategy is mainly used to optimize order picking. This paper summarizes the order-picking strategy, optimization objectives, research problems, and solutions of the retrieved studies. The secondary problems are not further categorized. The specific contents of the summary are shown in Table 4.

Table 4. Summary of literature related to the "picker-to-parts" picking system.

Author	Layout Design	Storage Assignment	Routing Method	Order Batching	Zoning	Optimization Objectives	Dimension of Optimization Indicators	Research Problem	Solution
[20]				✓		Minimize the total length of all order-picking tours and improve the total order throughput rate	Efficiency and other	B2B order pre-processing problem	An intelligent B2B order handling system, cloud database management, fuzzy logic, genetic algorithm approach
[21]		✓		✓	✓	Minimize the waiting duration of total batch picking, minimize the mean earliness and tardiness of each customer order	Time and other	Synchronization of two-stage picking and sorting order	Cyber-physical systems, variable neighborhood search algorithm, genetic algorithm
[22]				✓	✓	Balance operational workload	Other	Operational workload balance problem	Mixed integer programming model, iterated local search algorithm
[23]		✓		✓		Minimize the total travel distance	Other	Order batch picking optimization problem considering different storage scenarios	Order batch picking optimization problem model, 1–1 storage system, branch-and-price algorithm, tabu search batching algorithm, C#
[24]		✓				Minimize working time and walking distance	Time and other	Dynamic storage location assignment under traversing routing method	Heuristic algorithm
[25]		✓				Minimize order fulfillment times	Time	Dynamic stocking location problem	Mixed-integer program model, heuristic algorithm
[26]		✓				Minimize travel distance	Other	Assignment problem of duplicate storage locations	Integer programming model, heuristic algorithm, particle swarm optimization
[27]						Picking density and turnover time of an order	Efficiency and time	The pivotal issues of performance analysis of flow picking systems, and comparison between batch picking systems and flow picking systems	Approximate analytic models, discrete event simulation model, gradient descent algorithm, tabu search algorithm, combined algorithm
[28]				✓		Minimize the fulfillment cost	Cost	Warehouse-based supermarket picking and transport	Mixed integer linear programming model, Gurobi solver

Table 4. *Cont.*

Author	Layout Design	Storage Assignment	Routing Method	Order Batching	Zoning	Optimization Objectives	Dimension of Optimization Indicators	Research Problem	Solution
[29]				✓		Minimize picking and delivery costs	Cost	Integrated order batching and delivery planning of an online retailer that stores a variety of products in a warehouse and sells them online	Mixed-integer nonlinear programming model, rule-based heuristic algorithm, genetic algorithm
[30]						Minimize order-splitting and replenishment costs	Cost	Inventory and order allocation between traditional warehouse and new warehouse	Integer linear programming model, hybrid algorithm alternating between the large neighborhood search and local search
[31]		✓	✓			Minimize the total costs of the picker tour	Cost	Single-picker routing problems in e-commerce warehouse	Dynamic programming algorithm, Gurobi solver
[32]						Operation efficiency of manual picking	Efficiency	Non-parametric efficiency measurement for sustainable retail logistics	Non-parametric data envelopment analysis, free disposal hull approach
[33]						Minimize total cost (picking and delivery)	Cost	An integrated order-picking and vehicle routing problem assuming same-day delivery in the field of omnichannel retailing	Mixed-integer program model, general variable neighborhood search-based algorithm
[34]				✓		Minimize the number of tardy orders	Other	Solving the online batching problem using deep reinforcement learning	Deep reinforcement learning approach, proximal policy optimization algorithm, greedy batching algorithm
[35]				✓		Minimize the total picking distance and the total tardiness of orders	Other	Address the order batching and assignment problem with total tardiness objective under the order splitting policy	Mixed integer programming model, column generation-based algorithm, heuristic algorithm based on order kitting and due date
[36]			✓	✓		Minimize the picking time	Time	Integrated order batching, batch scheduling, and picker routing problem	Mixed integer programming model, heuristic algorithm
[37]		✓			✓	Minimize the wait time	Time	The storage assignment problem for CPS-based pick-and-pass system	CPS-based pick-and-pass system model, CPS, heuristic multi-objective genetic algorithm
[38]			✓	✓		Minimize cost	Cost	Alibaba vehicle routing algorithms enable rapid pick and delivery problem	Adaptive large neighborhood search algorithm, deep learning-based approach
[39]						Minimize processing time for delayed orders		Order delay in electronic commerce warehouse	Data-driven approach, Gantt graphs, Marey's graphs

Table 4. *Cont.*

Author	Layout Design	Storage Assignment	Routing Method	Order Batching	Zoning	Optimization Objectives	Dimension of Optimization Indicators	Research Problem	Solution
[40]				✓		Minimize the waiting time before packing	Time	Integrating the planning of order picking and packing process problems	Mixed-integer nonlinear programming model
[41]			✓	✓		Minimize the makespan and tardiness	Time and other	Integrating batching, routing and scheduling decision problems	Large neighborhood search algorithm
[42]		✓	✓	✓		Minimize the makespan and labor cost	Time and cost	Wave order-picking under the mixed-shelves storage strategy	Bi-objective mixed-integer linear program model, heuristic algorithm

4.1.1. Single Order Picking Strategy

Facing the management of discrete and frequently arriving e-commerce orders, Leung et al. [20] proposed an intelligent B2B order processing system to batch e-commerce orders based on both fixed and variable time-window batching, which can reduce the repeated journey of the picker in the storage area. Reducing the distance of this non-productive activity can also reduce the order-picking time, thus improving the order-picking efficiency. Due to the tight delivery schedules, Shavaki and Jolai [29] combined order batching and order delivery based on order delivery date used the degree of similarity of orders to generate batches and proposed a mixed-integer nonlinear programming model to deliver orders while reducing the number of delayed orders and transportation cost. Cals et al. [34] modeled the online order batching problem as a semi-Markov decision process model, batched orders based on a fixed time window, and used Deep Reinforcement Learning to solve the OBSP problem, minimizing the number of delayed orders that cannot be delivered on time. Jiang puts forward a strategy of aggregate order decomposition and batch processing. Orders are batched based on close positions, and a MIP model is built to minimize the total picking distance. The proximal policy optimization algorithm is used to solve the problem. In addition to the general types of warehouses, the current chain supermarkets are also beginning to accept online orders. Warehouse-based supermarkets face more complex picking situations when selling food products online. Vazquez-Noguerol et al. [28] classified these goods into dry, fresh and frozen categories and then used batch picking based on time windows to reduce the cost of order picking. They proposed a mixed-integer linear programming model to solve the problems of order picking, transportation time windows and truck allocation on distribution routes to maximize efficiency and minimize delivery costs. Zhong et al. [40] integrated and optimized order batching and goods packaging and established a mixed-integer nonlinear programming model to minimize the waiting time before goods packaging. In this paper, order picking in batches can be performed based on close locations and time windows and can also be combined with other processes in the warehouse to reduce the time of non-productive activities; minimize order tardiness, order picking and delivery costs; and thus improve order-picking efficiency.

Reasonable batching of orders in the warehouse and reasonable storage of goods can help the picker to complete order picking. Multiple storage methods can be used in the storage area. Previously, the same goods were stacked together. Zhang et al. [25] proposed an explosive storage strategy (random storage) and a commingled bin storage strategy, which means that small batches of the same goods or SKUs are scattered in multiple positions in the warehouse. Then, a mixed-integer programming model was used to minimize the order-picking time. Jiang et al. [26] proposed a scattered storage strategy based on product correlation, established an integer programming model, and used a genetic algorithm and particle swarm optimization algorithm to minimize the order-picking distance. Xu and Ren [24] proposed to dynamically adjust the storage location of SKUs in the warehouse in real-time, and established the adjustment gain model. They solved it using a genetic algorithm, thus improving the efficiency of order picking.

4.1.2. Multi-Order Picking Strategy

In the order-picking process, there are often many different types of problems, and these problems can be analyzed and solved by integrating multiple-picking strategies. Vanheusden et al. [22] proposed a mixed-integer programming model in combination with the picking strategy of order batching and zoning based on a fixed time window. They also applied an iterative local search algorithm to solve the workload balance problem of order pickers and the delivery problem of goods to improve the picking efficiency of pickers. Haouassi et al. [36] referred to the problem of combining the divided orders into batches based on a fixed time window and then reformulating the optimal picking route. They proposed a mixed-integer programming model and a heuristic algorithm to reduce the picking time by 30% to 60%. D'Haen et al. [41] studied the problem of order batching and optimal picking routing based on active trucks, combined with the vehicle delivery problem, to minimize the picking time. They also allocated orders to specific trucks according to the destination of customer orders to ensure that goods can be delivered within the delivery time to reduce order tardiness, and they proved the necessity of predicting the arrival of future orders to maintain high customer service levels. Hu et al. [38] found a combination of order batching, picking routing and delivery for e-commerce warehouses in Alibaba. Rasmi et al. [42] proposed a dual-objective mixed-integer linear programming model to solve the problems of order batching, mixed-shelves storage strategy, and optimal picking routing strategy based on goods categories. They also analyzed the balance between customer service level (completion time) and labor level (labor cost). Yang et al. [23] considered the optimization of order batch picking under 1–1, 1–n, and n–n storage systems. They proposed the location interval distance algorithm, location selection algorithm, routing algorithm, and order batching algorithm to minimize the order-picking distance.

Regarding the process of order picking, Kong et al. [21] recommended the storage of goods specially and reasonably according to the speed of movement. They formed a batch based on orders with similar storage locations and time windows. They established a model to balance the simultaneity of picking and the punctuality of sorting. They aimed to minimize the waiting time for picking the whole batch by measuring the start and end time of order picking of a batch in the parallel picking area. Goeke and Schneider [31] adopted a scattered storage strategy to decouple the picker and cart, multiple-end depots, and work out the optimal picking route, thus greatly saving the cost in the order-picking process. Tu et al. [37] proposed a sort of picking based on an information physics system and a heuristic multi-objective genetic algorithm, which is used to solve the storage assignment problem of picking operations in e-commerce warehouses and reduce the waiting time in the order picking and transmission process as much as possible. In terms of multiple order-picking strategies, most researchers comprehensively consider order batching, storage assignment, and other issues.

4.1.3. Other

In addition to the above categories, some scholars studied order picking under different conditions. This section's main problem does not include the five previously mentioned order-picking strategy. Wang et al. [30] divided the orders, assigned the SKU picking task in the order to two warehouses, modeled these problems using virtual warehouses, and solved this model using a hybrid algorithm. Their research found that the unit order splitting cost had an important impact on the total cost of the storage assignment scheme. Schubert et al. [33] developed a decision support model and a general variable neighborhood search-based algorithm for order picking and order delivery problems, which can save an average of 13% of the total cost compared with sequential picking. Yang et al. [27] established an analysis model for the average order-picking density and order turnover time of the process picking system and compared it with the batch-picking system. It was concluded that the process-picking system was better than the batch-picking system under certain circumstances. Klumpp and Loske [32] used non-parametric data envelopment analysis to evaluate the efficiency of manual picking. Tang et al. [39] proposed a visual analysis system based on warehouse event data to monitor and process orders in the warehouse in real-time, aiming to minimize the processing time of delayed orders.

4.1.4. Joint Scheduling Strategy

In the process of reviewing the relevant literature on the "picker-to-parts" picking system, five studies were found related to the problem of goods delivery. In order to understand the research situation of this kind of problem more clearly, this paper briefly summarizes the relevant literature. Vanheusden et al. [22] focused on the combination of picking workload and goods delivery in the B2B environment to achieve workload balance. To deliver large, durable consumer goods on the same day, Schubert et al. [33] proposed to combine order picking with order delivery. Shavaki and Jolai [29] proposed combining order batching and order delivery based on the order delivery date. Vazquez-Noguerol et al. [28] integrated the time window of order picking and vehicle routing with vehicle-site dependencies. D'Haen et al. [41] proposed assigning the order to specific trucks according to the destination of the customer's order to ensure that the goods can be delivered within the delivery period. Alibaba has developed a set of algorithms for vehicle routing problems, including an open-architecture adaptive large neighborhood search to solve various routing problems and a deep learning-based method to quickly generate online solutions [38].

4.1.5. Order Splitting Strategy

At present, most of the literature mainly focuses on order batching, and there are few related studies on order splitting strategy, but it is also a research direction worthy of attention. This paper has summarized the related literature from a period of nearly three years. To address e-commerce orders with small batches and tight delivery times, Jiang et al. [35] proposed a new picking strategy of splitting and reorganizing orders. Haouassi et al. [36] also proposed splitting orders and forming new order lines for batch processing to complete order picking faster. When traditional warehouses and automated warehouses coexist, Wang et al. [30] split the orders and assigned the SKU picking task in the order to two types of warehouses, one with a "picker-to-parts" and one with a "parts-to-picker" picking system. Vazquez-Noguerol et al. [28] split the orders according to the types of food goods involved in the orders (dry, fresh, frozen) and then formed a picking batch to minimize the order-picking cost.

4.2. "Parts-to-Picker" Picking System

In the "parts-to-picker" picking system in the automated warehouse, in addition to the mobile robot for shelf movement, the potential equipment types in the storage area of the automated warehouse are: conveyors, carousels, vertical lift modules and AS/RS [16]. Based on the research on 12 related studies, the current research types are mainly AS/RS and RMFS, as shown in Table 5. The research problems focus on the coordination and order assignment of people, picking stations and mobile robots, and there is little research on order-picking strategies. Therefore, in the "parts-to-picker" picking system, this paper analyzes the current system optimization objectives from the perspective of AS/RS and RMFS.

Table 5. Summary of literature related to the "parts-to-picker" picking system.

Author	Classification of Automation Systems	Layout Design	Storage Assignment	Routing Method	Order Batching	Zoning	Optimization Objectives	Dimension of Optimization Indicators
[43]	RMFS						Minimize the travel time of mobile robots,	Time
[44]	RMFS						Maximize the picking efficiency, minimize staff workload	Efficiency and other
[45]	AS/RS, SBS/RS				✓		Maximize the throughput	Efficiency
[30]	RMFS						Minimize order-splitting and replenishment costs,	Cost
[34]	SBS/RS				✓		Minimize the number of tardy orders	Other
[46]	SBS/RS				✓		Minimize throughput time	Time
[47]	RMFS						Minimize turnover time	Time
[48]	RMFS						Maximize throughput	Other
[49]	RMFS						Minimize average cost	Cost
[50]	RMFS		✓				Minimize the travel time of mobile robots	Time
[51]	RMFS				✓		Minimize the completion time and cost	Time and cost
[52]	RMFS				✓		Minimize order throughput time	Time
[53]	RMFS						Minimize the number of rack movements	Other
[54]	RMFS						Minimize picking time	Time
[55]	RMFS		✓				Minimize robot travel and waiting time	Time
[56]	RMFS						Minimize the order-fulfillment time. and operating cost	Time and cost

4.2.1. AS/RS

To optimize efficiency, Bansal et al. [45] compared the batch processing strategy and dynamic batch processing strategy applied by all AS/RS in waveless order release environments, compared the order throughput difference between single and multiline orders at the picking station, and calculated the threshold value of multiline order batches. Regarding batch processing of orders, Cals et al. [34] also proposed an in-depth reinforcement learning method to minimize the number of tardy orders and considered that SKUs are stored in two warehouse systems and picked at three different types of workstations to batch and pick the arrived orders. Differing from the warehousing system studied by Bansal et al. [45], the automated warehouse studied by Cals et al. [34] adopts AS/RS based on shuttles. This system has greater flexibility in order throughput [8]. Bansal and Roy [46] studied the multiline order integration problem of shuttle-based AS/RS and realized that the integrated system minimized the average throughput time. The size of the order batch directly affected the average throughput time. Because the order batch formation would be delayed, the order batch size also has a threshold. It can be seen that in AS/RS, adopting a more flexible shuttle-based system and the picking strategy of batching orders can improve the throughput of orders within a certain order size and reduce the number of tardy orders and throughput time.

4.2.2. RMFS

RMFS combines mobile shelves, picking stations and mobile robots, which is different from traditional automated storage systems. Therefore, there is still much room for the development of RMFS, and it is worth discussing its optimization objectives. This section describes the optimization objectives in the past three years from time, cost and other perspectives.

- Time Optimization

The mobile robot is used in RMFS to replace the manual picker moving in the storage area, thus reducing the non-productive time. However, due to the limitation of the required delivery date and the need to improve customer service satisfaction, other methods can be used to optimize time in the order-picking process. To address the problems related to the robot storage area, Gharehgozli and Zaerpour [43] regarded it as a traveling salesman problem with asymmetric distance and imposed different priority constraints according to the urgency of customer orders. They concluded that the mobile robot's moving time will be reduced by increasing the number of storage locations in a fulfillment center. Different storage strategies and their combination will also affect the time when the robot moves in the storage area. Mirzaei et al. [50] stored the goods most likely to be picked at the same time in the warehouse closer to each other according to the data in the warehouse and then stored the goods in a decentralized manner. The related scattered storage strategy in an automated warehouse may reduce the mobile robot's moving time more than random storage, turnover storage, and related storage. Yang et al. [47] developed a semi-open queueing network model to characterize the multi-deep compact robotic mobile fulfilment system and used the approximate mean value analysis to solve indicators in RMFS. They concluded that keeping 0.1% empty locations between shelves can reduce order turnover time.

In addition to research on storage, some scholars also studied robots, picking stations, and shelves. Gong et al. [48] classified the orders into two major classes, expedited shipping and standard shipping, according to the order priority and established a high-dimensional Markov model to determine the optimal number of robots. Based on the example of JD.com, Qin et al. [56] studied the scheduling problem of robots, tracks, and workstations for order picking in intelligent warehouses. They created a linear programming model and aimed to minimize the operating cost and order-fulfillment time. Rimélé et al. [55] also considered the waiting time of the mobile robot when picking at the picking station. Robot mobility planning and reasonable coordination can avoid unnecessary congestion caused by the mobile robot at the picking station. In the automated warehouse, in addition to combining RMFS with general order-picking strategies, Wang et al. [52] proposed that one rack can integrate two or more order-picking strategies at one time, and they combined order assignment, order sequencing, shelf selection and shelf sequencing to achieve the goal of minimizing the total throughput time.

In RMFS, in addition to the research on robots and picking stations, the optimization of time by people in the picking station is also a very important factor. Different pickers have different picking capabilities. When the pickers stand in front of the shelves with different picking workloads, everyone's working state will fluctuate. Therefore, man-machine coordination may also optimize the order-picking time. Wang et al. [54] assigned the shelves with different workloads to different pickers, proposed a stochastic dynamic programming model and conducted a case study. They concluded that considering the picker's work state could reduce the picking time by 10%.

Placing the goods on the mobile shelf in the area where manual picking is required. The manual picker places the goods on the mobile shelf, moves them to the forward area of the mobile robot, and then moves them to the picking station by the mobile robot. Therefore, how to conduct synchronous coordination and cooperation between the two regions is also a problem that needs attention. Jiang and Huang [51] described this problem as a delivery-driven intralogistics synchronization problem. They used a mixed-integer programming model and a variable neighborhood search algorithm to minimize the completion time and cost of picking and sorting.

- Cost Optimization

In RMFS, resources mainly include humans, robots, shelves, and picking stations, which are included in the cost of order picking. Effective integration and coordination of these resources may further reduce the cost of order picking. Lamballais et al. [49] considered the coordination between mobile robots and picking stations in picking and replenishment. The results show that peak demand will have an impact on resource allocation. Wang et al. [30] also studied the replenishment cost. The difference between these studies is that Wang et al. [30] studied the application of the order-splitting strategy to the warehouse combined with the "picker-to-parts" and "parts-to-picker" picking systems. The order needs to be split and merged according to the type of system to generate the order-splitting cost. The SKUs of the two warehouses complement each other to generate the replenishment cost. The authors then proposed a hybrid algorithm that alternates large neighborhood searches and local searches. The most time-consuming module in the algorithm is optimized to reduce the order splitting cost and replenishment costs. The capacity of two pickers in the replenishment area is equivalent to that of seven pickers in the order picking sequential approaches, thus reducing the human resource and replenishment costs [51].

- Other Optimizations

The process of picking mainly involves multiple mobile robots and multiple picking stations. If the resource coordination is unbalanced, rack conflict and unbalanced workload distribution may occur in the warehouse. Considering the problem of multi-workstation scheduling and rack scheduling with workload and rack conflict, this paper introduces an adaptive large neighborhood search algorithm based on an efficient data-driven heuristic, which can greatly reduce the number of rack movements and rack conflicts at the picking station [53]. Kudelska and Niedbał [44] proved that the technology (RMFS) and organizational innovation implemented in the warehousing process can improve the order-picking efficiency and reduce the workload of workers through the experiment of e-commerce warehouse.

In sum, regarding the "parts-to-picker" picking system, the current research is mainly focused on RMFS, resource allocation, man-machine cooperation, rack conflict, cooperation with the picking station and other issues in the picking process. The optimization goal is mainly to optimize the time for relevant operations in the picking process.

5. Conclusions

In past literature reviews, few scholars conducted their reviews from the perspective of "picker-to-parts" and "parts-to-picker" picking systems. From 2020 to 2022, many scholars have conducted in-depth research on the order-picking process, picking strategy and system optimization of e-commerce warehouses. This paper mainly reviews the literature of the past three years about the order-picking strategy, AS/RS and RMFS systems from the perspective of the "picker-to-parts" and "parts-to-picker" picking systems.

In the aspect of the "picker-to-parts" picking system, the related papers are summarized from three categories, including single picking strategy, the synthesis of multiple picking strategies and others. In addition, the order-splitting strategy and joint scheduling method are separately summarized. The following conclusions can be drawn. First, at present, single picking and multiple picking strategies mainly focus on order batching and storage allocation strategies. Second, some scholars have studied the order-splitting strategy in recent three years. Third, some scholars have simultaneously studied the order delivery problem and order-picking strategy.

Regarding the "parts-to-picker" picking system, we mainly studied AS/RS and RMFS. The following conclusions can be drawn. First, more scholars have examined RMFS. Second, the main research direction focuses on the relationships and coordination among people, mobile robots, picking stations, and shelves. Third, most of the optimization goals involve the reduction of the time and cost of order picking.

6. Future Research

In the present summary of the literature from the past three years, it can be seen that many scholars in this field have proposed innovative model designs and perspectives. In the future, the following two aspects can be studied further.

In terms of the "picker-to-parts" picking system, the picking process can be optimized according to the characteristics of differentiated orders in different segments such as B2C, B2B and C2C of e-commerce. Future work can also deeply study the order splitting strategy, delivery problem, other order-picking strategies, and integrate multiple order-picking problems. Moreover, dynamic uncertainties in the warehouse, such as warehouse congestion, can be considered when making model assumptions.

In terms of the "parts-to-picker" picking system, the automated picking system can be combined with other picking strategies in the future. In addition to the use of mobile robots, the picking mechanisms of other robots (such as crawling robots) can also be integrated.

Moreover, different categories of goods (such as perishable products) can be considered when building the model.

In addition, the following aspects can also be studied in the future. The information synchronization problem caused by the simultaneous use of the "picker-to-parts" and "parts-to-picker" picking systems can also be further studied. Under different picking systems, special conditions such as epidemic situations and seasons should also be considered to optimize the order-picking process. For example, the disinfection of goods will affect the steps of the whole order-picking process and the efficiency of order picking. Seasonal changes require the warehouse to be flexible and able to handle goods of different types and packaging sizes. These factors should thus be taken into account when building relevant problem models to further optimize the order-picking process.

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