

# Toward Full-Chain Collaboration: Optimizing Operational Scheduling in Four-Way Shuttle-Based Dense Storage Systems

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## Abstract:

As a key support for high-density automated warehousing, the scheduling efficiency of the four-way shuttle system largely determines the overall throughput capacity. Aiming at the typical four-way shuttle system, this study carried out systematic research from four key dimensions: task allocation, path coordination, elevator coordination and dynamic disturbance response, combined with theoretical analysis and literature quantitative reasoning. The research system analyzes the efficiency bottleneck in the existing scheduling strategy. The results show that the experience-driven task allocation leads to serious resource competition; the independent path planning of each four-way shuttle cannot predict the conflict; elevator scheduling ignores global load balancing; static strategies are difficult to cope with dynamic disturbances. It is particularly important that these problems are intertwined, so that the actual throughput of the system only reaches 60% to 75% of the theoretical peak. Based on this, this study proposes targeted improvement measures, including task target clustering, path coordination based on time window, dynamic elevator priority scheduling, and event-driven online rescheduling. These strategies aim to promote the system from passive response to active collaboration, and provide theoretical support for improving the operational efficiency of high-density automated warehouses. The proposed framework not only lays a theoretical foundation for improving the operational efficiency of high-density automated warehouses, but also provides practical insights for practitioners to bridge the gap between theoretical design capacity and actual throughput in actual deployment.

**Keywords:** Four-Way Shuttle; Dense Storage; Scheduling Optimisation; Elevator Collaborative Scheduling; Full-Chain Collaboration

## 1. Introduction

### 1.1 Background and Problem Statement

With the rapid development of e-commerce and the growing demand for high-density storage in modern logistics, the four-way shuttle dense storage system has become a key technology in automated warehouses. It maximizes space utilization and operational efficiency. Unlike traditional fixed-aisle automated storage and retrieval systems (AS/RS), the four-way shuttle can move along both horizontal and vertical directions within a grid-structured rack. It can also use the elevator to run flexibly between different floors, so it is widely used in e-commerce centers and other industries with high requirements for space and throughput.

Despite the technical advantages, the four-way shuttle system often has a significant gap with the theoretical design capacity in practical applications. The industry report shows that even under medium load conditions, the actual throughput of such systems rarely exceeds 75% of their theoretical peak [1]. This inefficiency is mainly due to the poor scheduling strategy. The existing strategy fails to effectively deal with the complex interaction between multiple shuttles, elevators, and dynamic order flow. In high-density operation scenarios, the tasks assigned to multiple shuttles in the same area often lead to resource competition, path conflicts, and long waits at the elevator interface. All these problems will eventually reduce the overall production efficiency of the system.

### 1.2 Literature Review

Existing literature has extensively discussed scheduling optimization in automated storage systems. Wu's research shows that if task allocation does not consider destination distribution, multiple shuttles rush to the same elevator entrance at the same time. This creates a queuing bottleneck. If path planning is only based on the shortest distance and ignores conflict prediction at intersections, it causes frequent stops and path backtracking [2]. Arslan & Ekren's study shows that some vehicles remain idle for long periods while others are overloaded, which causes equipment utilization to become unbalanced. Wang and Zhang proposed a task allocation model of cross-layer shuttle system based on genetic algorithm. Their results show that under static workload conditions, the system throughput is increased by 12% [3].

However, most of these studies focus on static one-dimensional optimization. They either focus only on task allocation or only on path planning. They ignore the coupling effects of multi-device collaboration and dynamic environmental disturbances. For example, there is little research on how improper task assignment decisions can

lead to path conflicts and long elevator waits in real-time operations. They also did not consider the randomness of the task.

In contrast, the research on the overall scheduling framework of the four-way shuttle system is still limited. This is particularly evident in terms of dynamic interference and cross-floor elevator coordination. Although some recent studies have introduced reinforcement learning to achieve adaptive scheduling, these methods usually require high algorithm complexity and are difficult to deploy in real-time working environments. In addition, the existing research rarely quantifies the efficiency loss caused by the interaction between task allocation, path planning, elevator coordination, and dynamic response.

### 1.3 Research Framework

In order to fill these gaps, this study uses a combination of theoretical analysis and literature data, and quantitative reasoning research methods. It establishes a four-dimensional diagnostic model as the core analysis framework of the whole paper. The four dimensions are task allocation, path coordination, elevator coordination, and dynamic disturbance response.

First, the study evaluates how the local greedy task allocation strategy leads to resource imbalance and spatial congestion. Secondly, the limitations of independent path planning in predicting conflicts are analyzed. Thirdly, the inefficiency of static elevator scheduling in high-position warehouse operation management is discussed. Finally, the shortcomings of the static scheduling framework in adapting to random order fluctuations are evaluated.

Based on these diagnoses, the study proposes targeted optimization strategies. These strategies aim to improve the throughput and robustness of the system. They provide practical methods for practical applications, and also make theoretical contributions to the research of automated warehouse scheduling.

### 1.4 Innovation points

This study focuses on the pain points of "more single-dimensional optimization, less full-link coordination, and difficult theoretical landing" in the scheduling field of four-way shuttle intensive storage system. The core innovations are as follows:

Firstly, a multi-dimensional coupling efficiency bottleneck diagnosis framework is constructed. This paper breaks through the limitation that the existing research only focuses on the single dimension of task allocation or path planning. For the first time, the four coupling dimensions of task allocation, path coordination, hoist scheduling and dynamic disturbance response are included in the unified analysis system. The system quantifies the efficiency loss caused by the mutual conduction and superposition of

problems in each dimension, and clarifies the core conclusion that the coupling of multiple problems makes the actual throughput of the system only 60 % ~ 75 % of the theoretical peak, which makes up for the shortcomings of the existing research on the analysis of the causes of system-level performance degradation.

Secondly, a lightweight full-link collaborative scheduling strategy set is proposed. Aiming at the pain points of high real-time requirements and difficult deployment of high complexity algorithms in industrial scenes, an optimization scheme that can be directly implemented is designed : First, the task allocation model combining K-means clustering and Hungarian algorithm takes into account spatial agglomeration and equipment load balancing. Second, the multi-device collaborative path planning mechanism based on time window reservation eliminates the intersection conflict from the root. Third, horizontal-vertical linkage dynamic hoist priority scheduling rules, reduce the no-load rate of more than 40 %. Last, event-driven lightweight online rescheduling mechanism, combined with digital twin pre-simulation to achieve rapid response under dynamic disturbances, solves the problem of high computational complexity and difficulty in industrial implementation of existing reinforcement learning methods. Finally, a research conclusion that takes into account both theoretical value and practical guidance is formed.

Through literature quantitative deduction and industry data verification, the applicable scenarios and expected benefits of each optimization strategy are clarified, which provides a transformation path from " passive response " to " active coordination " for warehousing operators. At the same time, the contribution of scheduling optimization to energy consumption reduction is quantified, which is in line with the development goals of green logistics and dual carbon, and expands the social value dimension of automated warehousing scheduling.

## 2. System Configuration and Current Scheduling Practice

### 2.1 System topology and operation architecture

The four-way shuttle dense storage system is composed of high-density shelves, four-way shuttles, transmission elevators and WCS scheduling system. The shuttle can move freely on the single-layer X-axis and Y-axis, and can also use the elevator to access different layers. At present, simple scheduling rules are commonly used in the industry, including first-come-first-served, recently idle shuttle priority allocation, and fixed partitions.

**Table 1. Summary of Current Scheduling Practices and Resulting Deficiencies**

| Scheduling Dimension  | Current Practice                                           | Key Deficiencies                                             | Observed Impact on System                                   |
|-----------------------|------------------------------------------------------------|--------------------------------------------------------------|-------------------------------------------------------------|
| Task Allocation       | First-Come-First-Served (FCFS); Nearest-Idle-Shuttle-First | Ignores destination distribution; lacks spatial planning     | Local congestion; queuing bottlenecks at elevator entrances |
| Path Planning         | Independent shortest-path search (Dijkstra-based)          | No conflict prediction; no time-window coordination          | Frequent stops & backtracking; 20%–30% longer travel time   |
| Elevator Coordination | Static queue (FCFS); isolated horizontal/vertical control  | No dynamic load balancing; information silos between devices | >40% empty trips; bidirectional waiting waste               |
| Dynamic Response      | Fixed parameters; preset static logic                      | Zero real-time adaptation to disturbances or urgent orders   | Severe order backlog during peak periods (e.g., promotions) |

As summarized in Table 1, these simple rules lead to serious resource imbalance, spatial congestion, and significant efficiency loss under high-density multi-task conditions. In general, these defects limit the actual system throughput to only 60% -75% of the theoretical maximum, highlighting the urgent need for system scheduling improvement.

### 2.2 Typical workflow disassembly

The core operations of the system are divided into three categories : warehousing, outbound, and transfer. Taking typical warehousing operations as an example, the complete process is as follows : First, WMS receives upstream

warehousing orders and disassembles the orders into fine-grained tasks of ' tray-target location '. Then WCS completes the ' task-shuttle ' matching according to the current scheduling rules. Then the target shuttle runs along the planned path to the pickup position, lifts the tray and drives to the nearest hoist entrance. Then the hoist transports the shuttle car with the goods to the target floor. Finally, the shuttle runs to the target cargo space to complete the storage, and the task is returned to complete the signal. The outbound and transfer operation process is symmetrical with the warehousing logic, and only the starting point and the end point of the task are different. The inventory operation in special scenarios is directly issued by WCS,

and the idle shuttle vehicle is scheduled to complete the verification of the specified cargo space.

### 3. Root-Cause Analysis of Efficiency Bottlenecks

Current four-way shuttle dense storage systems face a dilemma in real operations. This dilemma is “high theoretical design values but low actual throughput.” The actual operating efficiency of the system is usually only 60% to 75% of its theoretical peak. A single factor does not cause this performance gap. Instead, it results from problems in four dimensions that interact with and reinforce each other. These dimensions are task allocation, path planning, elevator coordination, and dynamic response.

#### 3.1 Local Greediness in Task Allocation

Existing systems commonly use allocation rules such as “nearest idle shuttle first” or “first come, first served” (FCFS). These rules are essentially static greedy strategies based on local information. They ignore the spatiotemporal relationship between tasks and resources.

##### 3.1.1 Destination-Clustering-Induced local congestion

When the destinations of multiple storage tasks are concentrated in the same rack area (for example, deep within the same aisle or near a prime location such as an elevator), simple allocation rules send multiple shuttles to that area at the same time. This scheduling method lacks spatial planning. It easily causes physical congestion in local aisles. Multiple shuttles have to queue and wait in narrow aisles. It may even cause deadlocks. Eder’s research shows that under the FCFS rule, the interaction waiting time between elevators and shuttles grows nonlinearly as system load increases. When the filling rate of the shelf exceeds 80%, the throughput of a single layer may decrease by 15% to 25% [4].

##### 3.1.2 Unbalanced equipment load

The fixed partition or simple nearest shuttle assignment strategy cannot be dynamically adjusted according to real-time vehicle status (such as battery power or failure rate) and task characteristics. This leads to some ‘popular’ shuttles in a high-load operating state for a long time, and their wear increases, and the risk of failure increases. At the same time, other shuttles are idle for a long time. Ekren and Akpunar further confirmed that the increase in the variance of elevator service time is a key factor in the decline of system performance [5]. Basically, the existing rules regard ‘tasks, shuttles and resources’ as independent decision-making units, lacking a global perspective of coordinated optimization.

#### 3.2 Spatial Conflicts and Idealized Assumptions

The four-way shuttle runs on an orthogonal grid-shaped shelf plane with intensive intersections. The existing scheduling system usually uses the Dijkstra algorithm to plan the shortest path for each shuttle independently. They do not perform conflict prediction or time window coordination.

##### 3.2.1 Nonlinear conflict escalation at intersections

Mao et al. found that when there are more than 15 shuttles running simultaneously in the system, the probability of path overlap at key nodes (such as crossroads and T-junctions) will increase sharply [6]. This is because each shuttle is independently looking for its own route. In order to avoid collisions, shuttles must frequently stop to wait or perform complex path backtracking operations. This increases the average travel time per shuttle by 20% to 30%. This kind of ‘fighting each other’ ‘planning mode will lead to a slight decrease in the overall system efficiency with the increase in shuttle density.

##### 3.2.2 Neglect of multi-device coupling

Zhen et al. pointed out that if the path and task coupling relationship between shuttles, AGVs, and elevators is not included in the unified optimization framework, the independent decision-making of each device will lead to a significant loss of global efficiency [7]. Current path planning usually assumes a barrier-free ideal environment. However, in the actual dense storage system, multiple shuttles share limited space. Any path planning that ignores the existence of other shuttles and traffic flow will inevitably lead to frequent conflicts and disorderly operations.

#### 3.3 Vertical Bottleneck and Information Isolation

Elevators serve as the only vertical passage connecting different levels. Their scheduling efficiency directly determines the upper limit of system throughput. However, current scheduling strategies show a clear separation between the “horizontal” and “vertical” dimensions [8].

##### 3.3.1 Static service strategy and load imbalance

Most current systems use a simple queue strategy called “first-come, first-served.” This strategy ignores differences in task urgency across levels and the global load distribution. Arslan and Ekren point out that task arrival rates on different levels are often unevenly distributed. For example, one floor may receive many inbound tasks, while the top floor may receive fewer outbound tasks. This causes the elevator to frequently run empty or repeatedly travel between specific floors. The data shows that the no-load elevator travel may account for more than 40% of the total running time. This seriously wastes the core vertical transportation capacity.

### 3.3.2 Information silos between horizontal and vertical dimensions

There is a lack of information linkage between elevators and shuttles. After the shuttle reaches the elevator entrance, it often has to wait for the elevator to complete the current task before responding. Conversely, when the elevator reaches the floor, it may find that the shuttle is not ready or the goods are not ready. This two-way waiting fully reflects the information island and scheduling disconnection between the vertical dimension (elevator) and the horizontal dimension (shuttle).

### 3.4 Rigidity and Lag in Dynamic Response

In real warehouse operations, order arrivals show significant randomness and fluctuation. An example is the pulse-like traffic during e-commerce promotions. However, existing systems lack online sensing and real-time adjustment capabilities.

#### 3.4.1 Inflexibility of static parameters

Current scheduling logic is mostly based on preset static parameters (such as fixed priorities and fixed paths). It is hard for them to adapt to real-time traffic conditions, equipment failures, or urgent order insertions. Ekren points out that parameter optimization without accounting for dynamic environmental fluctuations may result in actual performance that significantly deviates from theoretical expectations [9,10]. In the peak period of promotion, this strict scheduling strategy will lead to a big gap between system throughput and actual demand. As a result, there will be serious order accumulation.

#### 3.4.2 Insufficient disturbance response capability

When an emergency occurs (such as vehicle failure, network delay, or temporary traffic control), the system lacks a fast fault isolation and task reallocation mechanism. Simple retry logic often aggravates system congestion and cannot quickly reconstruct a feasible operation path. Therefore, the local fault will spread into an overall collapse.

In general, the current four-way shuttle dense storage scheduling system has significant deficiencies in four aspects: task allocation, path planning, elevator coordination, and dynamic response. These problems interact and reinforce each other. Unreasonable task allocation will aggravate the path conflict, and the path conflict will prolong the elevator waiting time. Eventually, this will lead to a spiral decline in the efficiency of the entire system.

## 4. Optimization Strategies for Full-Chain Collaborative Scheduling

In order to solve the identified problems, a comprehensive

optimization system should be constructed from the perspective of the overall system. This system should include task clustering, time window reservation, dynamic priority, and online rescheduling. The goal is to achieve the transition from ‘passive response’ to ‘active collaboration’.

### 4.1 Task Destination Clustering for Allocation Optimization

The traditional ‘recent shuttle priority’ model should be replaced by an intelligent task allocation model based on spatio-temporal relationships.

**Spatial clustering and batch processing:** Using clustering algorithms such as K-means, orders arriving in a short time window are clustered according to the physical coordinates of the destination (aisles, rows, and layers). Tasks close to each other will be grouped and assigned to the same shuttle or the same group of shuttles. This reduces the invalid driving distance of the shuttle on the warehouse ground, and also reduces the probability of cross-collision in the local area.

**Global assignment model for load balancing:** A comprehensive evaluation function is established, which combines real-time shuttle status (location, power, task queue length) and task urgency. Then, the Hungarian algorithm or genetic algorithm is used to obtain the optimal task-shuttle matching scheme. This breaks through the limitation of the local greedy strategy, realizes the dynamic balance of the equipment utilization of the whole fleet, and avoids the situation that some shuttle cars are overloaded and other idle.

### 4.2 Time-Window-Based Collaborative Path Planning

Independent path planning is upgraded to collaborative planning with space-time constraints, and the paradigm is changed from ‘contention for right of way’ to ‘reserve right of way’.

**Time window reservation for conflict resolution:** For each shuttle, path planning not only considers the spatial trajectory, but also includes a reserved time window through key nodes (such as intersections and one-way road entrances). Through distributed or centralized conflict detection, it can actively identify potential spatio-temporal overlaps, so as to achieve dynamic speed adjustment or alternative path selection. This ensures that each shuttle car appears in the right position at the right time, and fundamentally eliminates the situation of parking and waiting at the intersection.

**Integrated multi-device path planning:** The trajectories of shuttles, elevators, and AGVs are integrated into a unified topology network to achieve joint optimization. Establish a communication handshake mechanism between devices.

This ensures a seamless connection between horizontal and vertical transport. It solves the problem of missing multi-device coupling and realizes the global optimization of the entire warehouse logistics path.

#### 4.3 Dynamic Priority Scheduling for Elevators

The fixed mode based on the first-come-first-served is replaced by a dynamic vertical transport capacity allocation based on the principle of maximizing overall efficiency. Load-aware dynamic scheduling: real-time monitor the task backlog and elevator waiting time at each layer, and dynamically adjust the elevator service priority accordingly. Priority response to the needs of severely crowded floors. Alternatively, the elevator will take the initiative to transfer to the task-intensive floors in advance. By predicting the future task arrival rate of each floor, the forward-looking planning of the elevator line is realized. This greatly reduces the empty trip.

Horizontal-vertical linkage coordination: strengthen the information integration between the shuttle and the elevator through the warehouse control system (WCS). When the shuttle is close to the entrance of the elevator, an appointment request will be sent to the elevator in advance. After completing the current task, the elevator determines the next service target according to the reservation queue and the global state. Through the close information linkage, the two-way waiting is eliminated, and the transformation from 'shuttle waiting for elevator' to 'elevator waiting for shuttle' is realized.

#### 4.4 Lightweight Online Rescheduling for Robustness

The scheduling system has the ability to adapt to environmental change and self-healing to cope with dynamic interference.

Event-driven online rescheduling: A real-time monitoring system is deployed to detect abnormal events (such as order fluctuations, equipment failures, and traffic congestion) at the millisecond level. Once the interference is detected, it will immediately trigger the rescheduling process. According to the remaining tasks, available shuttle status, and time constraints, it will quickly generate a new optimization plan. For example, it will dynamically shift the task from a faulty shuttle to a nearby idle shuttle. This ensures the continuity of operation.

Pre-operation simulation based on digital twin: Before the actual implementation, a lightweight digital twin model is used to quickly simulate and evaluate the scheduling scheme. The performance of different strategies under dynamic conditions is evaluated by simulation, and the scheme with the strongest anti-interference ability is selected for execution. This 'first simulation, then execution' mode effectively compensates for the lack of a static strat-

egy and significantly improves the robustness and reliability of the system in complex environments.

### 5. Conclusion

This study systematically studies the causes of efficiency bottlenecks in four-way shuttle dense storage systems from four dimensions: task allocation, path coordination, lift scheduling, and dynamic disturbance response. It is found that the local greedy task allocation strategy will lead to resource competition and local congestion. Each shuttle's independent path planning is based on idealized operational assumptions and cannot predict cross-conflicts. Lift scheduling is disconnected from the shuttle task, and the phenomenon of 'shuttle car such as lift' or 'shuttle car such as lift' often occurs, which aggravates the vertical throughput bottleneck. In addition, the static scheduling framework lacks adaptability to random order fluctuations. This will lead to a decline in efficiency during periods of peak demand. In order to solve these problems, this study proposes targeted optimization strategies, including task-destination clustering, path coordination based on time window, dynamic elevator priority scheduling, and online local rescheduling. These strategies jointly transform the system from passive response to active planning.

The practical significance of this study is to provide practitioners with feasible methods. By implementing the proposed strategy, warehouse operators can narrow the gap between the theoretical design capacity and the actual throughput. This helps to reduce logistics costs, improve order processing speed, and enhance the competitiveness of automated warehousing in the fields of e-commerce, cold chain logistics, and pharmaceutical distribution. At the social level, the optimal scheduling system can reduce unnecessary shuttle and no-load elevator operation, thereby saving energy. This is also in line with the global sustainable development goals and supports more environmentally friendly logistics operations.

This study has some limitations. It mainly relies on the existing data and theoretical analysis, and does not combine the actual enterprise storage system field simulation verification. The actual effect of the optimization strategy needs to be further tested. Based on these limitations, three future research directions are proposed. First, build a high-fidelity warehouse simulation platform to verify the optimization strategy. Second, conduct field tests with logistics companies and use real operating data to calibrate the optimization plan. Third, integrate intelligent algorithms, such as reinforcement learning, to further study dynamic scheduling algorithms.

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