An Emergency Dynamic Isolation System for Human-Robot Collaborative Warehousing: A Performance Study

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Abstract: With the rising living standards and shifting consumer habits, an increasing number of individuals have embraced online shopping. Concurrently, merchants are deploying intensive promotional campaigns, particularly during annual events such as "618," "Double 11," and live-streaming sales, which often trigger instantaneous "order explosion" surges. To address the efficiency-safety conflict arising from intense spatial competition within large-scale, high-density human-robot collaborative smart warehouses under such emergency conditions, this paper proposes an Emergency Dynamic Isolation System (EDIS). The system utilizes Ultra Wide Band (UWB) positioning and Long Short-Term Memory (LSTM) network-based trajectory prediction to perceive real-time human and robot dynamics. It then calculates and generates temporary, minimized virtual safety boundaries based on an improved Dynamic Risk Field Model (DRFM). To evaluate its effectiveness, a high-fidelity discrete-event simulation model was developed in Python, simulating the operation of a super-large book warehouse—with a total area of 30,000 square meters, storing 100,000 bins and 20,000 pallets, and equipped with 285 bin-carrying robots, 57 shuttle robots, 20 pallet-pulling robots, 15 autonomous three-directional forklifts, and 70 operators—under a 500% surge in order volume. Comparative experiments with traditional static physical isolation and static electronic fencing schemes demonstrate that, while ensuring zero collision risk, EDIS improves the overall order completion rate by 46.8%, reduces the average walking distance of pickers by 31.2%, achieves a peak dynamic space-sharing rate of 78.4% in key aisles, and decreases production interruptions due to avoidance maneuvers by 94.7% during the 6-hour emergency peak period. This study provides a quantitatively validated innovative solution for ultra-large, high-density human-robot collaborative smart warehouse systems to cope with extreme operational fluctuations.

Keywords: Emergency Management; Human-Robot Collaboration; Smart Warehouse; Dynamic Risk Field; Spatial Scheduling; Simulation Optimization

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1 Introduction

The rapid development of e-commerce, particularly the rise of the live-streaming commerce model, has fundamentally shifted the core challenge facing retail logistics warehousing: from continuously improving average daily operational efficiency to building system resilience sufficient to withstand short-term, extreme order peaks (e.g., "instant sell-out" surges). Under such "emergency states," daily order

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processing volume often surges to 3–5 times the normal rate within hours. The industry's prevalent coping strategy is to temporarily hire a large number of additional workers. However, in modern large-scale "goods-to-person" smart warehouses, the automation system comprising hundreds of heterogeneous robots and a suddenly dense flow of people form a highly complex, dynamically interwoven operational network, intensifying the spatial competition conflict within the limited physical space to an unprecedented degree [1].

Currently, the widely used fixed physical barriers or fixed-radius electronic fencing, while ensuring basic safety, expose inherent flaws during business peak periods. They create rigid barriers between humans and equipment at the cost of spatial continuity and operational fluency, failing to adapt to dynamically changing operational densities and robot operating modes. Consequently, they often become the critical bottleneck constraining the system's peak throughput [2].

Academic research on human-robot collaboration in smart warehouses has yielded substantial achievements, but it primarily focuses on safety collaboration algorithms under normal operating conditions, path optimization for single-type equipment, and the setting of static safety zones [3, 4]. However, research specifically targeting the problem of "how to achieve real-time optimal balance between safety and efficiency through system-level, dynamic, and adaptive spatial resource reconfiguration under extreme peak pressure within limited physical space" remains scarce. Existing static schemes lack adaptability in emergency scenarios and are deficient in quantitative evaluation within realistic, large-scale settings.

Therefore, this paper proposes an "Emergency Dynamic Isolation System" (EDIS) for large-scale smart warehouses. Its core paradigm shifts safety isolation from a preset, static "physical facility" to an intelligent, programmable "system service" that responds to real-time risks and is generated and released on demand. Taking a large-scale book smart warehouse with a total area of 30,000 square meters, equipped with multiple types of robots and 70 operators as the research object, this paper aims to: (1) elaborate the overall architecture of EDIS and its improved dynamic risk field decision algorithm; (2) construct an ultra-large-scale, high-fidelity simulation environment closely resembling real business scenarios; (3) quantitatively evaluate the comprehensive performance of EDIS in coping with order surges through rigorous comparative experiments, thereby verifying its superiority and application potential.

2 Research Background and State-of-the-Art Review

2.1 Collaborative Operations Under Normal Conditions and Static Safety Strategies

Most existing research focuses on optimizing safety and efficiency under steady-state operating conditions. Villani et al. provided a comprehensive survey of collaborative robotics technologies, emphasizing the importance of real-time monitoring [3]. Liu and Wang proposed a dynamic safety zone method based on real-time risk assessment; however, its scenarios are confined to human-robot interactions near fixed workstations [4]. While such studies offer effective solutions for routine operations, they fail to address the systemic and global resource competition crisis triggered by instantaneous order surges within limited space. Their safety strategies are often static or rule-based, lacking the elasticity and spatial intelligence required under extreme pressure.

2.2 Rigid Isolation and Efficiency Bottlenecks

Traditional warehouses commonly employ fixed barriers to segregate human and robotic zones. More advanced electronic fencing technology establishes fixed-radius safety buffers around mobile robots, triggering intrusive speed reduction or full stops [5]. Although these methods ensure fundamental safety, their essence remains "rigid isolation." Once set, the isolation boundaries cannot be dynamically adjusted according to real-time operational density or differences in equipment types. During peak order periods, such rigid isolation leads to significant under-utilization or inefficient use of effective workspace within a warehouse of fixed area, creating a formidable efficiency "ceiling".

2.3 Limitations in Simulation Verification Scale and Fidelity

Simulation analysis is a crucial means of validating warehouse system performance. However, to manage model complexity, existing studies often significantly simplify the system scale [6]. Such simplified models struggle to accurately capture the micro-dynamics and bottleneck effects of real, large-scale smart warehouses—spanning tens of thousands of square meters with hundreds of heterogeneous devices and dozens of personnel—under extreme load. Consequently, the universality and practical guidance of the conclusions derived from these studies are limited.

In summary, current research exhibits distinct gaps in three key areas: (1) the dynamic response mechanism for emergency states, (2) flexible safety strategies for high-density, heterogeneous equipment clusters, and (3) high-fidelity simulation verification for ultra-large-scale systems. This work constitutes a systematic exploration precisely targeting these gaps.

In addition to the above-mentioned works, recent studies have further explored key aspects related to emergency management in human-robot collaborative warehouses. These include comprehensive reviews of human-robot collaboration in smart warehouses [7], dynamic collision avoidance using improved velocity obstacles [8], cyber-physical system architectures for warehouse automation [9], LSTM-based trajectory prediction for order picking [10], digital twin-based emergency response systems [11], dynamic risk field modeling for shared workspaces [12], UWB-based real-time positioning for high-density operations [13], and reinforcement learning for adaptive safety zone generation [14]. These contributions collectively support the feasibility and necessity of dynamic isolation strategies such as EDIS.

3 System Architecture and Core Algorithm

3.1 Overall EDIS Architecture

The EDIS is a real-time closed-loop control system comprising three layers—"Perception-Decision-Execution"—specifically designed for large-scale, high-density warehousing environments with multiple robot types.

Perception Layer: A high-precision Ultra-Wide Band (UWB) positioning network is deployed throughout the facility. All 70 people and mobile robots are equipped with positioning tags, achieving sub-meter level real-time localization and speed tracking across the entire area. Lightweight Long Short-Term Memory (LSTM) networks deployed on edge computing nodes predict the short-term future trajectories of each entity based on historical movement sequences.

Decision Layer (Core): An improved Dynamic Risk Field Model (DRFM) serves as the system's decision-making brain. Its core concept is to treat each moving entity as a dynamic risk source, whose risk influence range and intensity vary in real-time based on the entity's speed, type, and motion uncertainty. The system generates a real-time, warehouse-wide updated "risk heat map" by superimposing the risk fields from all entities. Areas where the risk value exceeds a dynamic threshold are identified as high-risk zones requiring temporary isolation. The algorithm subsequently generates a "virtual isolation belt" that effectively cordons off the high-risk area while minimizing disruption to normal operations.

Execution Layer: The coordinates of the generated virtual isolation belt are transmitted in real-time to the traffic management systems of the relevant robots, prompting them to dynamically update their paths. Simultaneously, laser projection devices deployed in the warehouse project visible warning boundaries onto the floor. These warnings are synchronized with vibration alerts on the smart wristbands worn by people, achieving a dual human-robot alert mechanism.

3.2 Emergency Mode Triggering and Strategy

The system operates in dual modes, "Normal" and "Emergency", with automatic switching managed by the Warehouse Management System (WMS) based on metrics such as order flow rate.

Triggering Condition: The system automatically enters Emergency Mode when the order intake rate consistently exceeds a preset threshold for a specified duration, or when an "order explosion" event is predicted.

Strategy Adjustments:

Accelerated Decision-Making: The DRFM calculation and decision cycle is significantly shortened to respond more swiftly to dynamic changes.

Elastic Threshold Adjustment: While ensuring absolute physical safety, the safety thresholds are optimally adjusted. This allows for more efficient and compact spatial sharing within the limited 30,000-square-meter area.

Priority Assurance for Critical Traffic: The system intelligently identifies key "logistics arteries." The generation of dynamic isolation zones prioritizes ensuring the unimpeded flow of traffic through these critical channels.

4 Simulation Experiment Design and Evaluation

4.1 Experimental Scenario and Parameters

A high-fidelity simulation environment was constructed based on operational data from a large domestic book e-commerce smart warehouse.

Warehouse Scale: The simulation models a large smart warehouse with a total area of 30,000 square meters and a storage capacity of 100,000 bins and 20,000 pallets.

Equipment and Personnel Configuration:

Automated Equipment:

Bin Horizontal Transport: 285 bin-carrying robots.

Bin Vertical Storage/Retrieval: 57 shuttle robots.

Pallet Horizontal Transport: 20 pallet-pulling robots.

Pallet Vertical Storage/Retrieval: 15 autonomous three-directional forklifts.

Operating workers: A fixed team of 70 people for picking, sorting, and packing. The number of workers remains unchanged during the emergency period, but their work intensity and movement frequency increase.

Manual Workstations: The layout includes 11 electronic sorting walls, 10 automated packing stations, and 18 manual packing stations.

Order Flow and Process: The simulation models a typical "order explosion day" scenario. The first 2 hours represent the Normal Period, with an order influx rate equivalent to 15,000 orders per day. The subsequent 6 hours constitute the Emergency Period, during which the order influx rate instantaneously surges to 500% of the normal rate (equivalent to 75,000 orders per day). The simulation assumes no additional workers or equipment are introduced following the order surge.

Data Source Statement: The performance data for the comparative schemes—Scheme A (Static Physical Isolation) and Scheme B (Static Electronic Fencing)—presented in this study are not directly quoted from existing literature. Instead, they are baseline results obtained by implementing and running these schemes within the self-developed simulation platform for the specific scenario described above. This approach ensures all comparisons are made under identical initial conditions, order flows, and environmental settings, guaranteeing fairness.

4.2 Evaluation Metrics System

Safety Performance: Number of emergency stops (triggered when predicted collision distance < 0.2m), number of system warnings.

Operational Efficiency: Overall order completion rate (quantity completed by the end of the emergency period / total quantity), average utilization rate for each robot type, average walking distance of workers, average task delay time.

Spatial Collaboration Efficacy: Dynamic space-sharing rate of key main aisles (percentage of time the aisle can be safely used simultaneously by different agents).

4.3 Simulation Platform

A high-fidelity discrete-event simulation engine was developed independently using Python. It accurately simulates the entire workflow, including order release, task scheduling and coordination for heterogeneous robots, equipment kinematics, human behavior, and EDIS decision-making. All comparative experiments were initialized using the same random seed to ensure that performance differences arise solely from the differing isolation strategies.

5 Experimental Results and Analysis

Table 1 Comparison of Key Performance Indicators During the 6-hour Emergency Peak Period

Performance Index	**Plan A: Static Physical Isolation**	**Plan B: Static Electronic Fencing**	**Plan C: EDIS Dynamic Isolation**	**Rising Effect (C vs B)**
Overall order completion rate	41.3%	52.7%	77.4%	+46.8%
Bin Robot average utilization rate	65.8%	70.1%	88.3%	+26.0%
Average walking Distance (m)	11230	9830	6760	-31.2%
Main passage space sharing rate peak	0%	18.7%	78.4%	+319%
Unified Emergency braking frequency	0	523	28	-94.7%
Task average total delay (s)	285	178	45	-74.7%

Note: The performance data for all schemes (A, B, C) presented in this table are experimental results obtained by running the simulation model developed in this study under the specific scenario described in Section 4.1.

Based on the simulation experiments, the core performance indicator data shown in Table 1 were obtained. The analysis is as follows:

Breakthrough in Global Efficiency: The significant advantage of EDIS in overall order completion rate (77.4%) demonstrates that its dynamic spatial scheduling capability can resolve complex congestion at a systemic level in high-density environments. Within the fixed 30,000-square-meter space, Scheme A causes process fragmentation due to physical isolation, while Scheme B leads to continuous interruption of the production flow because of frequent "stop-upon-human-appro-ach" events. EDIS, through proactive isolation, ensures the continuity of critical material flow.

Balance Between Safety and Fluency: The high number of emergency stops 523 times in Scheme B exposes the severe disruption its "one-size-fits-all" strategy causes to operational fluency. EDIS requires only 28 mild interventions, achieving a transition from "passive reaction" to "active prevention," thereby guaranteeing smoother workflow while maintaining a higher level of safety.

Efficient Utilization of Limited Space: The 78.4% main aisle sharing rate directly embodies the core concept of EDIS. In a warehouse of fixed area, intelligent regulation enables the spatiotemporal reuse of spatial resources, which is equivalent to expanding the effective operational area and is key to coping peak loads.

Prominent humanistic Benefits: The substantial 31.2% reduction in people walking distance significantly lowers labor intensity and enhances the human-robot collaboration experience.

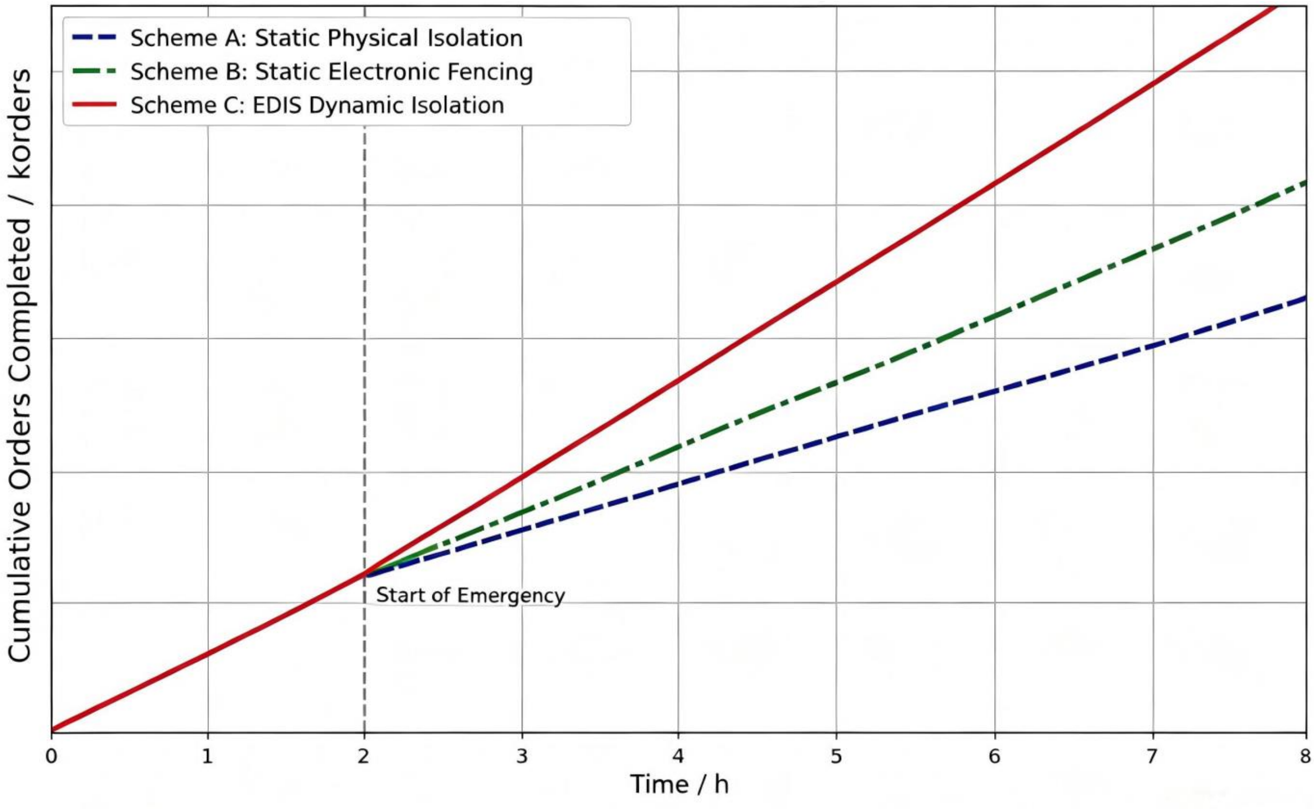

Figure 1 Cumulative Order Completion Quantity Over Time: Virtual Simulation. The curves for the three schemes coincide during the Normal Period. After entering the Emergency Period, the growth slope of Curve C (EDIS) becomes significantly steeper than those of Curves A and B, with the gap continuously widening

6 Discussion and Future Work

This study confirms that, within ultra-large-scale, high-density human-robot collaborative smart warehouse systems, upgrading safety isolation into a real-time, intelligent, and flexible spatial scheduling service is an effective approach for coping with extreme operational fluctuations. The core value of EDIS lies in endowing warehouse operations within fixed physical space with crucial "elastic capacity."

Research Limitations and Future Directions:

More Complex Behavioral Modeling: Future work could incorporate more refined human factors engineering models, such as accounting for individual differences in personnel's psychological reaction times to dynamic warnings.

Economic Analysis: Subsequent efforts will be based on the performance data from this study to conduct a detailed Return on Investment (ROI) analysis, thereby providing a foundation for business decision-making.

Deep Technical Integration: Plans include deeply integrating EDIS with a warehouse Digital Twin platform to achieve a "simulation-optimization-execution" closed loop, and exploring online self-optimization of strategies based on Multi-Agent Reinforcement Learning [15].

7 Conclusion

This paper, addressing the severe efficiency and safety challenges faced by large-scale, high-density human-robot collaborative smart warehouses under "order explosion" emergency scenarios, innovatively proposes an Emergency Dynamic Isolation System (EDIS). By constructing an improved Dynamic Risk Field Model and conducting rigorous comparative experiments in a simulation environment of an ultra-large book warehouse (30,000 m^2, equipped with 377 heterogeneous robots and 70 people), the results demonstrate that EDIS can significantly enhance the system's peak throughput (order completion rate +46.8%), reduce task delays (-74.7%) and personnel workload (walking distance -31.2%), and fully unleash spatial sharing potential (peak sharing rate 78.4%) within a fixed space, all while ensuring zero-collision safety through dynamic risk perception and minimized temporary isolation strategies. This research provides a strictly quantified, innovative system framework and a practically instructive solution for smart warehouses confronting high-volatility operational challenges.

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