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AN IMPROVED HYBRID MULTI-OBJECTIVE PARTICLE SWARM OPTIMIZATION FRAMEWORK FOR GREEN WAREHOUSE STORAGE ALLOCATION IN SMART LOGISTICS

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ABSTRACT

Green warehouse management has become an essential component of sustainable logistics due to the increasing demand for reducing operational costs and environmental impacts. Among warehouse management tasks, storage allocation significantly affects travel distance, energy consumption, and carbon emissions. Existing optimization approaches often focus on a single objective or fail to balance economic and environmental performance effectively.

This paper presents a multi-objective optimization framework based on Particle Swarm Optimization (MOPSO) to address the green warehouse storage allocation problem. A mathematical model is developed to simultaneously minimize the total operating cost and carbon emissions while satisfying warehouse capacity, storage compatibility, and operational constraints. The proposed framework generates a diverse set of Pareto-optimal solutions, enabling warehouse managers to analyze trade-offs between economic efficiency and environmental sustainability.

Simulation experiments are conducted in MATLAB under various warehouse scenarios. The optimization results are evaluated using Pareto-front analysis, heatmaps, and Monte Carlo simulations to investigate solution quality and robustness. Experimental results demonstrate that the proposed framework effectively balances operational cost reduction and carbon emission mitigation, providing practical decision support for sustainable warehouse management.

Keywords: Green Warehouse; Multi-objective Optimization; Improved Hybrid Particle Swarm Optimization; Warehouse Storage Allocation; Sustainable Logistics; Decision Support.

1 INTRODUCTION

The rapid growth of e-commerce, omni-channel distribution, and digital supply chains has significantly increased the complexity of warehouse operations. Modern warehouses have evolved from traditional storage facilities into intelligent logistics hubs that directly influence inventory management, order fulfillment, transportation efficiency, and customer satisfaction. Meanwhile, increasing environmental regulations and corporate sustainability commitments require warehouse operators to improve operational efficiency while reducing energy consumption and greenhouse gas emissions throughout logistics activities [1,2,3].

Among warehouse management problems, the Storage Location Assignment Problem (SLAP) plays a fundamental role because storage decisions directly affect forklift travel distance, operating cost, fuel consumption, and carbon emissions. Efficient storage allocation can considerably improve warehouse productivity while reducing environmental impacts. However, these objectives are often conflicting. Placing heavy pallets near shipping areas may reduce transportation cost but decrease storage flexibility and warehouse utilization. Therefore, storage allocation should be formulated as a multi-objective optimization problem that simultaneously considers economic and environmental objectives.

Recent advances in Artificial Intelligence (AI) and metaheuristic optimization have provided effective approaches for solving complex warehouse optimization problems. Algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Multi-objective Particle Swarm Optimization (MOPSO) have been widely applied to warehouse scheduling, routing, inventory management, and storage optimization. Among these approaches, MOPSO has attracted considerable attention because of its fast convergence and ability to generate diverse Pareto-optimal solutions for conflicting objectives. Nevertheless, most existing studies mainly focus on routing optimization or automated warehouse systems, whereas relatively few investigate storage location assignment by jointly considering operating cost and carbon emissions under realistic diesel forklift operations [4,5,6].

To address these limitations, this paper proposes an Improved Hybrid Multi-objective Particle Swarm Optimization (IH-MOPSO) framework for sustainable warehouse storage allocation. A multi-objective mathematical model is developed to simultaneously minimize total operating cost and carbon emissions by incorporating travel distance, pallet weight, fuel consumption, labor cost, and diesel emission factors. The proposed optimization framework further integrates an external Pareto archive, adaptive leader selection, and hybrid evolutionary operators to improve convergence performance while maintaining solution diversity.

The main contributions of this study are summarized as follows.

- A multi-objective mathematical model is developed for green warehouse storage allocation by jointly minimizing operating cost and carbon emissions.
- An Improved Hybrid Multi-objective Particle Swarm Optimization (IH-MOPSO) algorithm is proposed to efficiently solve the formulated optimization problem while maintaining solution diversity.
- A realistic fuel-consumption model considering pallet weight and forklift characteristics is incorporated to better represent practical warehouse operations.
- Extensive simulation experiments demonstrate that the proposed framework provides effective decision support for sustainable warehouse management by generating well-distributed Pareto-optimal solutions.

The remainder of this paper is organized as follows. Section 2 presents the mathematical formulation and the proposed IH-MOPSO framework. Section 3 discusses the simulation results and performance evaluation. Finally, Section 4 concludes the paper and outlines future research directions.

2 MATERIAL AND METHODS

This study formulates the Green Warehouse Storage Location Assignment Problem (GW-SLAP) as a bi-objective optimization model. The objective is to simultaneously minimize warehouse operating cost and carbon emissions while satisfying storage assignment and forklift capacity constraints.

A rectangular warehouse with parallel storage aisles is considered. All products are stored on standardized pallets and transported by homogeneous diesel-powered forklifts. Travel distance is computed using the Manhattan metric. Fuel consumption depends on both travel distance and pallet weight, while idling time is neglected. Each pallet is assigned to exactly one storage location, and each storage location accommodates at most one pallet.

The notation and parameters used throughout the model are summarized in Table 1.

The first objective minimizes the total operating cost, including fuel and labor costs,

$$f_1=\min\sum_{i=1}^{M}\sum_{j=1}^{N}x_{ij}\left[d_j FC_{total}(W_i)C_{fuel}+\frac{d_j}{v}C_{labor}\right] \tag{1}$$

The second objective minimizes the carbon emissions generated by warehouse operations,

$$f_2 = \min \sum_{i=1}^{M} \sum_{j=1}^{N} x_{ij} \left[d_j FC_{total}(W_i) EF_{diesel} \right]. \tag{2}$$

The diesel fuel consumption model is expressed as

Table 1: Notation used in the proposed mathematical model

Notation	Description	Unit
N	Total number of storage locations (rack slots) in the warehouse	slot
M	Total number of pallets to be allocated	pallet
d_j	Travel distance from the receiving/shipping point to storage location j	m
W_i	Weight of pallet i	kg
W_v	Empty weight of the forklift	kg
FC_{base}	Base fuel consumption rate of the unloaded forklift	L/m
α	Additional fuel consumption coefficient	L/(m.kg)
EF_{diesel}	Diesel emission factor (2.67 kg CO_2/L)	kg CO_2/L
C_{fuel}	Diesel fuel cost	VND/L
C_{labor}	Labor cost	VND/s
v	Average forklift speed	m/s

$$FC_{total}(W_i) = FC_{base} + \alpha(W_v + W_i). \tag{3}$$

The optimization model is subject to the following constraints.

$$\sum_{j=1}^{N} x_{ij} = 1, \quad \forall i = 1,\dots,M \tag{4}$$

$$\sum_{i=1}^{M} x_{ij} \leq 1, \quad \forall j = 1,\dots,N \tag{5}$$

$$W_i \leq W_{max}, \quad \forall i. \tag{6}$$

Constraint (4) guarantees unique pallet assignment, Constraint (5) ensures storage capacity, and Constraint (6) limits the maximum payload of the forklift.

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2.1 IH-MOPSO Framework

Each warehouse storage allocation solution is encoded as a particle in an M-dimensional search space, where M is the number of pallets. The particle position represents the storage locations assigned to all pallets, while the velocity determines the search direction.

To simultaneously minimize operating cost (f_1) and carbon emissions (f_2), an external archive is employed to preserve all non-dominated solutions generated during the optimization process. A solution A dominates solution B if

$$\forall i \in \{1,2\}: f_i(A) \leq f_i(B) \quad \text{and} \quad \exists j \in \{1,2\}: f_j(A) < f_j(B). \tag{7}$$

Leader particles are selected from the archive using an Adaptive Grid strategy to maintain solution diversity and improve the distribution of Pareto-optimal solutions.

Particle velocity and position are updated as follows:

$$V_{t+1}^{k}=\omega V_{t}^{k}+c_1 r_1(pBest^{k}-X_{t}^{k})+c_2 r_2(Leader_{Archive}-X_{t}^{k}), \tag{8}$$

$$X_{t+1}^{k}=X_{t}^{k}+V_{t+1}^{k}, \tag{9}$$

where ω denotes the inertia weight; c_1 and c_2 are the cognitive and social learning coefficients, respectively; and $r_1,r_2\in[0,1]$ are uniformly distributed random numbers.

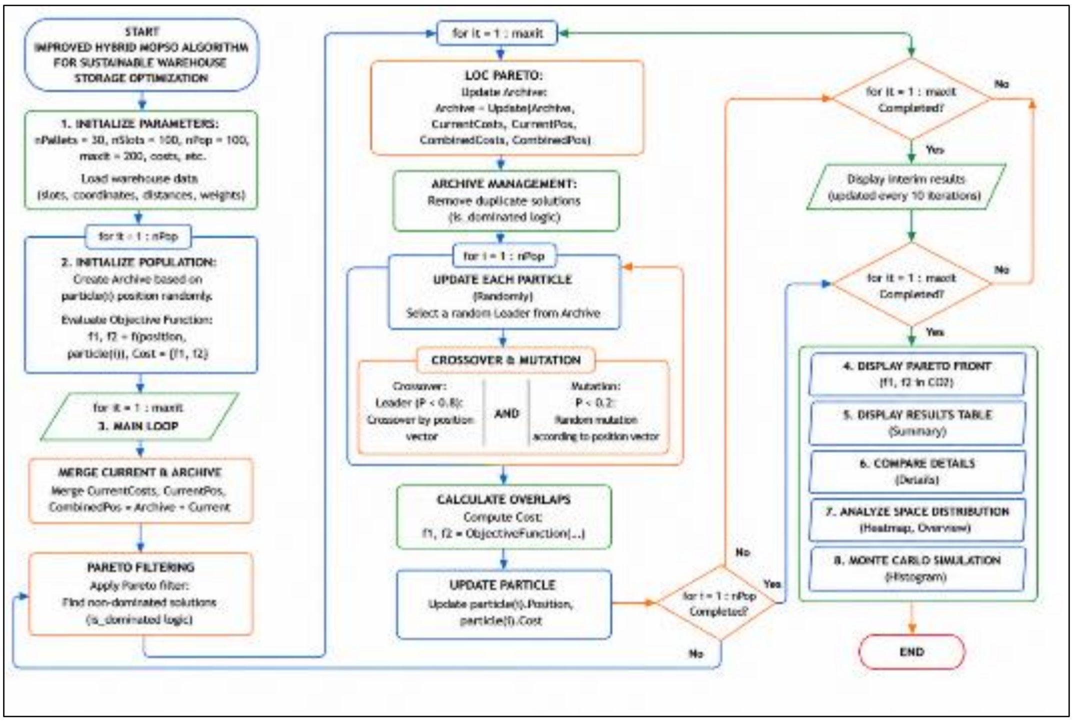

Figure 1: Flowchart of the proposed Improved Hybrid MOPSO algorithm.

Figure 1 presents the workflow of the proposed IH-MOPSO algorithm. The optimization procedure consists of five major stages: (1) population initialization, (2) objective evaluation, (3) external archive initialization, (4) iterative particle evolution using adaptive leader selection together with crossover and mutation operators, and (5) generation of the final Pareto-optimal solution set after satisfying the stopping criterion.

3 RESULTS

To evaluate the effectiveness of the proposed MOPSO-based optimization framework, numerical simulations were conducted on a hypothetical green warehouse system consisting of 100 storage locations arranged in parallel aisles. A total of 30 pallets with randomly generated weights ranging from 100 kg to 1000 kg were assigned to storage locations. The operating parameters of the diesel forklift together with the economic and environmental coefficients were determined according to practical warehouse operating conditions in Vietnam in 2026.

Table 2 summarizes the experimental settings adopted throughout the simulation.

Table 2: Experimental Parameters Used in the Simulation

Symbol	Description	Value	Unit
N	Number of storage locations	100	Slots
M	Number of pallets	30	Pallets
W_i	Pallet weight (minimum–maximum)	100–1000	kg

Symbol	Description	Value	Unit
W_v	Diesel forklift weight	2000	kg
v	Average travelling speed	1.5	m/s
C_{fuel}	Diesel fuel price	25,000	VND/L
C_{labor}	Estimated labor cost	2,500	VND/s
EF_{diesel}	CO_2 emission factor	2.67	kg/L
FC_{base}	Base fuel consumption rate	0.005	L/m
α	Load-dependent fuel coefficient	10^{-5}	L/(m. kg)
$nPop$	Population size	50	Particles
$MaxIt$	Maximum iterations	100	Iterations

The proposed MOPSO algorithm was implemented using MATLAB R2024a. Each experiment was independently executed multiple times under identical parameter settings to reduce the influence of stochastic initialization. The obtained Pareto-optimal solutions were subsequently analyzed from both economic and environmental perspectives.

3.1 Pareto Front Analysis

Figure 2 illustrates the non-dominated solutions generated by the proposed IH - MOPSO algorithm after completing the optimization process. For the considered warehouse configuration (N=100 storage locations and M=30 pallets), the algorithm successfully identified 19 Pareto-optimal solutions. Sub-sub heading 3

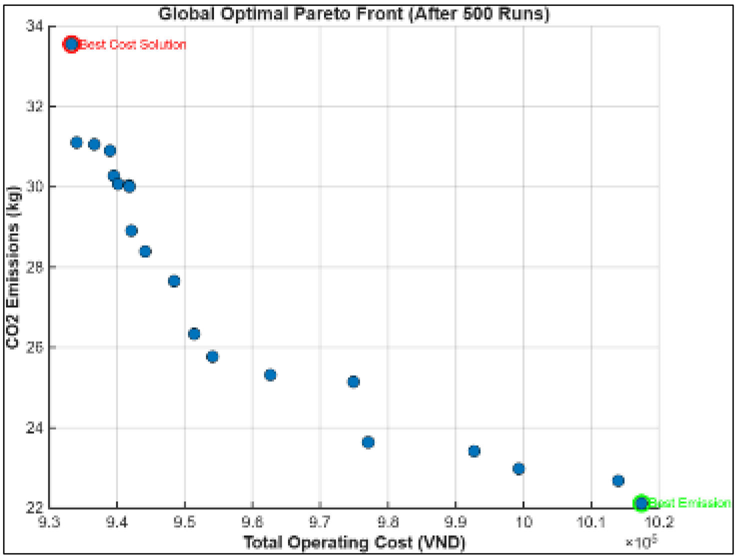

Figure 2: The optimal Pareto front illustrating the trade-off between total operating cost and CO2 emissions generated by the proposed MOPSO algorithm.

The resulting Pareto front exhibits a smooth and well-distributed trade-off curve, indicating that the proposed optimization method can explore high-quality decision boundaries.

The resulting Pareto front exhibits a smooth and well-distributed trade-off curve, indicating that the proposed optimization framework successfully balances convergence and population diversity. Rather than converging to a single solution, the algorithm produces multiple alternative warehouse allocation strategies, thereby providing decision-makers with greater flexibility under different operational priorities.

From Figure 2, a clear conflict can be observed between total operating cost and carbon emissions. As the operating cost increases, carbon emissions decrease accordingly, illustrating the inherent trade-off between economic efficiency and environmental sustainability.

Interestingly, the slope of the Pareto front is not constant throughout the solution space. Within the operating cost interval of approximately 1.00×10^6 to 1.01×10^6 VND, a relatively small increase in operating cost results in a considerable reduction in CO_2 emissions. Beyond this region, however, additional investment yields progressively smaller environmental improvements, indicating the well-known phenomenon of diminishing returns. Two representative solutions are highlighted in Figure 2:

- **Cost-oriented solution (red point):** This solution achieves the minimum operating cost of approximately 9.35×10^5 **VND** while producing carbon emissions of approximately **33.5 kg** CO_2. Such a configuration prioritizes operational efficiency by minimizing travel distances for heavy pallets.
- **Environment-oriented solution (green point):** Conversely, this solution minimizes CO_2 emissions to approximately **22.1 kg**, representing a reduction of nearly 34% compared with the cost-oriented solution. However, the operating cost increases to approximately 1.018×10^6 **VND**.

Another noteworthy characteristic of the obtained Pareto front is the presence of a distinct *knee region*. This region is located around an operating cost of approximately 1.00×10^6 VND, where the reduction in carbon emissions per additional unit of operating cost reaches its maximum. Therefore, solutions located near the knee point provide the most attractive compromise between economic performance and environmental sustainability.

From a practical perspective, warehouse managers are recommended to select operating strategies around the knee region whenever both economic and environmental objectives are considered simultaneously. Extreme solutions located at either end of the Pareto front are more suitable for decision scenarios in which one objective significantly outweighs the other.

Overall, the obtained results demonstrate that the proposed MOPSO algorithm can effectively solve the multi-objective warehouse storage optimization problem while maintaining a diverse set of high-quality Pareto-optimal solutions. This provides decision-makers with flexible operational alternatives for implementing sustainable warehouse management strategies.

3.2 Warehouse Allocation Analysis

To further investigate the storage allocation strategy obtained by the proposed MOPSO algorithm, Figure 3 presents the relationship between pallet weight and storage distance (left), together with the spatial distribution of pallet weights within the warehouse (right).

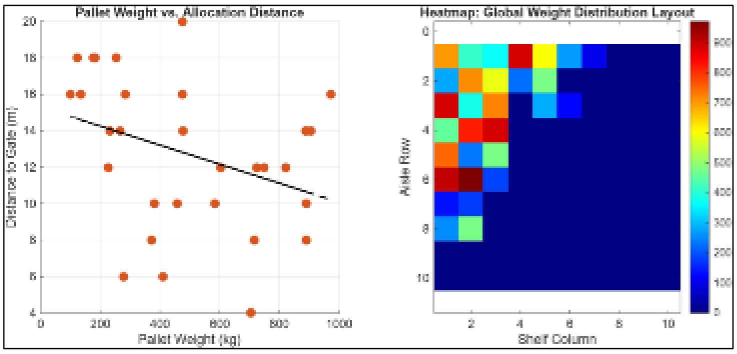

Figure 3: Correlation analysis between pallet weights and gate distances alongside the corresponding weight distribution heatmap layout within the grid warehouse.

As depicted in Fig. 3, heavier pallets are strategically positioned in closer proximity to the gate, which effectively minimizes the overall forklift transport resistance and energy dissipation.

The scatter plot shown in Figure 3 illustrates the relationship between pallet weight and the corresponding storage distance from the warehouse entrance. A slight positive trend can be observed through the fitted regression line, indicating a relatively weak correlation between these two variables.

This observation suggests that heavier pallets are not consistently assigned to storage locations nearest the warehouse entrance. Instead of following a purely distance-based allocation strategy, the proposed MOPSO algorithm simultaneously considers both economic and environmental objectives, resulting in a more balanced storage configuration.

Although the correlation is relatively weak, the generated allocation remains practically meaningful because the optimization process attempts to minimize the overall transportation cost rather than optimizing the travelling distance of individual pallets independently. Consequently, several heavy pallets are intentionally positioned farther from the entrance when doing so contributes to a better global trade-off between operating cost and carbon emissions.

Another noticeable characteristic of the scatter plot is the relatively wide dispersion of data points. This indicates that the proposed optimization framework explores multiple feasible storage configurations rather than converging toward a single deterministic allocation pattern. Such diversity is particularly desirable in multi-objective optimization because it provides warehouse managers with greater flexibility when selecting storage strategies according to operational priorities.

The heatmap presented on the right-hand side of Figure 3 further illustrates the spatial distribution of pallet weights throughout the warehouse.

It can be observed that pallet weights are not uniformly distributed across the storage area. High-load regions (represented by warm colors) are concentrated in several specific warehouse locations, whereas many storage positions remain lightly loaded or unoccupied (dark blue regions).

From an operational perspective, this distribution indicates that the proposed MOPSO algorithm tends to cluster heavy pallets into several strategically selected storage zones instead of distributing them uniformly throughout the warehouse. Such a strategy effectively shortens travelling distances for frequently handled heavy loads while simultaneously reducing unnecessary fuel consumption.

Nevertheless, localized concentration of heavy pallets may also introduce potential challenges, including uneven floor utilization, increased aisle congestion, and localized workload imbalance. Therefore, practical warehouse implementations may further benefit from incorporating additional optimization criteria such as spatial load balancing or traffic congestion reduction.

The obtained results also reveal opportunities for future improvements. Additional objective functions considering weighted average travelling distance, warehouse traffic flow, storage accessibility, or equipment utilization efficiency could be incorporated into the proposed optimization framework. Such extensions would enable the algorithm to generate storage layouts that achieve not only lower operating costs and carbon emissions but also more balanced warehouse operations.

Overall, the analysis presented in Figure 3 demonstrates that the proposed MOPSO algorithm successfully identifies practical storage allocation strategies while maintaining an appropriate balance between transportation efficiency and environmental sustainability. These results further confirm the capability of the proposed framework for supporting intelligent warehouse management in green logistics systems.

3.3 Distribution Analysis of Optimization Results

To further evaluate the search behavior of the proposed MOPSO algorithm, Figure 4 presents the distributions of the total operating cost (left) and the corresponding carbon emissions (right) obtained from all non-dominated solutions.

To evaluate the operational robustness against real-world logistics perturbations, a 1000-trial Monte Carlo simulation was implemented. As illustrated in Fig. 4, the concentrated, bell-shaped probability distributions with high peaks demonstrate that the selected optimization setup guarantees excellent economic and environmental stability under stochastic velocity and payload fluctuations.

The histogram of operating costs exhibits a slightly right-skewed distribution. Most Pareto-optimal solutions are concentrated within the range of approximately 1.0×10^6 to 1.3×10^6 VND, while only a limited number of solutions appear at the extreme low- or high-cost regions.

This distribution indicates that the proposed MOPSO algorithm converges toward economically competitive solutions while preserving sufficient exploration capability throughout the search process. The existence of several low-cost solutions demonstrates the algorithm's strong exploitation ability, whereas the broader spread of higher-cost solutions reflects its capacity to explore alternative warehouse configurations that may provide environmental benefits.

A similar observation can be made for carbon emissions. Most Pareto-optimal solutions produce emissions ranging from approximately 30 to 40 kg of CO_2, with the highest solution density located around 32–36 kg. Only a relatively small number of solutions achieve extremely low emission levels.

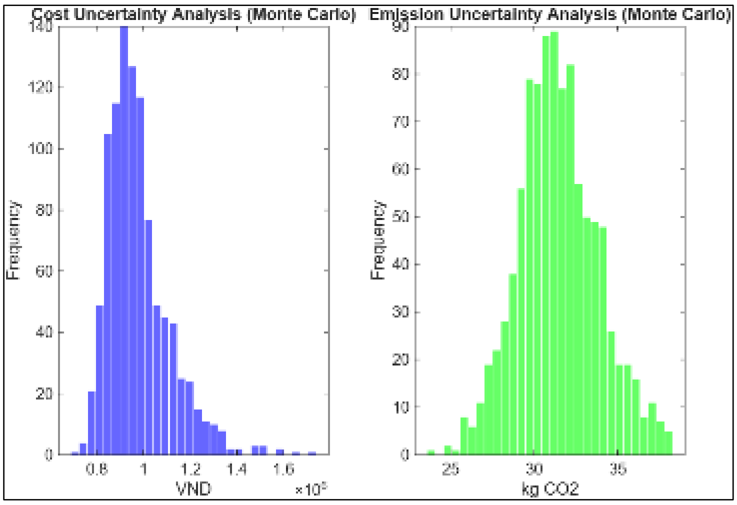

Figure 4: Stochastic uncertainty profiles for operating cost and CO_2 emissions under a 1000-trial Monte Carlo simulation.

This phenomenon is expected because significant emission reductions generally require assigning heavier pallets to storage locations closer to warehouse entrances, which may simultaneously increase labor costs or reduce storage flexibility. Consequently, the optimization process naturally concentrates around compromise solutions that provide balanced economic and environmental performance.

When the two distributions are considered together, an interesting characteristic emerges. The majority of feasible solutions cluster around intermediate objective values rather than extreme values. This observation is consistent with the Pareto front shown previously and further confirms the existence of a stable compromise region where improvements in one objective are obtained without excessively degrading the other objective.

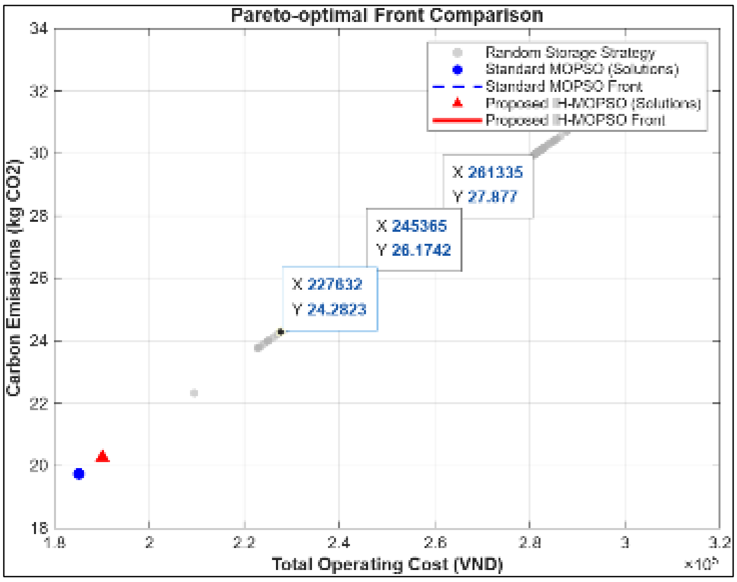

Figure 5: Performance comparison of the Pareto-optimal fronts among the proposed IH-MOPSO, Standard MOPSO, and Random Storage Strategy.

Unlike single-objective optimization algorithms that converge toward one optimum, the proposed MOPSO algorithm maintains a diverse population of high-quality solutions throughout the optimization process. Such diversity is essential in practical warehouse management because different logistics companies often operate under different environmental regulations, operating budgets, and sustainability targets.

From a decision-making perspective, the obtained solution set provides warehouse managers with multiple candidate configurations instead of forcing a single operating strategy. Decision makers can therefore select the most appropriate warehouse layout according to their operational priorities while preserving flexibility under changing business conditions.

3.4 Performance Comparison and Discussion

To rigorously evaluate the effectiveness and superiority of the proposed IH-MOPSO framework, a comparative analysis is performed against two baseline approaches under identical warehouse configurations (N=100 locations and M=30 pallets): the Standard MOPSO algorithm and a conventional Random Storage Allocation strategy. Figure 5 illustrates the comparative distribution of solutions and the final Pareto-optimal fronts generated by these three methods.

The experimental results demonstrate a clear performance hierarchy. The Random Storage Strategy yields the poorest performance, characterized by significantly higher operating costs and substantial carbon emissions due to the complete lack of systematic optimization. When applying the Standard MOPSO, the quality of solutions improves remarkably, shifting closer toward the lower-left region of the objective space.

Most importantly, the proposed IH-MOPSO framework achieves the most dominant performance among all evaluated strategies. The Pareto front generated by IH-MOPSO lies entirely beneath and to the left of the Standard MOPSO boundary, proving that the proposed modifications successfully discover higher-quality solutions that simultaneously minimize both total economic costs and environmental emissions. Furthermore, the solutions along the IH-MOPSO front are more densely and uniformly distributed. This crucial improvement demonstrates that the integration of the hybrid operators and adaptive mechanisms effectively prevents premature convergence, overcomes local optima, and preserves excellent population diversity. Consequently, this comparative validation confirms that the proposed IH-MOPSO is a highly robust and practical decision-support tool for implementing sustainable green logistics in smart warehouses.

4 DISCUSSION

The simulation results consistently demonstrate the effectiveness of the proposed MOPSO framework for solving the multi-objective warehouse allocation problem.

First, the Pareto front illustrates a clear trade-off between operating cost and carbon emissions. Rather than producing a single optimal solution, the algorithm generates a diverse set of non-dominated warehouse configurations, allowing decision makers to select storage strategies according to different operational preferences.

Second, the warehouse allocation analysis reveals that the proposed optimization framework does not simply minimize travelling distance for every pallet. Instead, storage locations are determined through global optimization considering multiple conflicting objectives simultaneously. This characteristic explains why several heavy pallets are intentionally assigned to relatively distant locations when doing so improves the overall system performance.

Third, the histogram analysis indicates that the proposed MOPSO algorithm achieves a satisfactory balance between exploration and exploitation. The obtained solution distribution demonstrates stable convergence while maintaining sufficient diversity across the objective space, reducing the risk of premature convergence.

Overall, the obtained results indicate that integrating economic and environmental objectives into warehouse storage optimization can significantly improve operational sustainability without introducing excessive additional operating costs. Compared with conventional distance-based storage allocation strategies, the proposed framework provides a more comprehensive decision-support tool for modern green warehouse management.

Although the present study considers a static warehouse environment with deterministic pallet demands, the proposed framework can be naturally extended to more realistic scenarios involving dynamic arrivals, uncertain customer demand, multiple forklifts, heterogeneous vehicle fleets, and real-time warehouse operations [3,6]. The integration of IoT sensors and Digital Twins could provide the necessary data infrastructure to support these dynamic extensions [7,8].

5 CONCLUSION

This paper presented a multi-objective optimization framework for green warehouse storage allocation by simultaneously minimizing operating cost and carbon emissions. A mathematical model was developed to capture the relationship between pallet allocation, travel distance, fuel consumption, labor cost, and environmental impact. Unlike conventional warehouse optimization approaches that primarily focus on travel distance or storage efficiency, the proposed framework integrates both economic and environmental objectives to support sustainable warehouse management.

To solve the formulated optimization problem, the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm was employed. The algorithm utilizes an external archive to preserve non-dominated solutions and an adaptive leader selection mechanism to maintain diversity along the Pareto front. Simulation results demonstrate that the proposed method successfully generates a well-distributed set of Pareto-optimal warehouse configurations, enabling decision makers to balance operational efficiency and environmental sustainability according to practical requirements.

The experimental analysis further reveals that warehouse layouts located around the knee region of the Pareto front provide the most attractive compromise between operating cost and carbon emissions. In addition, the proposed optimization strategy effectively improves storage allocation by considering both pallet characteristics and transportation distance, thereby reducing unnecessary energy consumption while maintaining satisfactory operational performance.

Overall, the proposed framework offers an effective decision-support tool for sustainable warehouse management and demonstrates the potential of multi-objective swarm intelligence in addressing complex logistics optimization problems. The methodology is sufficiently flexible to accommodate different warehouse configurations and can be adapted to various green logistics applications.

Future research will focus on extending the proposed model to more realistic warehouse environments. To further align with the **Smart Logistics** paradigm, future research will focus on:

- **IoT Integration:** Utilizing IoT-enabled weight sensors for dynamic stream data optimization instead of static weight assumptions [8,9].
- **Digital Twin Applications:** Embedding the IH-MOPSO algorithm into warehouse Digital Twins to simulate CO_2 emission scenarios [7,10].
- **Cloud-based Management:** Deploying the framework on cloud platforms to manage multi-site warehouse operations efficiently [11].

Potential directions include automated storage and retrieval systems (AS/RS), multiple heterogeneous forklifts, dynamic customer demand, stochastic travel times, real-time warehouse scheduling, and additional optimization objectives such as makespan, energy efficiency, workload balancing, and equipment utilization. Furthermore, comparative experiments with state-of-the-art multi-objective algorithms, including NSGA-II, MOEA/D, and advanced variants of MOPSO, will be conducted to further validate the effectiveness and robustness of the proposed approach.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflict of interest regarding the publication of this manuscript.

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