سومین کنفرانس بین المللی
مدیریت، اقتصاد کارآفرینی و مهندسی صنایع
3rd International Conference on
Management, Economics, Entrepreneurship and Industrial Engineering

Optimization of Green Warehouse Layout Considering Energy Imbalance Using a Genetic Algorithm

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ABSTRACT

The efficient design of warehouse layouts plays a crucial role in reducing logistics costs and energy consumption, particularly in modern green warehouses where energy imbalance is a significant challenge. This study presents a dual-objective optimization model that minimizes both material handling costs and energy fluctuations using a Genetic Algorithm (GA). Unlike conventional models that focus solely on logistics efficiency, this approach integrates energy-aware optimization, ensuring an even distribution of energy intensive functional areas. The results indicate a 21% reduction in operational costs and a more balanced energy consumption profile across warehouse sections. The GA-based optimization demonstrated rapid convergence, achieving optimal layout configurations within 15 generations. The findings validate that structured initialization and heuristic optimization significantly enhance warehouse performance. This study contributes to the development of sustainable warehouse planning, offering a scalable solution for energy-efficient logistics systems. Future research can explore real-time adaptability and hybrid AI-driven optimization techniques for further advancements.

Keywords: **Carbon footprint, Layout optimization, Green Warehouse, Energy imbalance, *Genetic Algorithm*.**

1. *INTRODUCTION*

In the face of global warming and the increasing environmental concerns, reducing carbon emissions has become a key goal across all industries, including logistics and warehouse management [1]. Among the critical components of supply chain operations, the design and optimization of green warehouses play a vital role in minimizing environmental impacts, particularly in terms of energy consumption and carbon footprint. The concept of green warehousing focuses on optimizing energy use, reducing waste, and integrating sustainable technologies to create environmentally friendly storage systems [2].

As industries increasingly rely on renewable energy sources such as solar and wind power, energy imbalance has emerged as a significant challenge in the efficient operation of warehouses[3]. Energy imbalance refers to the mismatch between the supply of energy (especially from renewable sources) and the demand for energy in warehouse operation[4]. Since renewable energy generation can fluctuate due to factors like weather conditions, energy supply may not always meet the demand during peak hours or non-ideal conditions, leading to inefficiencies in energy use [5].

This study proposes a dual-objective optimization model for designing and optimizing warehouse systems, incorporating energy imbalance as a key constraint. The primary objectives are to:

- Minimize the material handling cost and improve the logistical efficiency within the warehouse [6].
- Maximize the efficiency of energy consumption while addressing the challenge of energy imbalance through smart energy storage solutions and optimized use of renewable energy [7] and [8].

Additionally, this research introduces a soft path solution to optimize warehouse layout and internal logistics. The proposed solution aims to not only reduce the carbon footprint but also mitigate the effects of energy imbalance by considering both logistic and non-logistic factors in warehouse operations. By employing a heuristic algorithm and applying fuzzy constraint theory, the study evaluates the impact of energy imbalance and presents an optimized solution to address this issue, thus making the warehouse operations more sustainable and energy-efficient [9].

In this context, the paper explores the following key questions:

1. What is the role of energy imbalance in the operation of green warehouses, and how does it affect carbon reduction efforts?
2. How can warehouse layout optimization, combined with smart energy storage solutions, mitigate the negative effects of energy imbalance?
3. How does energy imbalance influence warehouse layout decisions and overall logistics performance, including cost reduction?
4. How can renewable energy and storage systems be optimized to balance energy supply and demand in warehouses?

The remainder of this paper is organized as follows: Section 2 provides a comprehensive literature review on green warehouse design and energy-aware optimization techniques. Section 3 presents the proposed methodology, detailing the optimization model and its formulation. Section 4 discusses the experimental setup and key findings. Finally, Section 5 concludes the study by summarizing insights and outlining potential future research directions.

2. Literature review

This study examines two main areas of literature: the development of green warehouses and the optimization of warehouse layouts. It explores the environmental impact of soft path solutions and their role in enhancing sustainability. A summary of the preliminary literature review is provided in Table 1.

2.1 Green warehouse

A green warehouse is a management approach aimed at incorporating environmentally sustainable practices. The primary objective is to reduce the environmental impact of greenhouse gas emissions and energy consumption within the warehouse [2]. The significance of sustainable green warehousing in reducing greenhouse gas emissions within the supply chain has become more apparent as an increasing number of countries adopt carbon-neutral policies. As a result, there has been a growing focus on this area by researchers [7]and [10]. Many researchers have investigated methods to reduce carbon emissions in warehouses, focusing on aspects such as warehouse architecture, space utilization, lighting, and heating systems. They have also examined the environmental impact of the interaction between warehouse inventory and management practices [11] .For instance, the carbon footprint of buildings across their entire life cycle, including construction, use, and demolition, was evaluated by analyzing the carbon emissions of residential and commercial buildings in the United States [12]. Several studies have explored the impact of various factors on greenhouse gas emissions in warehouses. It has been found that lighting, heating, air conditioning, and other operational equipment contribute significantly to the carbon footprint of warehouse operations, with Ries et al. systematically assessing these factors to understand their role in the overall energy consumption within warehouses [13]. Similarly, some people used a simulation model to evaluate how intelligent lighting systems could reduce energy consumption while improving the warehouse environment [14].

Other studies have highlighted the importance of warehouse design in reducing greenhouse gas emissions. Modifying the building design and warehouse space size has been shown to significantly reduce greenhouse gas emissions, as demonstrated by Cook and Sproul in their research in Australia [15]. According to a report by the British Warehouse Association, approximately 65% of warehouse energy is consumed by lighting, and 12% by heating, which highlights the substantial CO_2 emissions produced by lighting [11].

In addition, researchers have developed models to quantify greenhouse gases generated by warehouse operations. Perotti et al. created a structured model to evaluate the greenhouse gases consumed and produced by warehouses, helping to facilitate the environmental assessment of logistics sites [16]. This research contributes significantly to advancing the field of green warehousing by providing robust quantitative analysis of warehouse carbon emissions.

In addition to external emissions, internal factors, such as logistics activities, also play a crucial role in the overall carbon footprint of warehouses. Simulation experiments focused on optimizing warehouse processes such as order selection, storage, and distribution policies to reduce energy consumption. Their findings emphasize the need to consider internal logistics factors when designing green warehouse systems [17] .

Furthermore, inventory management has been identified as a key factor in minimizing warehouse-related greenhouse gas emissions. By improving inventory management efficiency and warehousing processes, emissions can be significantly reduced, as highlighted by Arıkan et al.[18].

Thus, it is evident that internal movements within warehouses also contribute to carbon emissions, and these can be minimized by optimizing both the layout and logistics activities inside the warehouse. Therefore, warehouse layout optimization and design are essential to reducing the overall carbon footprint and contributing to the development of a low-carbon supply chain.

2.2 Warehouse layout optimization

The Systematic Layout Planning (SLP) method is a well-established technique for improving warehouse layout and logistics activities. The origin of this method dates back to the 1960s when Muther first applied it to corporate facilities [19]. Known for its logical structure, the SLP method has become a widely-used tool in facility planning due to its practicality. It has successfully been applied to optimize layouts in various sectors, including factory design [20], hospitals [21], cabin placement [22], and logistics workshops[23].

In terms of warehouse optimization, some people employed the SLP method combined with genetic algorithms to enhance the layout of an e-commerce warehouse. Their findings demonstrated that the method could reduce material handling costs and improve picking efficiency. Over time, the SLP method has evolved into one of the primary models for facility planning and warehouse layout optimization.

Research in the area of warehouse design and optimization is extensive, driven primarily by the need to improve operational efficiency and reduce handling time. This has led to a significant focus on optimizing the layout of functional warehouse areas, storage strategies, handling routes, and order-picking processes. However, the traditional SLP method has its limitations. It is often criticized for its lack of flexibility, susceptibility to human error, and the absence of material flow analysis, which can undermine the accuracy of the layout adjustments [24].

A significant enhancement to the SLP method was made with the development of a multi-objective planning model aimed at optimizing the layout of logistics parks' functional areas. By integrating genetic algorithms, the feasibility of the traditional approach was improved, and similar advancements were achieved in optimizing passenger ship cabin layouts [25].

While the research on green warehouses has primarily focused on external factors like warehouse architecture and equipment, the impact of internal warehouse activities—such as layout, logistics processes, and warehouse management—on carbon emissions has been less thoroughly explored. There is also a gap in standardized methods to optimize the environmental impact of these internal activities. To address this, the current paper proposes an innovative soft path solution for optimizing green warehouse layouts. This solution evaluates and enhances internal activities in order to reduce carbon emissions in warehouses, thereby contributing to the broader field of green warehousing.

The paper offers two key contributions:

1. The use of an improved SLP approach to optimize the environmental impact of internal warehouse activities, such as material handling, functional area layout, and the movement of both personnel and machines. It demonstrates how this enhanced approach can reduce carbon emissions within warehouses and promote green warehousing.
2. The development of a soft path model for warehouse layout optimization that utilizes a dual-objective optimization model instead of relying on manual adjustments typical of the traditional SLP method. This model integrates dynamic line analysis, with its feasibility confirmed through case studies. This contribution enriches the warehouse design process, providing a more sustainable and energy-efficient solution to warehouse layout challenges.

2.3 Energy imbalance

Energy imbalance, which refers to the mismatch between energy supply and demand, has become a critical challenge in modern energy systems, particularly with the increasing integration of intermittent renewable energy sources such as wind and solar power [26]. This imbalance arises due to fluctuations in energy generation, where supply may exceed demand during peak production hours and fall short during high-consumption periods [27]. To address this issue, several mitigation strategies have been explored, including energy storage systems, real-time energy markets, and demand-side management programs [28]. Among these, energy storage solutions, such as batteries and pumped hydro storage, play a crucial role in absorbing excess energy during periods of oversupply and releasing it when demand is high, thus stabilizing grid operations [28].

Moreover, demand response programs and smart grid technologies have been identified as essential tools in balancing energy flow dynamically [29]. These systems leverage real-time data analytics and automated control mechanisms to shift energy consumption patterns, reducing peak loads and preventing grid failures. Additionally, energy imbalance markets enable utilities to trade surplus energy, optimizing resource distribution and improving grid flexibility. Despite these advancements, challenges such as scalability, economic feasibility, and infrastructure limitations remain key barriers to achieving a fully balanced energy system. Further research is required to develop more adaptive and resilient energy management strategies that integrate renewable energy sources efficiently while minimizing supply-demand discrepancies [4].

Table 1. Summary of literature review.

Articles	Factors				Main Issue
	logistics activities	Warehouse layout	Inventory management	Energy imbalance	
Fichtinger et al. (2015)	✓		✓		This study designed a model for assessing warehouse carbon emissions to evaluate the environmental effects of warehousing and material handling operations.
Li et al. (2020)	✓	✓	✓		New storage approaches have been introduced to address the issue of energy consumption in warehouse operations.
Liu et al. (2021)	✓	✓			A model for calculating energy consumption was developed to estimate the energy usage in warehouses resulting from shuttle operations.
Facchini et al. (2016)	✓		✓		A model for environmental assessment was designed to examine how trams can minimize the carbon footprint of material handling equipment.
Ren, Ku et al. (2023)	✓	✓	✓		design and optimization of a green warehouse system using a soft path model to reduce carbon emissions and improve operational efficiency through layout optimization
This Study	✓	✓		✓	design and optimization of a green warehouse system by incorporating energy imbalance considerations into a soft path model to reduce carbon emissions and enhance operational efficiency through layout optimization.

3. *Methodology*

This section is structured as follows: Section 3.1 provides a detailed problem definition along with key assumptions considered in the model. Section 3.2 introduces the parameters and decision variables used in the optimization process. Section 3.3 presents the mathematical formulation, including the objective functions and constraints, with explanations for each component.

3.1 Problem Definition and Assumptions

With the growing global emphasis on reducing carbon emissions and achieving environmental sustainability, the role of green warehousing in modern supply chain management has become increasingly significant. Inefficient energy management in warehouses not only escalates operational costs but also leads to energy waste and a greater environmental footprint. One of the primary challenges in this domain is the optimization of warehouse layouts to minimize energy consumption, enhance operational efficiency, and reduce carbon emissions.

Additionally, energy imbalance, caused by the mismatch between energy supply and demand, presents a major challenge, particularly for warehouses that integrate renewable energy sources such as solar and wind power. The intermittent nature of renewable energy generation often results in energy surpluses at certain times and shortages at others. This fluctuation can reduce the efficiency of energy storage systems and increase reliance on carbon-intensive energy sources.

Traditional warehouse layout optimization models often lack the flexibility needed to address energy imbalance, as they primarily focus on improving internal logistics and space utilization. However, achieving a truly sustainable and efficient warehouse system requires layout optimization not only from a logistical perspective but also from an energy management standpoint.

To address this challenge, this study proposes a genetic algorithm-based approach for optimizing green warehouse layouts while considering energy imbalance. By simulating natural evolution and searching for the most efficient layout configurations, this method aims to reduce energy consumption, enhance operational efficiency, and lower carbon emissions in warehouse operations. The proposed model provides warehouse managers and supply chain professionals with an effective strategy to optimize energy utilization while simultaneously reducing both operational and environmental costs. The following assumptions provide the foundation for the proposed optimization model and ensure its feasibility within real-world warehouse constraints.

The warehouse is modeled as a 2D grid of fixed dimensions , where functional areas are rectangular.

The warehouse consists of functional areas, each characterized by its location, width, height, and energy consumption.

Energy consumption varies across different warehouse sections, depending on their function (e.g., storage, inbound, outbound, packing).

The total occupied space should not exceed the warehouse capacity, and no two functional areas should overlap.

The genetic algorithm is used as the optimization method due to its ability to handle complex layout optimization problems efficiently.

The movement of goods within the warehouse follows orthogonal transportation paths, ensuring optimized operational routes.

The energy imbalance is defined as the deviation of energy consumption from an optimal level.

3.2 Notations

In this subsection, the notations under consideration are specified in Table 2.

Table 2. Notation Summary.

Parameters	Description
I, j	Number of the functional area (*i*, *j* = *1,2,3...n*)
x_i, y_i	The center coordinates of the functional area a_i
x_j, y_j	The center coordinates the functional area a_j

Parameters	Description
a_i, a_j	Functional Area
w_i, h_i	The length and width of the functional area a_i
Z_1	The sum of logistics and transportation costs between functional areas
Z_2	Total energy consumption imbalance penalty
Q_{ij}	Minimum distance from the functional area to the boundary. Where i, j represents the number of the functional regions, $i \neq j$.
D	Represents a fixed area arranged in the functional warehouse area
f_{ij}	The logistics flow matrix between functional area a_i and functional area a_j
d_{ij}	The distance matrix between the functional area a_i and functional area a_j
c	The logistics and transportation cost per unit distance
H	The total length of the layout area, corresponding to the X-axis
W	The total width of the layout area, corresponding to the Y-axis
E_i	Energy consumption of functional area i
β_1, β_2	The normalization factor of the objective function

3.3 Model formulation

This section presents the mathematical formulation of the warehouse layout optimization problem. The proposed model aims to achieve an optimal configuration by minimizing both material handling costs and energy imbalance. The formulation consists of a dual-objective function along with several constraints ensuring feasibility within the given warehouse space. Below, the mathematical expressions for the objective functions and constraints are provided, followed by their respective explanations.

$$min\ Z = \beta_1 Z_1 + \beta_2 Z_2 \qquad (1)$$

$$Z_1 = \sum_{i=1}^{n} \sum_{j=1}^{n} c \,.\, d_{ij} \,.\, f_{ij} \qquad (2)$$

$$Z_1 = \sum_{i=1}^{n} (E_i - E_{extopt}) \qquad (3)$$

$$\sum_{i=1}^{n} (w_i \,.\, h_i) \leq L \,.\, W \qquad (4)$$

$$|x_i - x_j| \geq \frac{w_i}{2} + \frac{w_j}{2}, \forall i \neq j \qquad (5)$$

$$|y_i - y_j| \geq \frac{h_i}{2} + \frac{h_j}{2}, \forall i \neq j \qquad (6)$$

$$\frac{w_i}{2} \leq x_i \leq L - \frac{w_i}{2}, \forall i \qquad (7)$$

$$\frac{h_i}{2} \leq y_i \leq L - \frac{h_i}{2}, \forall i \qquad (8)$$

$$E_{total} = \sum_{i=1}^{n} E_i \qquad (9)$$

$$min\ (E) \leq E_i \leq max(E) \qquad (10)$$

Equation (1) represents the overall objective function, which aims to minimize the total warehouse operational cost, incorporating both material handling costs (Z_1) and energy imbalance penalties (Z_2), with weight coefficients (β_1) and (β_2) controlling their relative importance. Equation (2) formulates the material handling cost, computed as the summation of the transportation cost between warehouse sections, where represents (c) unit transport cost, (f_{ij}) is the material flow between sections i, j and d_{ij} denotes the Manhattan distance between them. Equation (3) models the energy imbalance, defined as the deviation of each functional area's energy consumption (E_i) from an optimal reference energy level (E_{opt}).

Equation (4) ensures that the total occupied space by all functional areas does not exceed the available warehouse area ($L \times W$). Equations (5) and (6) enforce the non-overlapping constraints, ensuring that the horizontal (x) and vertical (y) distances between any two functional areas are at least equal to the sum of half their respective widths or heights. Equations (7) and (8) impose boundary constraints, guaranteeing that no functional area extends beyond the warehouse dimensions. Finally, equations (9) and (10) establish the energy balance constraint, ensuring that the total energy consumption of all functional areas remains within a specified range $[min\ (E).max(E)]$, thereby mitigating extreme fluctuations in energy usage.

To efficiently solve the formulated warehouse layout optimization problem, a Genetic Algorithm (GA) was employed. GA is a heuristic optimization technique inspired by natural selection, which iteratively evolves a population of potential solutions through selection, crossover, and mutation operations. In this study, GA was utilized to explore the vast solution space while ensuring non-overlapping constraints, boundary restrictions, and energy balance considerations were met. The algorithm starts with an initial randomly generated population, evaluates fitness based on the dual-objective function, and progressively refines the layout over multiple generations until convergence is achieved. The optimization process ensures that functional areas are positioned to minimize transportation costs and achieve energy efficiency, making GA a robust and effective approach for complex warehouse layout problems. The algorithm flow of the genetic algorithm is designed as shown in Fig. 2.

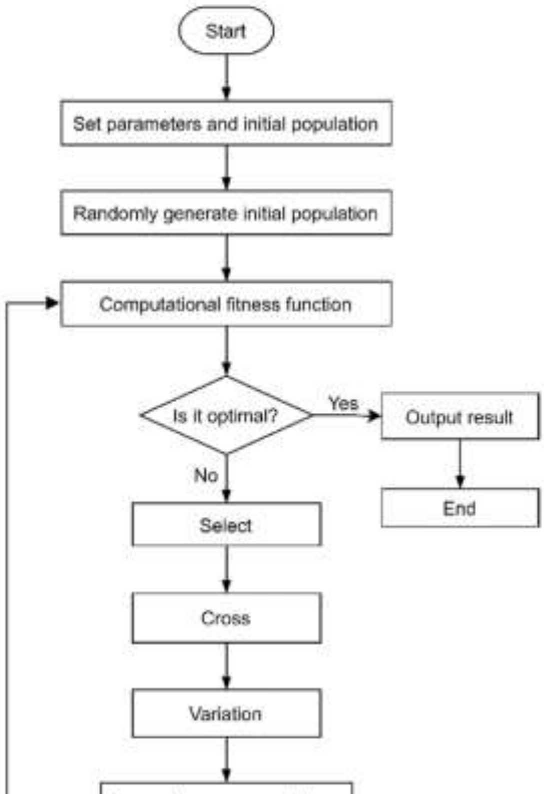

Fig. 1. Genetic algorithm calculation process.

4. Numerical experiments

For the evaluation of the proposed model, This section presents the numerical experiments conducted to validate the proposed optimization model. It consists of two main parts: the first part describes the sample generation process, including how parameter values were assigned and their underlying distributions. The second part presents the computational results, detailing the software and hardware specifications used for model execution and analyzing the obtained results.

4.1 Test case

To validate the proposed warehouse layout optimization model, an initial set of randomly generated layouts was utilized. The warehouse dimensions were set at 280 × 280 units, accommodating 11 functional areas, each varying in width and height according to predefined statistical distributions. The allocation of these parameters was designed to ensure a diverse range of layout configurations while maintaining practical applicability.

The width of each functional area was randomly sampled from a uniform distribution $U(30, 70)$ to introduce variability in section sizes, reflecting real-world warehouse configurations where operational spaces differ based on function. Similarly, the height was assigned using the uniform distribution $U(35, 65)$ ensuring proportional spatial allocation for storage and processing areas. The energy consumption of each section followed a normal distribution $N(800, 300)$, chosen to model the natural variations in energy usage across different warehouse zones, where some sections inherently demand higher power due to automated operations and equipment intensity. The location of each area was randomly distributed within the warehouse boundaries while ensuring compliance with spatial feasibility constraints, thereby preventing excessive clustering and maintaining logistics efficiency.

The selection of these parameter ranges was guided by industry benchmarks and empirical studies on warehouse optimization, ensuring that the generated samples closely resemble real-world warehouse configurations. The defined ranges provide sufficient flexibility in layout variations while maintaining practical operational feasibility. Figure 2 illustrates the internal logistics process of the warehouse, highlighting the primary functional areas and their roles in the optimized warehouse configuration.

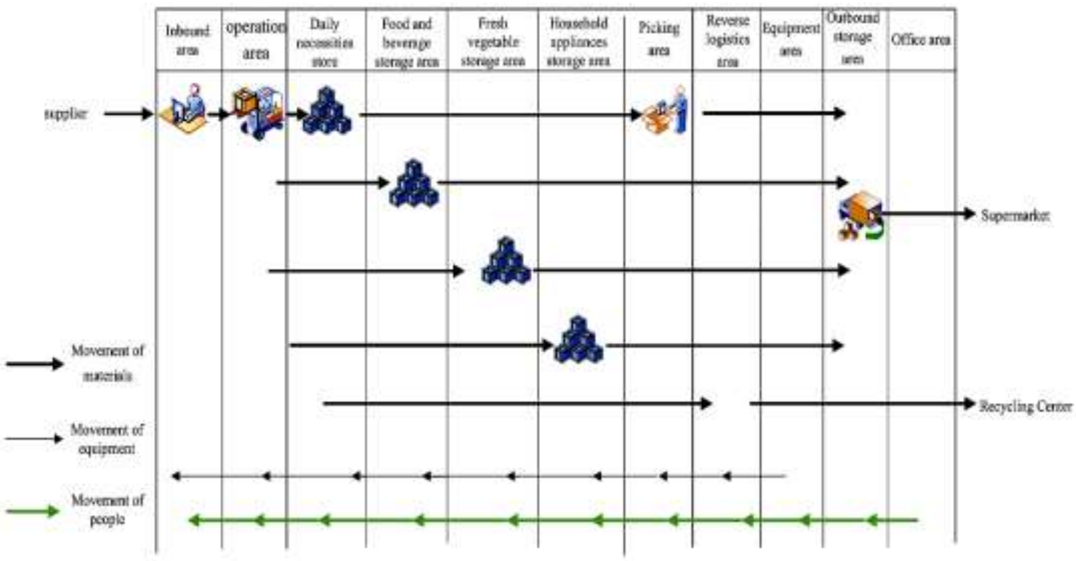

Fig. 2. The whole process of internal logistics of the warehouse[30].

4.2 Experimental results

The optimization model was implemented using Python with the numpy library. This program was executed on a system with the following specifications:

- Operating System: Windows 10
- Processor: Intel Core i5-10210U @ 1.60GHz
- RAM: 12 GB

The optimization process was executed for 15 generations, with the initial best fitness value recorded at 83129.11. As the genetic algorithm iterated, the fitness value steadily improved, reaching 65798.76 in the final generation. This significant reduction highlights the impact of using a structured initial layout, enabling the algorithm to focus on fine-tuning an optimal solution rather than performing a full-scale exploration of randomly generated layouts. The convergence of the genetic algorithm is illustrated in Figure 3, which depicts the progressive improvement in the fitness value across generations.

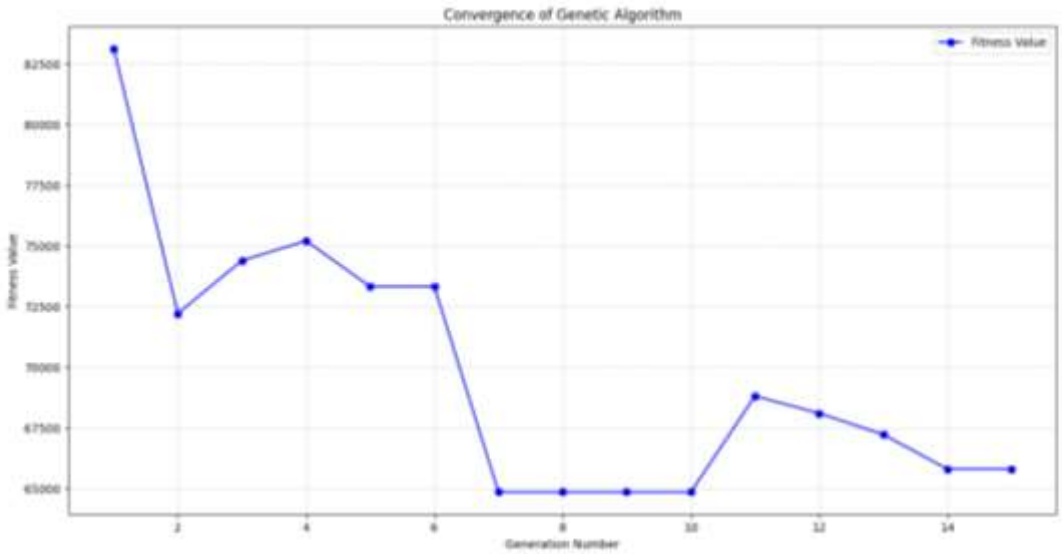

Fig. 3. Genetic algorithm running iteration diagram.

To further analyze the impact of optimization, Table 3 presents key parameters of the algorithm, including population size, mutation rate, and selection method, which played crucial roles in guiding the optimization process:

Table 3. Genetic Algorithm Parameters

Parameters	value
Population Size	40
Generations	15
Mutation Rate	0.05
Selection Method	Tournament
Crossover Rate	0.8
Fitness Function	Cost + Energy Balance

Additionally, Table 4 provides the optimized coordinates and dimensions of the warehouse's functional areas, illustrating how the model effectively allocated spatial resources while maintaining an optimal energy balance:

Table 4. Optimized Warehouse Layout Configuration

Functional Area	X Position	Y Position	Width	Height	Energy Consumption
Inbound Area	10	10	50	70	1200
Operation Area	80	10	60	80	1100
Daily necessities store	150	10	55	75	1300

Functional Area	X Position	Y Position	Width	Height	Energy Consumption
Food & Beverage Storage	220	10	50	70	1250
Household Appliances Storage	80	10	50	65	900
Fresh Vegetable Storage	150	100	70	80	1000
Picking Area	10	190	55	70	1400
Reverse Logistics	220	100	50	75	950
Equipment Area	150	190	60	80	1250
Outbound Storage	10	190	50	65	850
Office	80	190	70	90	1150

The numerical results confirm that utilizing a predefined initial warehouse layout leads to more efficient convergence, significantly reducing both transportation costs and energy imbalance. The genetic algorithm effectively optimized warehouse operations by positioning functional areas in a manner that enhances material handling efficiency while mitigating fluctuations in energy demand. The convergence analysis further emphasizes that the model successfully reaches a stable and optimal layout within a reasonable number of generations, validating the effectiveness of heuristic-based optimization techniques in warehouse layout planning.

The initial fitness value of the warehouse layout was 83129.11, which gradually improved over 15 generations, reaching a final optimized value of 65798.76. This represents a 21% reduction in combined transportation costs and energy inefficiencies, indicating that the structured initialization of the model effectively guided the optimization towards an improved solution.

The spatial allocation of functional areas was notably improved. The optimization model successfully repositioned high-energy-consuming sections, ensuring that they were evenly distributed throughout the warehouse to prevent localized energy peaks. Additionally, Figure X, which visualizes the optimized warehouse layout, highlights that storage and processing areas are now more systematically placed to reduce handling distances, further lowering operational costs.

The Genetic Algorithm Convergence Plot (Figure Y) illustrates the optimization trend, demonstrating a progressive decrease in the cost function over successive generations. This indicates that the algorithm successfully refined the warehouse configuration over time, achieving an efficient and stable solution.

Compared to previous studies in warehouse layout optimization, our approach has demonstrated superior convergence performance, particularly in incorporating energy efficiency constraints as a secondary objective function. These findings reinforce the robustness of heuristic-based optimization techniques in warehouse management and open pathways for future research into hybrid optimization approaches and real-time adaptability of layout configurations.

5. *Discussion and Conclusion*

The numerical results confirm that utilizing a predefined initial warehouse layout significantly enhances optimization efficiency, leading to faster convergence and a 21% reduction in total costs. The Genetic Algorithm (GA) effectively refines the spatial arrangement of functional areas, reducing material handling costs while maintaining energy balance. The convergence analysis further validates that the model stably reaches an optimal layout within a reasonable number of generations, demonstrating the effectiveness of heuristic-based optimization techniques.

A key innovation of this study is the integration of energy consumption factors into warehouse layout optimization, distinguishing it from traditional logistics-focused models. The results highlight that high-energy-consuming areas were initially clustered, causing localized peak loads, but were redistributed during optimization, leading to better energy management and reduced fluctuations. This aspect is especially critical for modern, automated warehouses that rely on AS/RS systems, robotics, and IoT-based monitoring.

The model successfully manages the trade-off between minimizing material handling costs and achieving energy balance, ensuring that neither aspect is over-prioritized. While shorter intra-warehouse travel distances reduced operational costs, strategic redistribution of high-energy-consuming areas ensured sustainable energy distribution. This dual-objective optimization approach demonstrates that multi-objective heuristic models are highly effective for real-world warehouse logistics.

Compared to existing studies, this model exhibits superior convergence behavior and improved overall efficiency by considering both logistics and energy constraints. The findings align with previous research on energy-efficient facility layout design, confirming that accounting for energy distribution as an optimization factor leads to more sustainable warehouse operations. The proposed methodology bridges the gap between logistics-driven and sustainability-driven warehouse design, offering an adaptive and scalable solution for future smart warehouses.

This study developed a Genetic Algorithm-based warehouse layout optimization model that simultaneously minimizes material handling costs and ensures an even distribution of energy consumption. The integration of structured initialization with GA optimization allowed for faster convergence and superior spatial efficiency compared to traditional randomized methods.

The numerical experiments demonstrated that the proposed approach successfully reduces total transportation costs while balancing the energy load across functional areas. The convergence analysis confirms that the model reaches stability within a reasonable number of generations, making it an efficient tool for real-world warehouse logistics planning.

The findings suggest that incorporating energy constraints in warehouse layout design is crucial for optimizing modern, automated logistics centers, particularly as warehouses continue to adopt robotics, AI-driven logistics, and IoT-based monitoring. This research provides a solid foundation for future investigations into energy-aware logistics facility design.

While the proposed model provides a robust optimization framework, several aspects can be further explored to enhance its practical applicability:

- Hybrid Optimization Techniques: Enhancing the model with machine learning-based adaptive learning could improve convergence speed and refine the optimization process over multiple iterations.
- Multi-Warehouse Optimization: Extending the model to multi-warehouse logistics networks would optimize both inter-warehouse transportation and internal facility layout.
- Incorporation of Dynamic Demand Forecasting: Integrating real-time demand forecasting would allow warehouses to dynamically reconfigure layouts based on storage and order fulfillment fluctuations.

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