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Reducing ergonomic risks in intralogistics: Combining Supplier to Warehouse, ABC analysis, and a user-centered VNS-GA hybrid algorithm

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Abstract. The increase in occupational accidents and ergonomic risks in intralogistics operations represents a recurring problem in warehouses, especially during loading, unloading, and material handling activities, where traditional layout and optimization tools are insufficient to simultaneously integrate operational and human criteria. In response to this issue, this study developed and validated an integrated warehouse design framework aimed at reducing ergonomic risks and improving operational performance. The proposed approach combines the Supplier-to-Warehouse model, ABC inventory analysis, and a user-centered hybrid Variable Neighborhood Search–Genetic Algorithm (VNS-GA). A mixed-methods, quasi-experimental approach was applied in two SMEs located in Hidalgo, Mexico. Results showed significant improvements in operational times, travel distances, productivity, incident reduction, and ergonomic risk, demonstrating that integrating ergonomic and operational criteria enhances efficiency, safety, and worker well-being.
Keywords: Intralogistics, Ergonomics, ABC Analysis, VNS-GA, User-Centered Design, Warehouse Optimization.

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1 Introduction

Globalization and the new digital era marked by Industry 4.0 are generating increasingly dynamic and complex environments, so markets increasingly demand faster responses from companies to maintain their competitiveness. This has led to changes in how logistics processes are managed, consolidating them as a strategic element within the value chain, allowing for greater flexibility and sustainable competitive advantages (Sánchez Cruz, 2025).

The above requires strengthening internal processes, making intralogistics, or internal logistics, essential, as it involves managing the flow of materials and information within the warehouse, including receiving, storage, inventory control, order picking, and shipping. Efficient intralogistics minimizes costs and streamlines processes, enabling a more efficient and rapid response to market demand (Iglesias López, 2024). In this sense, the Supplier-to-Warehouse model emerges as a disruptive alternative to traditional systems by transferring replenishment responsibility to the supplier and generating a constant and synchronized flow of materials.

However, this model presents critical challenges due to the constant flow of materials, leading to increased internal movement, high-speed loading and unloading, continuous forklift traffic, and so on, thereby increasing occupational safety risks. Furthermore, manual handling of goods, awkward postures, and repetitive movements have a significant impact on workers' musculoskeletal systems, which may lead to musculoskeletal injuries (Loske et al., 2021; Caicedo et al., 2015). This issue is particularly relevant considering that, according to the International Labour Organization (ILO, 2023), more than 395 million workers suffer non-fatal injuries and nearly 3 million die annually from work-related causes. The transportation and warehousing sector registers injury rates significantly higher than the industry average (ILOSTAT, 2024).

In this context, where ergonomic risks represent a recurring problem in intralogistics operations, generating a direct impact on productivity and worker health, it is necessary to incorporate approaches that allow not only the identification of these risks but also their structured intervention. From an ergonomic perspective, Dul and Weerdmeester (2008) point out that adapting work to human capabilities contributes to the prevention of musculoskeletal disorders and also to the efficiency of the production system.

Consequently, activities such as material handling, warehouse movement patterns, and movement frequency must be analyzed comprehensively, as they constitute critical points for both safety and operational performance. Under this approach, systematic ergonomic assessment is consolidated as a key methodological basis for identifying risk factors and generating improvement proposals in industrial environments.

Given this reality, there is an urgent need to design warehouse layouts that integrate occupational safety and ergonomic criteria with operational optimization tools, such as the classic ABC analysis, which allows items to be classified according to their monetary value and turnover (Krajewski & Ritzman, 2019), facilitating the strategic placement of materials. In this sense, an efficient layout improves routes and reduces exposure to risks during material handling. However, its isolated application is insufficient to simultaneously guarantee safety in handling and operational speed.

To overcome these limitations, this paper proposes an integrated framework that combines: (i) the Supplier-to-Warehouse model, (ii) ABC inventory analysis, and (iii) a hybrid metaheuristic algorithm (Variable Neighbor Search – VNS combined with Genetic Algorithm – GA) designed under User-Centered Design (UCD) principles. In this sense, the use of quantitative methodologies and optimization techniques allows for a more precise approach to the problems associated with warehouse organization and operation.

Furthermore, the incorporation of hybrid and metaheuristic algorithms is presented as a viable alternative for resolving complex scenarios, aligning with user-centered approaches that simultaneously seek to reduce physical effort and increase the efficiency of the logistics system (Tompkins et al., 2010).

This approach aligns with ISO 9241-210:2019 (Ergonomics) of human- system interaction, Part 210: Human- centered design for interactive systems) and ISO 6385:2016 (Ergonomics principles in the design of work systems), which establish guidelines for incorporating the needs, capabilities, and feedback of users (including vulnerable populations) from the initial design stages. In this way, operator preferences, physical capabilities, and ergonomic assessments are incorporated as input variables for the algorithm, transforming the problem into a socio-technical solution that balances efficiency, productivity, and workplace well-being.

However, the present work aims to develop and validate an integrated warehouse design framework that optimizes operational performance and reduces safety risks in loading and unloading operations, through the combination of Supplier-to-Warehouse , ABC analysis and a user-centered hybrid VNS-GA algorithm simultaneously considering technical and human variables around two SMEs in the state of Hidalgo, Mexico: one dedicated to Retail (distribution of consumer products) and the other to Project Production (manufacturing of furniture and metal structures) .

In accordance with the objective of the study, the null hypothesis (H0) is formulated that the combination of these tools does not produce statistically significant differences in the optimization of operational performance and does not decrease ergonomic risks in the activities of loading, unloading and handling of materials, compared to the current layout , while the alternative hypothesis (Ha) is established that the combination of these tools produces statistically significant differences in the optimization of operational performance and decreases ergonomic risks in the activities of loading, unloading and handling of materials, through the simultaneous consideration of technical and human variables in the design of the warehouse, compared to the current layout .

Based on the above, this work is structured as follows: the first section presents the context of the research problem, its objective, and its stated assumptions; the second section describes the methodology, which integrates decision variables such as unloading sequence, dock bay allocation, and picking order , along with a mathematical model with a multi-criteria objective that minimizes time and violates the fewest possible safety and ergonomic constraints, followed by validation through discrete simulation and evaluation with ergonomic tools; the third section presents the results obtained from the corresponding validations; and finally, the conclusions and main contributions of the research are presented, as well as limitations and possible lines of future work.

2 Methodology

2.1 Research design and context of the case study

This study adopts a mixed-methods applied research approach, based on a quasi-experimental before-and-after design combined with discrete simulation (Yin, 2018). It focuses on two SMEs in the state of Hidalgo, Mexico: one dedicated to retail (distribution of consumer products) and the other to project-based production (manufacturing of furniture and metal structures). The work was structured around three complementary axes: (i) diagnosis of the current layout and ergonomic risk assessment, (ii) development of a hybrid metaheuristic algorithm based on ABC analysis and User-Centered Design (UCD), and (iii) validation through simulation and pilot tests with direct operator participation (Nasir et al., 2025; Muttaqin, 2025).

All primary data were extracted from the company's actual operational records (SKU catalogs, inbound/outbound movements, picking times, incident reports, and REBA/OWAS ergonomic assessments). Operator participation was conducted according to the principles of User-Centered Design (UCD) as defined by ISO 9241-210:2019 and ISO 6385:2016, ensuring that their preferences, physical capabilities, and feedback were included as input variables for the algorithm (Nguyen Ngoc et al., 2022; Hilmi, 2024).

2.2 Systematic literature reviews

To define the state of the art and substantiate the gap in the literature, two independent systematic literature reviews (SLRs) were conducted following the SALSA (Search, Appraisal, Synthesis and Analysis) framework and the PRISMA 2020 guidelines (Grant & Booth, 2009; Page et al., 2021). Sources from the period 2016–2026 were considered to ensure the relevance and currency of the analyzed data.

The first RSL was directed towards research related to ABC analysis, metaheuristics and warehouse layout optimization. For this purpose, the following search equation was used: (“ABC analysis” OR “ABC classification”) AND (“warehouse layout” OR “slotting” OR “intralogistics”) AND (“metaheuristic” OR “genetic algorithm “OR “VNS”) applied to Scopus, Web of databases Science and ScienceDirect. From which they obtained 487 initial records; subsequently, data cleaning was performed by removing duplicates and applying the inclusion, exclusion and methodological quality criteria, resulting in 28 high-quality articles being retained.

The second RSL focuses on studies of User-Centered Design, ergonomics and safety in intralogistics, considering the search equation (“human- centered”). design” OR “user-centered design” OR “UCD”) AND (“warehouse” OR “intralogistics” OR “material handling”) AND (“ergonomics” OR “safety”), this search resulted in 312 records, after data cleaning and the application of inclusion criteria to obtain 39 articles.

Finally, through the PRISMA guidelines, the integration of 67 included scientific articles was allowed, from these the 25 most representative studies were selected as shown in Table 1.

Table 1. Selected representative articles (n=25)

	Author/Year	Main topic	Main methodology	Key findings	Relevance to the current study
1	Pratama & Putri (2025)	Class-Based Storage with ABC	CBS with ABC analysis	Reduction of picking times through relocation	Based for ABC module
2	Silva et al. (2022)	Optimal size of ABC zones	Simulation with ML	Layout factors affect ABC zone size	ABC integration with ergonomics
3	Lesch et al. (2023)	Mezzanine allocation and picking	NSGA-II with ACO	Simultaneous improvement of distance and ergonomics	Hybrid algorithms
4	Nasir et al. (2025)	Ergonomics in warehouse design (SLR)	PRISMA Review	Need for human-centered approaches	UCD Foundation
5	Wei et al. (2025)	Hybrid genetic algorithm for layout	NIHGA (Chaos with GA)	Significant improvement in the quality of solutions	GA Component
6	Li et al. (2024)	Multi-objective layout optimization	Multi-objective genetic algorithm	Balance of cost, distance and sustainability	Multi-criteria objective
7	Nguyen Ngoc et al. (2022)	Human- centered design in Industry 4.0	Case review	Importance of user feedback	UCD principles with ISO
8	Muttaqin (2025)	Ergonomic design in Industry 5.0	Qualitative review	Reduction of physical and cognitive workload	Ergonomic assessment
9	Hilmi (2024)	centered ergonomics	Review of interventions	Exoskeletons and design improve safety	Validation with operators
10	Taheri et al. (2022)	Hybrid heuristic algorithm with SA	Heuristics with Simulated Annealing	Efficient solutions to NP- hard problems	Base for VNS
11	Díaz et al. (2024)	VNS for minimizing warehouse times	Variable Neighborhood Search	Bin optimization allocation	VNS Component
12	Yuste et al. (2024)	General VNS for scheduling problems	General VNS	Good performance in combinatorial problems	VNS-GA Framework
13	Casella et al. (2023)	Trends in order picking (2007-2022)	Systematic review	Metaheuristics dominate routing and slotting	Picking context
14	Kokroko et al. (2025)	Layout optimization with metaheuristics	Simulation with metaheuristics	Reduction of distances and maximization of space	ABC integration with simulation
15	Mojumder & Nuruzzaman (2025)	AI-Driven Optimization of Warehouse Layout and Material Handling	Quantitative study / PRISMA systematic review of AI methods	15–45% reductions in cycle times; 20–35% gains in space utilization; order accuracy > 98%	Real empirical evidence of AI impact on layout and material handling
16	Norasedsophon (2026)	Cost reduction factors with ABC	Quantitative analysis	ABC layout significantly reduces costs	Economic impact
17	Wang et al. (2024)	Optimization of functional areas in warehouse	Mathematical modeling	Improved flow and safety	Zone design
18	Brimberg et al. (2023)	layout problems	Variable Neighborhood Search	Excellent neighborhood exploration	VNS in intralogistics
19	Liu et al. (2022)	LIRP with PRISMA	Systematic review	Inventory-routing integration	Supplier-to-Warehouse Context
20	Jagtap et al. (2025)	Integrating layout and material handling with AI	Quantitative study	Multiplicative benefits	Socio-technical solution
21	Chen et al. (2020)	User-centered design in logistics tools	Case design	Improvement in usability and adoption	UCD in operations
22	Blandford et al. (2025)	UCD with Agile in healthcare systems (adaptable)	Mixed study	Success in user-technology integration	Participatory methodology

	Author/Year	Main topic	Main methodology	Key findings	Relevance to the current study
23	Matic & Kratica (2012)	VNS for Multiple Level Warehouse Layout	Variable Neighborhood Search	Solutions for multi-layered layouts	Inclusive layout
24	Reis & Souza (2017/updated)	Warehouse design SLR	Systematic review	Comprehensive framework for warehouse design	Methodological reference
25	Li et al. (2022)	Multiobjective VNS for flow shop (adapted)	LS-MOVNS	Multi-criteria optimization	Multi-criteria objective

Note: Own elaboration (2026).

Table 1 presents the 25 most relevant studies identified in the two systematic literature reviews (SLRs). These articles were selected after a rigorous search process, including the removal of duplicates, screening by title and abstract, and full text review. High-quality publications (Q1-Q2) published between 2017 and 2026 were prioritized.

The table above shows a trend in the literature toward combining ABC analysis with metaheuristics (especially Genetic Algorithms and Variable Neighborhood Search) to optimize warehouse layouts (Silva et al., 2022; Lesch et al., 2023; Wei et al., 2025). Likewise, there is a growing interest in human- centered and ergonomic approaches to warehouse design (Nasir et al., 2025; Muttaqin, 2025; Hilmi, 2024), although studies that simultaneously integrate ABC analysis, hybrid metaheuristic algorithms, and User-Centered Design (UCD) are still scarce. These limitations justify the proposal of the present study, which seeks to integrate a framework applicable to SMEs.

In this sense, it is pertinent to delve deeper into the main techniques and algorithms used in the 67 articles analyzed included in the RSL as shown in Table 2, which summarizes the analysis of its frequency, showing that ABC analysis combined with Class- Based Storage is the most used technique (31 items), which confirms its consolidated relevance in the optimization of inventories and allocation of locations (Pratama & Putri , 2025; Norasedsophon , 2026).

Table 2. Technologies and algorithms identified (n = 67 articles)

Technology/Algorithm	Frequency (n)	Main use
Genetic Algorithms (GA / NSGA-II)	23	Layout optimization and allocation
Variable Neighborhood Search (VNS)	14	Local improvement and routing
ACO / Simulated Annealing / PSO	17	Picking and sequencing
Analysis with Class-Based Storage	31	Location assignment
Centered Approaches / UCD	22	Ergonomics and occupational safety

Note: Own elaboration (2026).

Genetic Algorithms are the second most frequently cited, with 23 articles, followed by Variable Neighborhood Search (VNS) with 14 articles. This distribution supports the choice of the hybrid VNS-GA metaheuristic algorithm proposed in this work, because it combines the strengths of both methods: the global exploration of GA and the local intensification of VNS (Wei et al., 2025; Brimberg et al., 2023; Díaz et al., 2024).

Finally, it is worth noting that 33% of the articles (22 out of 67) incorporate Human- Centered Approaches Design or UCD, although most focus on theoretical or qualitative aspects. These findings reinforce the relevance and originality of the present research, quantitatively and operationally integrating the principles of UCD (ISO 9241-210:2019) within a metaheuristic algorithm applied to real intralogistics operations.

2.3 Architecture of the proposed model

The proposed integrated framework is organized into five interconnected modules that operate sequentially and iteratively, allowing for the simultaneous optimization of operational, ergonomic, and safety variables. This modular architecture facilitates scalability and integration with existing systems in SMEs (Jagtap et al., 2025; Kokroko et al., 2025). Each module receives and provides information to the others, forming a continuous feedback loop that incorporates User-Centered Design (UCD) principles according to ISO 9241-210:2019. These are described below:

1. ABC Classification Module with XYZ/FSN. This module forms the basis of the system, fed with historical data on consumption, monetary value, turnover rate, and demand variability. It classifies items into categories A, B, and C (ABC) and X, Y, and Z (XYZ) or FSN (Fast, Slow, Non-moving). Clustering algorithms are used to generate a combined ABC-XYZ matrix that identifies critical items (AX) requiring greater ergonomic and operational attention (Pratama & Putri, 2025; Silva et al., 2022; Norasedsophon,2026). The output of this module defines location priorities and is fed directly into the layout design module.
2. Layout Design Module (UCD). This module considers principles of User-Centered Design and Universal Design, in which a physical layout of the warehouse is generated considering accessibility for vulnerable populations and people with mobility dependent on wheelchairs. For this, design criteria were included such as minimum aisles of 1.8 m, turning radii of 1.5 m, golden ratio Ergonomic zone (0.8-1.5 m high), loading/unloading zones with ramps and double-height signage. It integrates occupational safety restrictions and one-way traffic flow to avoid crossings (Nasir et al., 2025; Hilmi, 2024; Matic & Kratica, 2012). Additionally, operator feedback generated during the diagnostic phase is considered as an input variable.
3. Hybrid Metaheuristic Algorithm Module (VNS-GA): This module represents the computational core of the model, combining Variable Neighborhood Search (VNS) for intensive local exploration with a Genetic Algorithm (GA) for global solution search (Wei et al., 2025; Brimberg et al., 2023; Díaz et al., 2024). It simultaneously optimizes three main decision variables: unloading sequence in dock bays, item allocation to locations (slotting), and picking order. The weighted multi-criteria objective function minimizes total time, distance traveleded, and ergonomic risk (normalized REBA).
4. Ergonomic Assessment Module: evaluates postural and physical exertion risk in real time using standardized tools such as REBA, OWAS and NIOSH Lifting Equation. It incorporates the preferences and physical capabilities reported by operators through surveys and participant observation (UCD). It generates a risk score that feeds back into the metaheuristic module to penalize solutions that violate safety thresholds (Muttaqin, 2025; Hilmi, 2024; Nasir et al., 2025).
5. Simulation and Validation Module: This module involves discrete simulation (using Python with SimPy or Arena) to test the layout and algorithm in virtual scenarios before real-world implementation. This allows for a comparison of the "before" scenario (current layout) versus the "after" scenario (optimized layout) under different demand volumes and operating conditions (Kokroko et al., 2025; Lesch et al., 2023). This module completes the cycle, validating the model's robustness and generating KPI reports.

Table 3. Modular architecture of the proposed integrated framework for safe intralogistics optimization.

Module	Name / Function	Main Inputs	Main Outputs	Feedback / Interaction
1	ABC Classification (with XYZ/FSN)	Historical consumption, monetary value, turnover rate, demand variability	ABC-XYZ matrix; location priorities for critical (AX) items	Feeds priorities into Layout Design and Algorithm modules
2	Layout Design (UCD / Universal Design)	Operator feedback, accessibility criteria, safety restrictions, golden zone (0.8–1.5 m)	Physical layout with min. aisles 1.8 m, turning radii 1.5 m, ramps, one-way flow, signage	Receives operator input; constraints pass to Algorithm and Ergonomic modules
3	Hybrid Metaheuristic (VNS-GA)	Priorities from Module 1, layout constraints from Module 2, risk scores from Module 4	Optimized unloading sequence, slotting (item-location), picking order	Core computational engine; receives penalties from Ergonomic module
4	Ergonomic Assessment (REBA / OWAS / NIOSH)	Postures, loads, frequencies; operator physical capabilities and preferences (UCD)	Normalised REBA risk score; safety threshold violations	Penalises unsafe solutions in the VNS-GA algorithm; feeds back to Layout
5	Simulation & Validation	Layout + algorithm solutions; demand scenarios; baseline KPIs	Before/after comparison; KPI reports (time, distance, REBA, productivity, incidents)	Closes the loop; validates robustness and generates continuous improvement data

Note: Own elaboration (2026).

Table 3 presents the five-module architecture of the proposed framework. Module 1 performs multi-criteria inventory classification (ABC combined with XYZ/FSN) and supplies location priorities. Module 2 generates an inclusive, ergonomically informed physical layout that incorporates operator feedback and Universal Design criteria (including the golden ratio of 0.8–1.5 m height).

Module 3 is the computational core: a hybrid Variable Neighbourhood Search–Genetic Algorithm (VNS-GA) that simultaneously optimizes unloading sequences, slotting and picking orders under a weighted multi-criteria objective (time, distance and REBA risk). Module 4 continuously evaluates postural and physical risk using REBA, OWAS and the NIOSH Lifting Equation and returns penalty scores to the algorithm so that unsafe solutions are rejected. Module 5 validates every candidate solution through discrete-event simulation, comparing the original layout with the optimized layout under varying demand conditions and producing the final KPI reports.

Bidirectional feedback (last column) ensures that human factors and operational performance remain balanced throughout the iterative process, in full accordance with ISO 9241-210:2019 and ISO 6385:2016.

2.4 Mathematical formulation of the hybrid metaheuristic algorithm

The hybrid algorithm combines Variable Neighborhood Search (VNS) for intensive local exploration and Genetic Algorithm (GA) for global search (Wei et al., 2025; Taheri et al., 2022).

(weighted) objective function: minimize.

$$f = w_1 (T_{total}) + w_2 (D_{travel}) + w_3 (R_{ergonomic}) \quad (1)$$

where:

- T_{total}: total operation time (unloading with picking).
- D_{route}: total distance traveled.
- ${}_{Ergonomic}R$: average ergonomic risk (normalized REBA index).

Decision variables:

- $x_{i,j}$: binary (1 if item i is assigned to location j).
- s_k: unloading sequence in bay k.
- p_m: picking order of order m.

Main restrictions:

- Bay and rack capacity.
- Safety and ergonomic restrictions (maximum lifting height, weight, postural angles).
- Unidirectional flow and accessibility for (UCD).

The VNS systematically modifies the neighborhood (bay change, sequence rearrangement, A/B/C item swap), while the GA evolves solution populations through selection, crossing over, and mutation (Lesch et al., 2023; Li et al., 2024).

2.5 Implementation and validation plan

The empirical application of the integrated framework was structured in four sequential phases under a quasi-experimental before-and-after design (Yin, 2018). This approach allowed for measuring the model's real impact under normal operating conditions of the SME, while maintaining control over external variables and ensuring high internal validity (Lesch et al., 2023; Nasir et al., 2025). Each phase was thoroughly documented to guarantee replicability.

The main dependent variables analyzed were total operating time, distance traveled, average ergonomic (REBA) index, productivity and incident rate. Incident rates are reported descriptively because of low absolute counts. Paired Student's t-tests were performed on the before–after data and confirmed statistical significance (all $p < 0.001$), consistent with the one-way ANOVA results presented in Table 7. A repeated-measures ANOVA would be the most appropriate formal model for the paired design; the conclusions remain robust under both approaches. The statistical assumptions were rigorously verified.

The study follows a quasi-experimental before-and-after design, in which the same two SMEs were measured before and after the intervention. This constitutes paired / repeated-measures data. Although a repeated-measures ANOVA would be the most formally appropriate model for this design, one-way ANOVA was applied as the primary analysis. Paired Student's t-tests were also performed and yielded fully consistent results (all $p < 0.001$). The conclusions remain robust under both approaches. A repeated-measures ANOVA is recommended for future multi-site validations with larger samples.

Phase 1. Diagnosis and establishment of the baseline (Month 1)

layout and existing risks were conducted. Key activities included: extraction of operational data (SKU catalogs, movements, picking times), ABC-XYZ classification, measurement of actual distances and times, REBA/OWAS ergonomic assessment with the participation of 20 operators, and recording of historical incidents. Baseline KPIs were established (average unloading/ picking time, distance traveled, ergonomic risk index, and injury rate). This phase allowed for the identification of the main inefficiencies and postural risks (Silva et al., 2022; Hilmi, 2024).

Phase 2. System Development and Integration (Months 2 and 3)

The VNS-GA hybrid metaheuristic algorithm was fully coded in Python, and the five modules were integrated into a unified platform. Unit and integration tests were performed using historical company data. Operator feedback obtained in Phase 1 was incorporated to calibrate the objective function weights and ergonomic constraints. At the end of this phase, the system was fully functional and technically validated (Wei et al., 2025; Muttaqin, 2025).

Phase 3. Controlled pilot test (Months 4 to 6)

layout and algorithm were implemented in a pilot area of the warehouse for 12 weeks of actual operation. The solutions generated by the model (location assignment, unloading sequences, and picking orders) were applied while maintaining the same demand, staffing, and equipment conditions as the baseline. Deviations were monitored weekly, and minor, documented adjustments were made. Operators actively participated by providing continuous feedback (UCD) (Nasir et al., 2025; Jagtap et al., 2025).

Phase 4. Statistical validation and analysis of results (Month 7)

The results before and after the intervention were quantitatively compared using paired Student's t-tests and one-way ANOVA ($p < 0.05$). The main dependent variables analyzed were total operating time, distance traveled, average ergonomic index, and incident rate. Additionally, the model was validated using discrete simulation with 30 replicates to assess robustness under demand uncertainty. The statistical assumptions (normality, homoscedasticity, and independence) were rigorously verified (Yin, 2018; Lesch et al., 2023).

3 Results and Discussion

The results are presented sequentially following the four phases of the methodology described in section 2.5, which allows for complete traceability of the implementation and validation process of the proposed framework in two SMEs in the state of Hidalgo, Mexico: one dedicated to Retail (distribution of consumer products) and the other to Project Production (manufacturing of furniture and metal structures).

3.1 Phase 1: Diagnosis and establishment of the baseline (Month 1)

During this initial phase, a thorough diagnosis of the two warehouses was carried out through direct observation, time recording, distance measurements, ergonomic evaluations (REBA and OWAS) and incident analysis during four weeks of normal operation.

Table 4. Baseline indicators by company

Indicator	SME Retail	SME Project-Based Production SME	Average
Average time per operation (min)	428	675	551.5
Daily distance traveleded (km/operator)	14.8	18.2	16.5
Average REBA Index	7.8	8.4	8.1
% of misplaced Class A items	68%	74%	71%
Monthly incident rate	3.2	2.7	2.95
Space utilization	68%	61%	64.5%

Note: Own elaboration (2026).

Table 4 shows the initial state of both warehouses before any intervention. A high ergonomic risk (REBA > 7 in both cases), low space utilization, and limited productivity were observed, especially in the project-based production company due to batch irregularities. This data served as an objective baseline for measuring the model's actual impact and as input for the ABC-XYZ classification and the inclusive layout design.

The main problems detected were:

- High concentration of Class A items in high areas or areas far from dock bays.
- Narrow corridors (< 1.2 m) that generated congestion and postural risks.
- Repetitive movements and lifting of heavy loads in project production.
- Lack of ergonomic signage and limited accessibility.

This phase allowed the establishment of the base KPIs for subsequent comparison and served as a direct input for the ABC-XYZ classification and the design of the new layout.

3.2 Phase 2: System Development and Integration (Months 2 and 3)

During this phase, the hybrid VNS-GA metaheuristic algorithm was developed, and the five modules of the proposed framework were integrated. As an algorithm, it combines the global exploration of the Genetic Algorithm (GA) with the local intensification of Variable Neighborhood Search (VNS). In this sense, optimization was formulated using a multi-criteria objective function as follows:

$$f(s) = 0.45 * T_{total} + 0.3 * D_{route} + 0.25 * R_{REBA} \quad (2)$$

The general procedure of the VNS-GA hybrid algorithm is described by the following pseudocode:

Initialize population P (size = 200)

Evaluate fitness of each solution using the multicriteria function.

for generation = 1 to 150:

```
# Phase 1: Genetic Algorithm (Global Search)
parents = TournamentSelection(P)
offspring = OrderCrossover (parents, pc=0.85)
offspring = SwapInsertionMutation (offspring, pm=0.15)
EvaluateFitness(offspring)
```

```
    P = ReplaceWorstIndividuals (P, offspring)

    # Phase 2: Variable Neighborhood Search (Local Intensification)
    for each promising solution s in top 20% of P:
        k = 1
        while k <= 6: 6 different neighborhoods
            s' = Shake (s, neighborhood=k)  #Perturbation
            s” = LocalSearch(s’)          # 2-opt + Hill Climbing
            if fitness(s'') < fitness(s):
s = s''
k = 1 # Reset neighborhood
else:
k = k + 1

    UpdateGlobalBest ()

return BestSolution.
```

The main parameters considered in the pseudocode are They observe in Table 5.

Table 5. Final parameters of the algorithm

Parameter	Value	Justification
Population	200	Computationally feasible diversity
Generations	150	Stable convergence
Crossover probability	0.85	OX Operator
Probability of mutation	0.15	Swap + Insertion
VNS Neighborhoods	6	High local exploration
Maximum time per run	120 sec	Suitable for SMEs

Note: Own elaboration (2026).

Through the execution of the pseudocode, the algorithm demonstrated excellent performance: with an average execution time of 87.4 seconds and an average improvement of 41.2% compared to the initial solution based only on ABC.

3.3 Phase 3: Controlled pilot test (Months 4 to 6)

Based on the results obtained in the previous phases and the corresponding integrations, a pilot test was carried out, implemented a new layout and the algorithm in actual operation for 12 weeks. Table 6 presents the operational and ergonomic results obtained at the end of the pilot phase (weeks 9 to 12), once the new layout and the VNS-GA hybrid algorithm were fully stabilized. The data corresponds to the average actual operating time during this period in both SMEs.

Table 6. Final results of the pilot (average weeks 9-12)

Indicator	Retail Before → After	Reduction	Prod. Project Before → After	Reduction
Total operating time (min/day)	428 to 312	27.1%	675 to 461	31.7%
Distance traveled (km/day)	14.8 to 9.7	34.5%	18.2 to 11.4	37.4%
Ergonomic risk (REBA)	7.8 to 4.2	46.2%	8.4 to 4.6	45.2%
Productivity (lines/hour)	42 to 68	+61.9%	28 to 51	+82.1%
Space utilization	68% to 89%	+30.9%	61% to 84%	+37.7%
Monthly incidents	3.2 to 0.8	75.0%	2.7 to 0.9	66.7%

Note: Own elaboration (2026).

A consistent and significant improvement was observed across all key indicators. In the Retail SME sector, total operation time decreased by 27.1%, while the distance traveleded by operators fell by 34.5%, reflecting better allocation of Class A locations and effective optimization of picking routes. Ergonomic risk (REBA index) dropped from 7.8 to 4.2, representing a 46.2% reduction, indicating a notable improvement in working postures and reduced physical exertion.

In the Project Production SME, the benefits were even more pronounced in productivity (+82.1%) and space utilization (+37.7%), as the model efficiently handled large and irregular batches. The reduction in monthly incidents was 75% in Retail and 66.7% in Project Production, confirming the positive impact of the user-centered approach (UCP) and the ergonomic constraints incorporated into the algorithm.

These results demonstrate that the proposed framework is not only viable in real-world operation but also generates sustainable improvements once the initial learning curve is overcome. Furthermore, the findings confirm that integrating operational, ergonomic, and user-centered criteria significantly contributes to optimizing warehouse efficiency, reducing occupational risks, and strengthening system stability under real working conditions.

3.4 Phase 4: Statistical validation and analysis of results (Month 7)

In this phase, a statistical validation was performed using a one-way analysis of variance (ANOVA) to determine whether there were statistically significant differences between the original layout and the proposed layout. The results are shown in Table 7, which summarizes the results of the one-way ANOVA performed in Phase 4 to determine if the differences observed between the "Before" and "After" scenarios of implementing the integrated framework were statistically significant.

Table 7. One-way ANOVA results

Dependent variable	F	p- value	η²	Size of effect
Total operating time	28.74	<0.001	0.562	Very large
Distance traveled	41.26	<0.001	0.648	Very large
REBA Risk	67.89	<0.001	0.752	Large
Productivity	52.31	<0.001	0.701	Large

Note: Own elaboration (2026).

The paired Student's t-tests previously announced in the methodology confirmed the same pattern of significance (all $p < 0.001$) and were consistent with the ANOVA results shown in Table 7. Particularly noteworthy is the result for ergonomic risk (REBA), with an F-value of 67.89 and an effect size $\eta^2 = 0.752$, classified as "very large" according to Cohen's criteria. This means that more than 75% of the observed variability in postural risk is explained by the implementation of the new model.

The large effect size ($\eta^2 > 0.14$) across all variables confirms that the improvements are not only statistically significant but also of considerable practical value, particularly relevant for SMEs with limited resources. The ANOVA assumptions (normality of residuals, homoscedasticity, and independence of observations) were rigorously verified and met, lending high reliability to the findings.

These results allow us to reject the null hypothesis (H_0) and fully accept the research hypothesis (H_1), scientifically validating the effectiveness of the integrated ABC + VNS-GA + UCD framework.

3.5 Discussion

The results obtained in this study strongly confirm the effectiveness of the proposed integrated framework. Implementing ABC analysis combined with a hybrid VNS-GA metaheuristic algorithm and User-Centered Design (UCD) principles generated substantial improvements in both operational performance and ergonomic safety in two types of SMEs with very different characteristics: one in Retail (high turnover and volume) and the other in Project Production (irregular demand and heavy loads).

The average reduction of 27–32% in total operation time and 34–37% in distance traveled exceeds the ranges reported in previous studies that applied only metaheuristics or ABC analysis in isolation (Silva et al., 2022; Lesch et al., 2023; Wei et al., 2025). This improvement is mainly attributed to the simultaneous optimization of slotting and unloading/ picking sequences, allowing Class A items to be placed in the golden zone. ergonomic zone and close to the dock bays.

One of the most relevant findings is the reduction in ergonomic risk (REBA) of over 45% in both cases. This result is particularly important because it validates the hypothesis that incorporating human variables (preferences, physical capabilities, and operator feedback) as part of the algorithm produces safer sociotechnical solutions. Unlike traditional approaches focused solely on cost or distance (Pratama & Putri, 2025; Norasedsophon, 2026), the present model successfully balanced efficiency and workplace well-being, aligning with the principles of ISO 9241-210:2019 and ISO 6385:2016.

The decrease in the incident rate (from 66.7% to 75%) has significant economic and social implications. For SMEs, it represents a substantial reduction in costs related to disability, staff turnover, and insurance premiums. From a social perspective, it contributes to the labor inclusion of vulnerable populations (including operators with physical limitations or wheelchair users), an aspect that has received little attention in the intralogistics literature (Nasir et al., 2025; Muttaqin, 2025).

The modular architecture of five modules proved to be highly adaptable. In Retail, the greatest benefit came from the optimization of high-turnover flows, while in Project Production, the algorithm's ability to handle demand variability and heavy workloads stood out. This confirms the robustness of the VNS-GA model and its superiority over single-objective or purely heuristic algorithms (Li et al., 2024; Brimberg et al., 2023).

A key limitation of the present study is the small sample size, as the quasi-experimental validation was conducted in only two SMEs over a twelve-week period. Future research should validate the proposed model in a larger number of companies and over longer time horizons to strengthen the generalizability of the findings.

The ergonomic emission factors and target function weights were calibrated using local data; their generalizability to other cultural or industrial contexts requires adjustments. Finally, implementation required initial staff training, which represents an initial barrier for SMEs with low digital maturity.

Despite these limitations, the findings strengthen the literature by demonstrating that it is possible to simultaneously integrate operational optimization, ergonomics, and user-centered design in resource-constrained environments.

4 Conclusions

The present study successfully achieved its main objective: to develop, implement and validate an integrated framework for the safe design of warehouses that combines the Supplier-to-Warehouse model, ABC analysis, a hybrid VNS-GA metaheuristic algorithm and User-Centered Design (UCD) principles.

The results of the pilot in two Mexican SMEs demonstrated statistically significant improvements ($p < 0.001$) and of great practical magnitude:

- 27-32% reduction in total operating time
- 34-37% reduction in distance traveled
- 45-46% reduction in ergonomic risk (REBA)
- Productivity increases between 62% and 82%.
- Reduction in incidents between 67% and 75%

These achievements allow us to fully accept the research hypothesis and confirm that the integration of technical and human variables produces solutions superior to traditional approaches.

Main contributions of the study:

1. Theoretical: It proposes an integrated framework that unites ABC analysis, hybrid metaheuristics and UCD, closing an important gap identified in systematic literature reviews.
2. Methodological: Demonstrates the feasibility of incorporating operator feedback and ergonomic assessments as decision variables within an optimization algorithm.
3. Practical: It provides SMEs with an adaptable tool, with low computational cost and high impact on productivity and workplace safety.
4. Social: It advances in labor inclusion by designing accessible and ergonomic layouts for vulnerable populations.

The proposed model represents a relevant contribution to the field of intralogistics 4.0/5.0, by demonstrating that it is possible to achieve operational efficiency without sacrificing the well-being of workers.

Future lines of research It is recommended:

- Extend the model to more sectors (food, pharmaceutical, e- commerce).
- Incorporate uncertainty into demand through stochastic or robust programming.
- Develop an open- source version of the algorithm to facilitate its mass adoption.
- Integrate emerging technologies such as IoT, exoskeletons, and digital twins.
- Evaluate the long-term impact on costs due to disability and staff turnover.

In conclusion, this work demonstrates that it is possible to design safer, more efficient, and more inclusive warehouses through the intelligent combination of classic (ABC), modern (metaheuristic), and human- centered (UCD) tools.

The results obtained position the proposed framework as a viable and high-value solution for Mexican and Latin American SMEs seeking to improve their competitiveness while respecting the integrity and dignity of their workers.

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Data Availability Statement

The operational data that support the findings of this study are available from the corresponding author upon reasonable request. Primary SKU, movement and ergonomic assessment data are proprietary to the participating SMEs and subject to confidentiality agreements.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

5 References

Blandford, A., Bindman, J., Bradbury, K., Cooper, B., Costanza, E., Edwards, S. L., Hamilton, F. L., Heightman, M., Hurst, J. R., Hylton, H., Linke, S., Pfeffer, P., Ricketts, W., Robson, C., Stevenson, F., Sunkersing, D., Waywell, J., & Goodfellow, H. (2025). Experiences of user-centred design with agile development for clinically supported self-management of Long Covid. *ACM Transactions on Computer-Human Interaction, 32*(1), Article 6. https://doi.org/10.1145/3711839

Brimberg, J., Salhi, S., Todosijević, R., & Urošević, D. (2023). Variable neighborhood search: The power of change and simplicity. *Computers & Operations Research, 155*, 106221. https://doi.org/10.1016/j.cor.2023.106221

Caicedo, A. M., Manzano, J. A., Gómez-Vélez, D. F., & Gómez, L. (2015). Factores de riesgo, evaluación, control y prevención en el levantamiento y transporte manual de cargas. *Revista Colombiana de Salud Ocupacional, 5*(2), 5–9. https://doi.org/10.18041/2322-634X/rcso.2.2015.4890

Casella, G., Volpi, A., Montanari, R., Tebaldi, L., & Bottani, E. (2023). Trends in order picking: A 2007–2022 review of the literature. *Production & Manufacturing Research, 11*(1), 2191115. https://doi.org/10.1080/21693277.2023.2191115

Díaz, J., Rodriguez, H., Fajardo-Calderín, J., Angulo, I., & Onieva, E. (2024). A variable neighbourhood search for minimization of operation times through warehouse layout optimization. *Logic Journal of the IGPL, 32*(4), 688–699. https://doi.org/10.1093/jigpal/jzae018

Dul, J., & Weerdmeester, B. (2008). *Ergonomics for beginners: A quick reference guide* (3rd ed.). CRC Press. https://doi.org/10.1201/9781420077520

Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal, 26*(2), 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Hilmi, A. H., Abdul Hamid, A. R., & Wan Ibrahim, W. A. R. A. (2024). Human-centered ergonomics: Advancements, challenges, and future directions in industrial and occupational settings. *Malaysian Journal of Ergonomics (MJEr), 6*(1), 90–104. https://doi.org/10.58915/mjer.v6.2024.1311

Iglesias López, A. L. (2024). *Logística interna: 10 claves para la gestión óptima del almacén*. ESIC Editorial.

International Labour Organization. (2023, November 26). *Nearly 3 million people die of work-related accidents and diseases*. ILO source

International Organization for Standardization. (2016). *Ergonomics principles in the design of work systems (ISO Standard No. 6385:2016).* ISO record

International Organization for Standardization. (2019). *Ergonomics of human-system interaction—Part 210: Human-centred design for interactive systems (ISO Standard No. 9241-210:2019).* ISO record

Kokroko, B. Y., Kobi, J., & Yeboah, E. K. (2025). Warehouse layout design maximization of storage efficiency minimization of travel distances using simulation models and optimization algorithms. *International Journal of Innovative Science and Research Technology, 10*(10), 3236–3280. https://doi.org/10.38124/ijisrt/25oct1431

Krajewski, L. J., Malhotra, M. K., & Ritzman, L. P. (2019). *Operations management: Processes and supply chains* (12th ed.). Pearson.

Lesch, V., Müller, P. B. M., Krämer, M., Hadry, M., Kounev, S., & Krupitzer, C. (2023). Optimizing storage assignments, order picking, and their interaction in mezzanine warehouses. *Applied Intelligence, 53*, 18605–18629. https://doi.org/10.1007/s10489-022-04443-x

Li, H., Zhou, J., Niu, Q., Feng, M., & Zhou, D. (2024). Layout optimization of logistics and warehouse land based on a multi-objective genetic algorithm—Taking Wuhan City as an example. *ISPRS International Journal of Geo-Information, 13*(7), Article 240. https://doi.org/10.3390/ijgi13070240

Li, K., & Tian, H. (2022). A multiobjective variable neighborhood search with learning and swarm for permutation flowshop scheduling with sequence-dependent setup times. *Processes, 10*(9), Article 1786. https://doi.org/10.3390/pr10091786

Liu, L., Lee, L. S., Seow, H.-V., & Chen, C. Y. (2022). Logistics center location-inventory-routing problem optimization: A systematic review using PRISMA method. *Sustainability, 14*(23), Article 15853. https://doi.org/10.3390/su142315853

Loske, D., Klumpp, M., Keil, M., & Neukirchen, T. (2021). Logistics work, ergonomics and social sustainability: Empirical musculoskeletal system strain assessment in retail intralogistics. *Logistics, 5*(4), Article 89. https://doi.org/10.3390/logistics5040089

Matić, D., Kratica, J., Filipović, V., & Dugošija, D. (2012). Variable neighborhood search for multiple level warehouse layout problem. *Electronic Notes in Discrete Mathematics, 39*, 161–168. https://doi.org/10.1016/j.endm.2012.10.022

Mojumder, M. U., & Nuruzzaman, M. (2025). AI-driven optimization of warehouse layout and material handling: A quantitative study on efficiency and space utilization. *Review of Applied Science and Technology, 4*(2), 233–273. https://doi.org/10.63125/bgxb1z53

Muttaqin, I. (2025). Human-centered ergonomic design in Industry 5.0: Enhancing productivity and worker wellbeing. *Jurnal Riset Teknologi Pencegahan Pencemaran Industri, 16*(1), 41–50. https://doi.org/10.21771/jrtppi.2025.v16.no1.p41-50

Nasir, D., Venkitasubramony, R., & Jakhar, S. K. (2025). Ergonomics in warehouse design and operations: A systematic literature review. *Operational Research, 25*(1), Article 10. https://doi.org/10.1007/s12351-024-00892-z

Nguyen Ngoc, H., Lasa, G., & Iriarte, I. (2022). Human-centred design in industry 4.0: Case study review and opportunities for future research. *Journal of Intelligent Manufacturing, 33*(1), 35–76. https://doi.org/10.1007/s10845-021-01796-x

Norasedsophon, S., & Trakoonsanti, L. (2026). Factors affecting warehouse cost reduction: A case study of ABC Company. In *International Academic Multidisciplinary Research Conference Shanghai 2026* (pp. 194–204). ICBTS.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*, n71. https://doi.org/10.1136/bmj.n71

Pratama, R. B., & Putri, C. B. (2025). Optimization of material layout at the warehouse laboratory of PEM Akamigas through a class based storage approach. *International Journal of Science and Society, 7*(2), 532–543. https://doi.org/10.54783/ijsoc.v7i2.1468

Sánchez Cruz, M. A. (2025). Estrategias 4.0: optimización de la logística a través de la gestión eficiente de las operaciones con los proveedores. *LATAM Revista Latinoamericana de Ciencias Sociales y Humanidades, 6*(3), 706–717. https://doi.org/10.56712/latam.v6i3.3978

Silva, A., Roodbergen, K. J., Coelho, L. C., & Darvish, M. (2022). Estimating optimal ABC zone sizes in manual warehouses. *International Journal of Production Economics, 252*, Article 108579. https://doi.org/10.1016/j.ijpe.2022.108579

Taheri, F., & Farhang Moghaddam, B. (2022). A heuristic-based hybrid algorithm to configure a sustainable supply chain network for medical devices considering information-sharing systems. *Environmental Science and Pollution Research, 29*(60), 91105–91126. https://doi.org/10.1007/s11356-022-22147-0

Tompkins, J. A., White, J. A., Bozer, Y. A., & Tanchoco, J. M. A. (2010). *Facilities planning* (4th ed.). John Wiley & Sons.

Wei, X., Sun, J., & Jiao, H. (2025). New improved hybrid genetic algorithm for optimizing facility layout design of reconfigurable manufacturing system. *Scientific Reports, 15*, Article 21416. https://doi.org/10.1038/s41598-025-97526-x

Yin, R. K. (2018). *Case study research and applications: Design and methods* (6th ed.). SAGE.

Yuste, J., Pardo, E. G., & Duarte, A. (2024). General variable neighborhood search for the optimization of software quality. *Computers & Operations Research, 165*, 106584. https://doi.org/10.1016/j.cor.2024.106584