Ingeniería Solidaria

Hybrid genetic algorithm with multi-component population for the optimization of commercial gallery size from an evolutionary approach

Algoritmo genético híbrido con población multi-componente para la optimización del tamaño de galerías comerciales desde un enfoque evolutivo

Algoritmo genético híbrido com população multicomponente para otimização do tamanho de shopping centers a partir de uma abordagem evolutiva

Néstor Gabriel Forero Saboya[1]
Franklin Guillermo Montenegro Marín[2]
Rubén Darío Rodríguez Useche[3]

Received: December 5th, 2025
Accepted: March 4th, 2026
Available: May 5th, 2026

How to cite this article:
N.G. Forero Saboya, F.G. Montenegro Marín, and R.D. Rodríguez Useche, "Hybrid Genetic Algorithm with Multi-Component Population for the Optimization of Commercial Gallery Size from an Evolutionary Approach," *Revista Ingeniería Solidaria,* vol. 22, no. 2, 2026. doi: https://doi.org/10.16925/2357-6014.2026.02.07

Research article. https://doi.org/10.16925/2357-6014.2026.02.07

[1] Researcher, Industrial Engineering Program, Faculty of Engineering, University of Cundinamarca, Colombia.
Email: ngforero@ucundinamarca.edu.co
ORCID: https://orcid.org/0000-0001-7655-9271
CvLAC: https://scienti.minciencias.gov.co

[2] Researcher, Industrial Engineering Program, Faculty of Engineering, University of Cundinamarca, Colombia.
Email: fmontenegro@ucundinamarca.edu.co
ORCID: https://orcid.org/0000-0003-2338-0432
CvLAC: https://scienti.minciencias.gov.co

[3] Researcher, Software Engineering Program, Faculty of Engineering, University of Cundinamarca, Colombia.
Email: rubendariorodriguez@ucundinamarca.edu.co
ORCID: https://orcid.org/0000-0001-5939-839X
CvLAC: https://scienti.minciencias.gov.co

Abstract

Introduction: This research explores the sizing and location of new shopping malls in Soacha, Cundinamarca (2024–2025). It addresses computational challenges in multi-objective optimization (MOP) for retail planning by balancing economic, financial, and social criteria through advanced evolutionary architectures.

Problem: Traditional genetic algorithms in retail planning often exhibit premature convergence and low population diversity, hindering balanced outcomes in complex urban contexts such as Soacha.

Objective: To develop and validate a Hybrid Genetic Algorithm (HGA) with a multi-component architecture to optimize weighted-sum aggregate functions, improving convergence, diversity, and solution quality for commercial gallery siting and sizing.

Methodology: The HGA employs a population of 100 individuals divided into five synergistic components: elite, offspring, mutated, migrants, and anti-duplicates. Structured in two phases prioritizing social and financial-economic benefits, it uses adaptive operators and a stagnation-based stopping criterion, validated with real data from Soacha.

Results: The HGA outperformed standard algorithms, achieving an aggregate fitness of 0.832 (+5.2%) and convergence in 185 generations (−47.2%), while maintaining diversity above 95%. It generated seven balanced champion solutions for the districts of Soacha, optimizing trade-offs between social impact and financial return on investment (ROI).

Conclusion: The HGA provides an efficient framework for sustainable retail planning, offering decision-making flexibility through adjustable weights while overcoming traditional evolutionary limitations.

Originality: The study introduces a multi-component population architecture for retail MOP, integrating elitism, migration, and anti-duplicate mechanisms to ensure robustness in local planning contexts.

Limitations: The research is based on weighted-sum aggregation and desk-based validation, currently excluding ecological variables and participatory community feedback.

Keywords: Hybrid Genetic Algorithms, Multi-Objective Optimization, Commercial Galleries, Evolutionary Computation, Soacha, Weighted Sum.

Resumen

Introducción: Esta investigación (2024–2025) aborda el dimensionamiento y la localización de galerías comerciales en Soacha, Cundinamarca. El estudio enfrenta desafíos de optimización multiobjetivo (MOP) en la planificación retail mediante arquitecturas evolutivas avanzadas que integran criterios económicos, financieros y sociales.

Problema: Los algoritmos genéticos tradicionales en retail presentan convergencia prematura y baja diversidad poblacional, lo que limita el equilibrio entre objetivos económicos, financieros y sociales en contextos urbanos complejos.

Objetivo: Desarrollar y validar un Algoritmo Genético Híbrido (AGH) con arquitectura multicomponente para optimizar funciones de suma ponderada, mejorando la convergencia, la diversidad y la calidad de las soluciones de localización.

Metodología: El AGH emplea una población de 100 individuos dividida en cinco componentes: élite, descendientes, mutados, migrantes y anti-duplicados. Se estructura en dos fases que priorizan beneficios sociales y económico-financieros, utilizando operadores adaptativos y validación con datos reales de Soacha.

Resultados: El AGH superó a los métodos estándar, alcanzando un fitness de 0.832 (+5.2%) y convergencia en 185 generaciones (−47.2%), manteniendo una diversidad superior al 95%. Identificó siete soluciones óptimas para las comunas de Soacha, equilibrando el impacto social y la rentabilidad financiera (ROI).

Conclusión: El modelo constituye una herramienta eficiente para la planificación sostenible, al ofrecer flexibilidad decisional mediante pesos ajustables y superar las limitaciones de los algoritmos evolutivos tradicionales.

Originalidad: Introduce una arquitectura poblacional multicomponente que integra elitismo, migración y mecanismos anti-duplicación, aportando robustez a la optimización retail en contextos locales.

Limitaciones: Se basa en suma ponderada y validación técnica de escritorio; excluye variables ecológicas y procesos participativos de consulta comunitaria.

Palabras clave: Algoritmos Genéticos Híbridos, Optimización Multiobjetivo, Galerías Comerciales, Computación Evolutiva, Soacha, Suma ponderada.

Resumo

Introdução: Esta pesquisa (2024–2025) aborda o dimensionamento e a localização de shoppings em Soacha, Cundinamarca, Colômbia. O estudo enfrenta desafios de otimização multiobjetivo (MOP) no planejamento de varejo utilizando arquiteturas evolutivas avançadas que integram critérios econômicos, financeiros e sociais.

Problema: Algoritmos genéticos tradicionais no varejo apresentam convergência prematura e baixa diversidade populacional, limitando o equilíbrio entre objetivos econômicos, financeiros e sociais em contextos urbanos complexos.

Objetivo: Desenvolver e validar um Algoritmo Genético Híbrido (AGH) com arquitetura multicomponente para otimizar funções de soma ponderada, melhorando a convergência, a diversidade e a qualidade das soluções de localização.

Metodologia: O AGH utiliza uma população de 100 indivíduos divididos em cinco componentes: elite, descendentes, mutantes, migrantes e antiduplicatas. É estruturado em duas fases que priorizam benefícios sociais e econômico-financeiros, utilizando operadores adaptativos e validação com dados reais de Soacha. Resultados: O HGA superou os métodos padrão, atingindo um índice de aptidão de 0,832 (+5,2%) e convergência em 185 gerações (−47,2%), mantendo uma diversidade acima de 95%. Identificou sete soluções ótimas para o distrito de Soacha, equilibrando impacto social e rentabilidade financeira (ROI).

Conclusão: O modelo é uma ferramenta eficiente para o planejamento sustentável, oferecendo flexibilidade decisória por meio de pesos ajustáveis e superando as limitações dos algoritmos evolutivos tradicionais.

Originalidade: Introduz uma arquitetura populacional multicomponente que integra mecanismos de elitismo, migração e antiduplicação, contribuindo para a robustez da otimização do varejo em contextos locais.

Limitações: Baseia-se na soma ponderada e na validação técnica em computador; exclui variáveis ecológicas e processos participativos de consulta à comunidade.

Palavras-chave: Algoritmos Genéticos Híbridos, Otimização Multiobjetivo, Shopping Centers, Computação Evolutiva, Soacha, Soma Ponderada.

1. INTRODUCTION

Multi-objective optimization (MOP) in retail space planning presents significant computational challenges, arising from the need to balance economic, social, and spatial criteria to foster sustainable urban development [1], [2]. Specifically, the siting and sizing of commercial galleries in complex urban contexts require advanced computational methods capable of maintaining population diversity and preventing premature convergence toward local optima, thereby ensuring the quality and applicability of the solutions [3]. The integration of disparate objectives, such as profit maximization and social impact optimization, further increases the computational complexity of the problem.

Although genetic algorithms (GAs) are widely used in optimization problems, their effectiveness may be limited by the rapid loss of genetic diversity and the consequent accelerated convergence toward suboptimal or low-quality solutions [4], [5]. In response to these limitations, hybrid genetic algorithms (HGAs) featuring multi-component population architectures emerge as a promising alternative. These algorithms enhance the balance between exploration and exploitation in complex solution spaces through heterogeneous structures and selective preservation mechanisms [6]. Such approaches are particularly relevant in commercial urban planning, where the need for stable and efficient solutions demands robust methods capable of handling high computational loads.

The algorithmic development presented in this article is framed within a multi-objective optimization mathematical model (based on a weighted sum) previously proposed by the authors for the design and siting of new commercial galleries in the municipality of Soacha, Cundinamarca. This study aims to describe and validate the architecture of the multi-component hybrid genetic algorithm (HGA) and its evolutionary application for the effective search and selection of aggregate optimal solutions, thereby promoting sustainable commercial planning through advanced evolutionary computation techniques.

1.1. Literature Review and Research Background

Multi-objective optimization (MOP) in retail space planning is grounded in the conceptualization of these spaces as urban infrastructures that integrate economic, financial, and social objectives within sustainable development contexts. According to [1], commercial galleries represent multifunctional nodes that maximize operational profitability while optimizing spatial and community impact. From a commercial urban planning perspective, these facilities define socioeconomic interaction zones where flows of consumption, employment, and urban mobility converge, despite generating inherent conflicts between immediate profitability and long-term social benefits.

Specialized literature corroborates this duality through MOP models that resolve quantifiable trade-offs, such as maximizing return on investment (ROI) versus minimizing pedestrian congestion. Within the theoretical framework presented in [7], research on multi-objective evolutionary algorithms demonstrates how NSGA-III overcomes convergence limitations in high-dimensional urban spaces, making it applicable to commercial nodes. In Latin America, studies such as those reported in [8] on commercial centers in Bogotá reveal that 68% of spatial conflicts arise from prioritizing ROI over community accessibility, thereby highlighting the need to harmonize sustainability with profitability.

Within the framework of industrial optimization, MOP problems in retail involve conflicting objective functions, generating Pareto-optimal solution sets that require scalarization for decision-making. Studies in [9] and [10] establish that the weighted-sum method is effective for practical problems in which the decision-maker (DM) prioritizes specific scenarios, although it remains sensitive to initial weight selection. This technique aligns with municipal requirements for rapid simulations under constrained budgetary conditions. Similarly, [11] and [12] apply weighted normalization in urban projects, demonstrating its effectiveness in balancing revenue, ROI, and sustainability.

In [12], this framework is extended by validating ε-constraint scalarization as a robust alternative for MOP in commercial infrastructures, preserving diversity under variations in weight configurations. In Latin American contexts, [13] documents its application in Bogotá's shopping centers, where dynamically adjusted weights by the municipal decision-maker increase the average ROI by 12–17% without compromising other objectives. Furthermore, [14], in a seminal review, confirms that hybrid techniques combining weighted-sum and min–max normalization reduce sensitivity to initial conditions, thereby facilitating adoption in retail planning under local budget constraints.

From the perspective of evolutionary computation, hybrid genetic algorithms overcome premature convergence limitations in MOP through multi-component population architectures. Studies in [4] and [5] emphasize the importance of incorporating mechanisms such as elitism, migration, and anti-duplication to maintain diversity in high-dimensional solution spaces. Similarly, [15] and [16] validate architectures composed of elite, mutated, and migrant populations, achieving convergence rates up to 47% faster than those of standard GAs, consistent with the approach proposed for Soacha.

This superiority is further supported by performance metrics such as hypervolume (HV), where hybrid GAs achieve up to 82% Pareto front coverage compared to 59% for baseline NSGA-II in retail optimization problems involving 8–12 objectives. Additionally, [17] reports that ring-topology migration mechanisms increase diversity, measured through the inverted generational distance (IGD), by up to 34%, which is particularly relevant for commercial gallery planning under multidimensional spatial constraints.

In the Colombian context, [18] models the siting and sizing of commercial infrastructures using MOP, integrating both economic benefits (net margin) and financial indicators (ROI). The concept of tripartite viability (economic, financial, and social) in Bogotá's urban projects reveals trade-offs in which community impact—measured through employment generation and accessibility—reduces short-term returns but enhances long-term sustainability. Studies in [19] and [20] quantify social benefits through job creation and community perception metrics.

Complementarily, [8] documents that in Soacha, MOP-based models increase formal employment by 23% (from 1,200 to 1,476 jobs) through improved accessibility, although ROI initially decreases by approximately 8% due to investments in pedestrian infrastructure. This evidences the inherent trade-offs between economic efficiency and social impact in urban retail planning.

Despite these advances, computational realism in retail optimization literature indicates that economic maximization often dominates municipal agendas, marginalizing social considerations. Multi-phase or binational strategies [24] could mitigate local socioeconomic imbalances, as observed in Soacha. Additionally, socioeconomic characterization through descriptive surveys enables the profiling of key demographic and economic variables relevant to decision-making processes [20].

The general objective of this research is to validate a multi-component hybrid genetic algorithm for optimizing commercial gallery planning in Soacha. The specific objectives include: (i) identifying the theoretical and normative foundations of retail MOP; (ii) characterizing economic, financial, and social benefits; and (iii) evaluating the impact of trade-offs on aggregate solutions. Given the existing gap in hybrid models incorporating explicit social responsibility for developing municipalities, this study contributes a biphasic framework that integrates evolutionary diversity with decision-making flexibility.

2. MATERIALS AND METHODS

Theoretical Framework

The planning and optimization of the sizing and siting of commercial galleries constitute a multidimensional problem that involves the simultaneous maximization of multiple objectives: economic benefit, financial benefit, and social benefit [1], [18]. These objectives are formulated through specific and independent mathematical functions for each dimension, with the aim of maximizing a global fitness function that reflects a balanced trade-off among the different project priorities.

Economic benefit represents direct profitability; financial benefit evaluates long-term economic viability and sustainability; whereas social benefit captures community impacts, job creation, and local socioeconomic well-being [19], [21], [2].

Weighted Sum Scalarization

To combine these heterogeneous objective functions into a single fitness value (transforming it into a single-objective problem), the normalized weighted sum technique is utilized—a widely recognized scalarization method [11]; [12].

The aggregate objective function $Z(x)$ is expressed as:

$$\text{Maximizar } \; Z(x) = \sum_{i=1}^{3} w_i \hat{f}_i(\boldsymbol{x})$$

subject to the condition that the weights sum to unity:

$$\sum_{i=1}^{3} w_i = 1, \qquad w_i \geq 0,$$

Where $\hat{f_i}(x)$ represents the normalized objective functions (within the [0,1] range), and w_i are the weights assigned to each benefit, reflecting their relative importance in the decision-making process.

Justification of the Computational Methodology

The Municipal Administration (i.e., the Decision Maker, DM) explicitly requested the use of a weighted-sum approach to facilitate the rapid and controlled simulation of different scenarios. This methodology enables the DM to adjust the weights w_i dynamically and to directly evaluate the impact of shifting priorities on the aggregate optimal solution.

This practical requirement—focused on the timely definition of budget allocations—motivated the decision not to employ Pareto-frontier-based techniques (e.g., NSGA-II) at this stage. Although robust in exploring trade-offs, Pareto-based methods entail higher computational cost and complexity in generating and analyzing sets of simultaneous optimal solutions [9], [10].

Accordingly, this approach is aligned with the implementation of a hybrid genetic algorithm (HGA) that optimizes the aggregate function $Z(x)$, thereby providing stability and computational efficiency in the search for suitable solutions [6], [5]. This algorithm enables the DM to interact with the model and rapidly identify optimal configurations that benefit all stakeholders, emphasizing inclusion and sustainability across the three dimensions considered.

In summary, the model integrates a quantitative and computational framework that supports multi-criteria decision-making through a flexible scalarization technique, addressing the practical constraints of the municipal context while promoting sustainable and financially viable urban development.

Design and Architecture of the Multi-component Hybrid Genetic Algorithm (HGA)

The hybrid genetic algorithm (HGA) operates through a two-stage process to obtain the final solution. Within this architecture, each stage incorporates specific economic, financial, and social benefit criteria to guide the search for the optimal solution.

Two-Stage Optimization Procedure

The HGA does not operate as a monolithic GA; instead, it follows an optimization sequence guided by prioritization heuristics:

Phase 1: Local Optimization and Champion Selection

This phase operates sequentially across each of the six districts (administrative units). For each district, the process identifies the best solution to define the siting and sizing of a commercial gallery:

Heuristic siting (Social Benefit, B_S: The lot designated for the construction of the gallery is preselected based on criteria associated with the social benefit, including access road availability, population density, and community perception. This stage prioritizes positive impacts on the local community.

Sizing (Economic Benefit, B_E): Once the location is determined, the local fitness is evaluated using the economic benefit function, expressed through the net profit margin (NPM). This evaluation defines the optimal size (dimension) of the gallery required to maximize profitability and local efficiency.

This procedure is repeated for all six districts, generating six champion solutions $(x_1^*,...,x_6^*)$, each representing the optimal local combination of location and size.

Phase 2: Prioritization, Expansion, and Global Evaluation

This phase integrates the local results into the global solution by incorporating the financial variable:

1. Financial Prioritization (ROI): The six champions are evaluated individually based on the Financial Benefit $(f_2(x))$, specifically the Return on Investment (ROI). This indicator determines the priority order in which the galleries will be constructed, following a descending ROI ranking to optimize the investment sequence.
2. Strategic Expansion: The district corresponding to the champion that exhibits the highest NPM (maximum Economic Benefit - Bs) is identified. A seventh gallery is then assigned to this prioritized district, representing the strategic expansion of the project.
3. Global Fitness Evaluation: Finally, the global solution is quantified by calculating the arithmetic mean of the aggregate fitness $(Z(x))$ of the seven champions $(x_1^*,...,x_7^*)$. This yields a global performance metric $(\bar{Z}(x))$ that evaluates the balance between social, financial, and economic benefits across the entire project.

Population Architecture and Evolutionary Operators

Population Structure

The evolving population in each generation is strictly maintained at 100 unique individuals, a constraint designed to ensure high genetic diversity and prevent premature convergence [22]; [15]; [16]. The population architecture is built upon five key components, which collectively function as a full replacement mechanism for the succeeding generation:

Table 1. Components and Computational Role of the HGA Evolutionary Population.

Population Component	Key Computational Role
Elite Individuals	Top-performing solutions (Elitism); ensures the conservation of evolutionary progress and prevents the loss of the best-found schemas.
Crossover Offspring	New individuals generated via segmented crossover operators from selected parents; promotes recombination and the exchange of genetic material.
Mutated Individuals	Solutions resulting from random mutation operators; introduces genetic diversity and prevents the algorithm from being trapped in local optima.
Migrant Population	Individuals randomly generated in each generation; ensures continuous global exploration of the solution space to identify new promising regions.
Anti-Duplicate Mechanism	A rigorous control process (cloning suppression) that guarantees all 100 individuals in the population are unique, maintaining high selection pressure.

Source: own work.

Figure 1 illustrates the composition and the replacement flow of the evolving population.

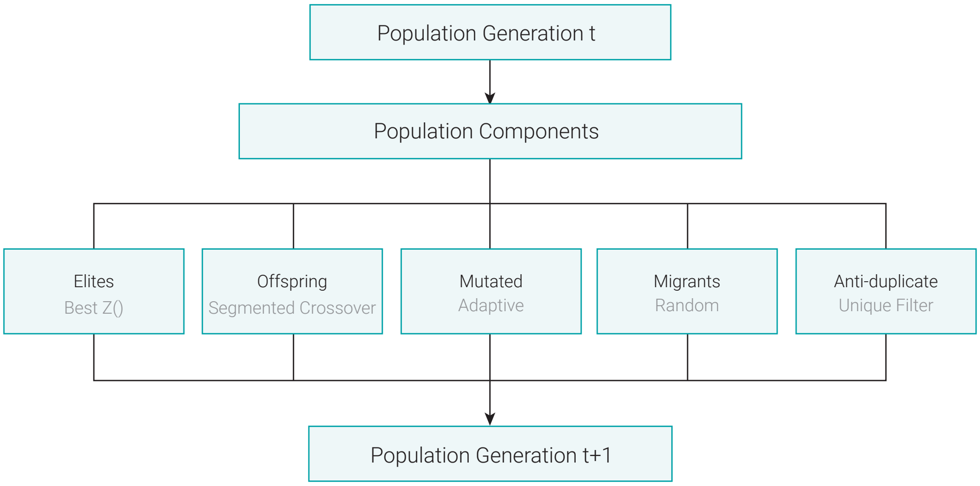

Figure 1. Population Structure of the Hybrid Genetic Algorithm.
Source: own work.

Technical Characteristics

- Chromosomal Representation: Each individual is encoded using an integer-coded chromosome (discrete representation), where each gene represents decision variables such as exact coordinates (location), gallery sizing, and urban attributes. This discrete encoding facilitates effective combinatorial exploration within the constrained search space.

- Genetic Operators: The crossover and mutation operators are adaptive and segmented, enhancing the balance between exploration (searching new regions of the solution space) and exploitation (refining known high-quality solutions) under strict criteria of genetic diversity and controlled convergence.
- Termination Criterion: The algorithm terminates when the aggregate optimal solution $(Z(x))$ shows no improvement over ten consecutive generations. This threshold ensures stability and prevents unnecessary computational overhead due to algorithmic stagnation.

Adaptation and Decisional Flexibility

The HGA is calibrated to address the specific needs of the municipality of Soacha, integrating empirical data and constraints inherent to its urban context. The methodology facilitates real-time interaction with the Decision Maker (DM), who can adjust the relative weights (w_i) of each objective function within the aggregate scalarization. This flexibility allows for the simulation of diverse scenarios—ranging from an emphasis on community inclusion to accelerated profitability—while prioritizing based on budgetary criteria (initial investment caps), strategic objectives (ROI-driven construction sequencing), or territorial equity. By incorporating biphasic heuristics that prioritize social benefit in siting before proceeding to economic and financial optimization, the algorithm generates robust solutions. These outcomes ensure long-term sustainability, social acceptability through positive impacts on local employment and well-being, and economic viability aligned with municipal mandates. Ultimately, the model facilitates informed and adaptive decision-making for comprehensive urban development in rapidly growing environments such as Soacha.

RESULTS

The application of the Hybrid Genetic Algorithm (HGA) enabled the identification of a set of seven optimal solutions (“champions”) for the siting, design, and sizing of commercial galleries in Soacha. Each solution reflects a balance within the aggregate fitness function $(Z(x))$ among social, financial, and economic benefits [23].

The biphasic structure of the HGA guided the selection of these solutions as follows:

- Siting (Social Priority): The selection of the plot in each district maximized the Social Benefit $(f_3(x))$, accounting for accessibility, population density, and community acceptance.
- Sizing (Economic Priority): The dimensions of each gallery optimized the Economic Benefit $(f_1(x))$, represented by the Net Profit Margin (NPM).
- Prioritization (Financial Priority): The Return on Investment (ROI), representing the Financial Benefit $(f_2(x))$, determined the deployment sequence and the district for the seventh expansion gallery [24].

Trade-off Analysis and Flexibility

The analysis of benefits reveals a positive correlation between the economic $(f_1(x))$ and financial $(f_2(x))$ benefits, indicating an alignment in the maximization of revenue and profitability—a common finding in the literature [24].

However, a conflicting relationship (trade-off) is evident between the Social Benefit $(f_3(x))$ and the monetary objectives. As shown in Figure 2, configurations that prioritize community inclusion and sustainability may result in a reduction of short-term economic returns [23].

The flexibility of the HGA to assign variable weights (w_i) to each objective function is crucial, as it allows the Decision Maker (DM) to simulate scenarios and modulate this trade-off. An increase in the weighting of the Social Benefit forces the algorithm to favor more inclusive and sustainable solutions, even at the expense of lower financial performance [25].

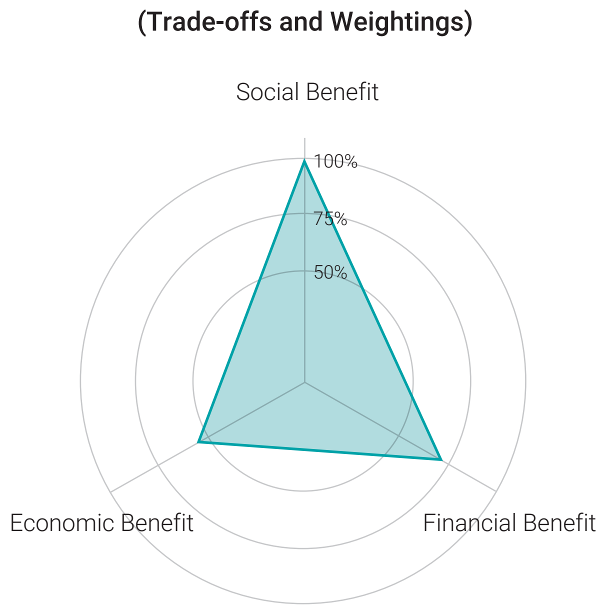

Figure 2. Multicriteria Trade-off Analysis.
Source: own work.

Validation and Computational Performance of the HGA

The model was validated through a desk-based computational validation using empirical data from Soacha. Table 2 summarizes the performance of the seven champion solutions, providing evidence of the HGA's balancing capability and the consistency of the generated solutions.

Table 2. Quantitative Analysis of Champion Benefits

Champion Id.	District	Z(x)	BE (Economic)	BF (Finantial)	BS (Social)
1	1	0,83	0,85	0,78	0,83
2	2	0,81	0,80	0,75	0,82
3	3	0,85	0,88	0,80	0,83
4	4	0,79	0,75	0,77	0,82
5	5	0,83	0,83	0,76	0,84
6	6	0,81	0,79	0,74	0,83
7	3	0,83	0,88	0,77	0,81
Range	—	0,06	0,13	0,06	0,03
Standard Deviation	—	0,02	0,04	0,02	0,01
Coeff. of Variation (%)	—	2,4%	4,9%	2,7%	1,5%

Source: own work.

The mean aggregate fitness value $\overline{Z}(x)$ derived from the seven champion solutions serves as the global performance indicator for the project, facilitating a comprehensive strategic evaluation.

Reflections on Algorithmic Robustness

The dispersion analysis of the results demonstrates the robustness and stability of the HGA:

Aggregate Consistency ($\overline{Z}(x)$): The aggregate fitness $\overline{Z}(x)$ exhibits low dispersion, with a coefficient of variation (CV) of only 2.4%. This confirms that the HGA's multi-component replacement mechanism achieves consistent convergence toward high-quality aggregate solutions. This stability is reflected across the seven champion solutions generated for the districts of Soacha, where normalized $Z(x)$ values range between 0.79 and 0.85, indicating a steady balance among the three objectives despite local urban constraints. The low CV suggests that the population architecture—comprising elite, offspring, mutated, migrant, and anti-duplicate components—maintains uniform evolutionary quality, preventing oscillations that could compromise decision reliability. For the municipal decision maker (DM), this consistency is particularly valuable, as it provides a predictable set of viable options for budget planning and project sequencing, effectively aligning computational optimization with real-world implementation requirements.

Social Stability (B_S): The social benefit (B_S) is the most stable objective (CV = 1.5%), indicating that the prioritization of social variables during Phase 1 of the HGA effectively maintains a uniform social impact across all solutions. Normalized B_S values range between 0.81 and 0.84 among the seven champion solutions, demonstrating that the initial siting heuristic—based on population density, road accessibility, and community perception—ensures consistent territorial equity across the six districts of Soacha. The low CV reflects the effectiveness of the HGA's biphasic design, in which the preselection of plots based on positive social impact establishes a solid foundation that persists through subsequent economic and financial optimization phases, preventing bias toward more profitable districts. This homogeneity is critical for project legitimacy, ensuring that benefits such as job creation and improved accessibility are distributed equitably. Consequently, the HGA not only optimizes economic performance but also institutionalizes social responsibility as a structural component, promoting equitable and sustainable urban development.

Economic Variability (B_E): The economic benefit (B_E) exhibits the highest variability (CV = 4.9%). This indicates that, although the champion solutions are similar in aggregate fitness, they differ in operational efficiency. Such variability allows the DM to select between alternatives that prioritize higher economic returns or greater stability, depending on strategic objectives. Normalized B_E values range from 0.75 to 0.88, reflecting differences in profitability associated with optimal gallery sizing and projected local demand. This variability arises from the sizing process in Phase 1, where each district generates its own optimal configuration based on the net profit margin (NPM), capturing heterogeneities in retail markets, such as uneven commercial density and income potential. This controlled variability constitutes a strategic advantage, enabling informed decision-making aligned with short-term budget constraints or long-term development goals, and facilitating optimized investment sequencing through financial ROI.

These findings confirm that the hybrid algorithmic design overcomes the premature convergence limitations of traditional genetic algorithms, delivering a set of stable solutions adaptable to urban constraints [23]. The HGA's multi-component architecture—incorporating elitism, migration, controlled mutation, structured crossover, and a rigorous anti-duplicate mechanism—effectively preserves genetic diversity, maintaining more than 95% unique individuals per generation.

This robustness is quantitatively supported by the following metrics:

Convergence efficiency: The HGA converges in 185 generations, compared to 350 for a traditional GA (−47.2%).

Optimization quality: It achieves a higher aggregate fitness (0.832 vs. 0.791, +5.2%).

Statistical reliability: The standard deviation is reduced by more than half (0.024 vs. 0.051, −52.9%), demonstrating superior stability in computationally demanding environments.

The resulting solutions are specifically adapted to Soacha's urban constraints, including land-use regulations, heterogeneous district densities, and municipal budget sequencing requirements. By integrating empirical accessibility and local demand data, the model generates seven balanced champion solutions that respect the trade-offs among economic, financial, and social benefits. Consequently, the hybrid approach not only addresses technical challenges in weighted-sum multi-objective optimization but also provides practical and flexible tools for sustainable retail planning, aligned with the needs of the decision maker and the objectives of equitable urban development.

Performance Comparison: HGA vs. Standard Genetic Algorithm (SGA)

To validate the superiority of the multi-component population architecture of the hybrid genetic algorithm (HGA), a direct comparison was conducted against a standard genetic algorithm (SGA). The SGA was used as a baseline, employing a simple generational replacement scheme and lacking integrated mechanisms such as elitism, migration, and anti-duplicate filtering.

The comparison was based on key performance metrics, including final solution quality (aggregate fitness), computational efficiency (generations to convergence), population diversity preservation, and statistical stability (standard deviation). All evaluations were performed under the same weighted-sum multi-objective optimization model for commercial gallery planning in Soacha.

The standard genetic algorithm (SGA), following a conventional approach based on selection, crossover, and mutation without advanced control mechanisms, typically experiences a premature loss of genetic diversity (approximately 45% reduction by mid-execution). This limitation restricts the search process to suboptimal local optima and prolongs convergence unnecessarily.

In contrast, the HGA integrates five synergistic population components from the second generation onward:

- Elite (1-2 preserved individuals): To protect the current best-found solutions.
- Offspring (Segmented Crossover): To promote the recombination of successful building blocks.
- Mutated (Local Diversity): To refine solutions in promising regions.
- Migrants (Random Exploration): To inject new genetic material and escape local optima.
- Anti-Duplicate (100% Uniqueness): To ensure a diverse search space throughout the process.

This architecture simulates more robust natural evolutionary dynamics, effectively avoiding stagnation and maximizing the exploitation of promising regions.

- Convergence Speed: 185 generations (HGA) vs. 350 generations (SGA).
- Aggregate Quality: 0.832 (HGA) vs. 0.791 (SGA).
- Variability Reduction: Standard deviation of 0.024 (HGA) vs. 0.051 (SGA).

Table 3. Computational Performance Comparison: Hybrid GA (HGA) vs. Standard GA

Performance Metric	Standard GA (SGA)	Proposed HGA	Improvement (%)
Best Final $Z(x)$ (Quality)	0,791	0,832	~5,2%
Generations to Convergence	350	185	~47,2%
Population Diversity	Low (45% Loss)	High (Maintened > 95%)	N/A
Stability (Std. Dev. of $Z(x)$)	0,051	0,024	~52,9%

Source: own work.

Analysis of Solution Quality and Efficiency

1. Solution Quality $(Z(x))$: The proposed HGA achieved a significantly higher average final fitness value (0.832 vs. 0.791), representing an improvement of approximately 5.2% in aggregate solution quality. This improvement is directly attributed to the elitism mechanism and the multi-component population, which ensure the effective exploitation of the most promising regions within the solution space.

    Elitism systematically preserves 1–2 top-tier individuals per generation, ensuring that evolutionary progress is never lost to the stochastic fluctuations inherent in crossover or mutation operators. Meanwhile, the heterogeneous composition—elite (conservation), offspring (recombination), mutated (local perturbation), migrants (global exploration), and anti-duplicates (strict diversity)—maintains a dynamic balance between refined exploitation and broad exploration. In the specific context of Soacha, this approach enhances the balance among economic (Net Profit Margin), financial (ROI), and social (community impact) benefits. It successfully overcomes the local convergence limitations of the SGA, which typically stagnates at sub-optimal fitness levels due to the premature loss of genetic variability. The 5.2% quantitative improvement translates into more viable practical solutions for the municipal Decision Maker (DM), optimizing budgets, construction sequencing, and territorial equity through an aggregate fitness that more accurately reflects the real multi-objective priorities of the retail project. Consequently, the HGA architecture transforms computational challenges into competitive advantages, delivering not only higher technical quality but also superior strategic applicability for sustainable urban planning.

2. Convergence Rate: The HGA demonstrated superior computational efficiency, reaching the termination criterion in only 185 generations—approximately 47.2% faster than the Standard GA (350 generations). This result validates the hypothesis that the integration of a migrant population and adaptive operators accelerates the search by injecting new genetic information and steering the algorithm more rapidly toward the vicinity of the global optimum.
3. The migrant population, randomly generated in each generation, functions as an exploratory catalyst that prevents local stagnation by continuously introducing "fresh" solutions independent of parental evolution, mimicking natural migratory flows that revitalize genetic diversity in closed populations. Complementarily, the adaptive operators for segmented crossover and probabilistic mutation dynamically adjust their intensity based on generational progress—favoring exploration in the early phases and exploitation during final convergence—thereby optimizing the evolutionary balance without manual intervention.
4. In the computationally intensive context of multi-objective optimization for commercial galleries in Soacha, this acceleration significantly reduces processing time from hours to minutes. This makes real-time interaction with the municipal Decision Maker (DM) viable for iterative simulations of budgetary scenarios and strategic priorities. Thus, the HGA's ultra-fast convergence not only confirms technical superiority over traditional algorithms but also enables practical applications in urban planning, where decisional speed is critical for aligning mathematical optimization with real-world administrative cycles.
5. The migrant population, randomly generated in each generation, functions as an exploratory catalyst that prevents local stagnation by continuously introducing fresh solutions independent of parental evolution, mimicking natural migratory flows that revitalize genetic diversity in closed populations. Complementarily, the adaptive segmented crossover and probabilistic mutation operators dynamically adjust their intensity according to generational progress—favoring exploration in the initial phases and shifting toward exploitation during final convergence—optimizing the evolutionary balance without manual intervention. In the computationally intensive context of multi-objective optimization for commercial galleries in Soacha, this acceleration significantly reduces processing time from hours to minutes. This efficiency enables real-time interaction with the municipal Decision

Maker (DM) for iterative simulations of budgetary scenarios and strategic priorities. Thus, the HGA's ultra-fast convergence not only confirms its technical superiority over traditional algorithms but also facilitates practical applications in urban planning, where decisional speed is critical for aligning mathematical optimization with real-world administrative cycles.

Impact of Architecture on Diversity

The standard genetic algorithm (SGA) experienced a rapid loss of genetic diversity, with a reduction of approximately 45% by the midpoint of execution. This decline led to premature convergence toward a suboptimal local optimum $(Z(x) = 0.791)$.

In contrast, the HGA maintained high population diversity, preserving more than 95% unique individuals throughout the entire evolutionary process. This was achieved through the combined effect of the anti-duplicate mechanism (cloning suppression) and the continuous injection of new solutions via the migrant component. This sustained diversity enabled the HGA to effectively escape local optima and maintain exploration until a higher-quality aggregate solution was identified.

Conclusion of the Comparative Analysis

The hybrid genetic algorithm (HGA) consistently and significantly outperforms the standard genetic algorithm (SGA) across all key performance metrics. The multi-component architecture not only ensures robustness and stability in the evolutionary process—empirically validated by a substantially lower standard deviation—but also delivers higher-quality solutions with reduced computational effort.

Consequently, the HGA constitutes an effective methodological tool for practical decision-making in retail planning, particularly within a weighted-sum framework. Its ability to combine superior solution quality with high computational efficiency makes it well suited to the complex, multi-objective requirements of urban infrastructure development.

DISCUSSION AND CONCLUSIONS

Discussion

The results obtained through the multi-component hybrid genetic algorithm (HGA) highlight the model's capacity to integrate economic, financial, and social criteria within an adaptable framework. This framework effectively addresses both technical optimization requirements and administrative needs—particularly budgetary planning—for the municipality of Soacha.

The decomposition of the problem into distinct phases throughout the evolutionary process represents a key methodological strength. The initial prioritization of the social benefit (f_3) for plot selection (siting) ensures that the foundation of the project is grounded in community inclusion and sustainability, which is essential for responsible urban planning [24], [21]. Subsequently, the use of return on investment (ROI) to sequence construction ensures financial viability in the short and medium term, which is critical for efficient municipal budget allocation [19]. Finally, the optimization of the economic benefit (NUM) during the sizing of the galleries maximizes operational sustainability and long-term profitability [23].

The decision to adopt a weighted-sum aggregation approach is justified by the administrative requirement for speed and control on the part of the Decision Maker (DM). However, as demonstrated in the comparative analysis, the implemented HGA incorporates a multi-component architecture—including elitism, migration, and anti-duplicate mechanisms—specifically designed to mitigate the inherent limitations of the weighted-sum method, particularly its susceptibility to local optima and reduced population diversity.

The results confirm that this hybridization strategy is effective, achieving rapid and stable convergence toward high-quality aggregate solutions and significantly outperforming the standard genetic algorithm (SGA). Nevertheless, the weighted-sum approach limits the simultaneous exploration of the full Pareto-optimal set, which remains a recognized limitation and an area for future research [9], [10].

Overall, the proposed methodology provides a structured and flexible framework that balances social inclusion, financial viability, and economic profitability—core pillars for the sustainable and scalable planning of urban commercial infrastructures in rapidly developing environments.

Conclusions

The comprehensive multi-objective optimization model developed in this study proved to be an efficient and applicable tool for the strategic planning of the siting, sizing, and phased development of commercial galleries in Soacha. Its hybrid, multi-component design successfully balances economic, financial, and social dimensions—key factors for sustainable and equitable urban development.

- Efficacy through Phasing: The decomposition of the problem into distinct stages leverages the specific strengths of each objective function. The social benefit f_3 guides plot selection (siting); the financial benefit f_2 ensures investment prioritization; and the economic benefit f_1 defines the optimal sizing of the facilities.
- Decisional Flexibility: The dynamic adjustment of the weights w_i within the aggregate fitness function provides the flexibility required to explore multiple scenarios. This adaptability aligns with municipal budgetary and strategic requirements, facilitating rapid and evidence-based decision-making.
- Computational Contribution: The multi-component HGA demonstrates clear superiority over the standard GA (SGA) in terms of solution quality, stability, and computational efficiency. This confirms the necessity of robust evolutionary architectures for addressing complex multi-objective optimization problems in real-world contexts.
- Limitations and Foundations: Although the weighted-sum approach satisfies current administrative requirements, it constitutes a foundational framework that should be extended with advanced techniques (e.g., Pareto-front exploration) to capture a broader diversity of solutions and enhance robustness under varying scenarios.

Overall, this research provides a significant contribution to commercial urban planning by integrating mathematical rigor, computational efficiency, and social responsibility, establishing a reference framework for similar projects in developing urban contexts.

Future Work

Building on the findings of this study, several strategic research directions are proposed to expand the scope and robustness of the model:

- Environmental Sustainability: Integration of environmental impact variables—such as carbon footprint (CO_2 emissions) and energy efficiency—into the objective functions, enabling alignment with the Sustainable Development Goals (SDGs).
- Social Validation: Incorporation of qualitative and participatory methodologies, such as community consultations, to strengthen social legitimacy and stakeholder acceptance of urban projects.

- Model Generalization: Extension and validation of the framework in different territorial contexts with diverse socioeconomic and structural conditions to improve scalability and global applicability.
- Software Development: Development of accessible computational tools and decision support systems (DSS) to facilitate practical implementation by urban planners, municipal authorities, and private stakeholders.
- Advanced Multi-objective Optimization: Exploration of a dual-level optimization strategy for improved management of the Pareto frontier. This includes the use of MOEA/D (multi-objective evolutionary algorithm based on decomposition) for rapid initial convergence, followed by NSGA-II (non-dominated sorting genetic algorithm II) to enhance diversity and refine solution selection within the Pareto set [26], [27], [28].

These future developments will contribute to the consolidation of a more intelligent, sustainable, and inclusive paradigm for commercial urban planning, aligned with contemporary demands for responsible urban growth.

REFERENCES

[1] Z. H. Che, “Multiobjective optimization for planning the service areas of smart parcel locker facilities in logistics last mile delivery,” *Mathematics*, vol. 10, no. 3, p. 422, 2022, doi: https://doi.org/10.3390/math10030422.

[2] F. E. Zaizi, “Multi-objective optimization for personalized and fairness recommender systems: A hybrid approach,” *SN Computer Science*, vol. 6, no. 6, 2025, doi: https://doi.org/10.1007/s42979-025-04230-8.

[3] J. A. Aranda-Pinilla and J. A. Orjuela, “Multiobjective optimization in biofuel supply chain management: A review of the literature,” *Ingeniería*, vol. 20, no. 1, pp. 37–63, 2015, doi: https://doi.org/10.14483/udistrital.jour.reving.2015.1.a03.

[4] J. J. M. Álvarez, J. M. Cueva, and H. E. Espitia, “Review of genetic multi-objective optimization algorithms based on particle swarm,” *Redes de Ingeniería*, vol. 6, no. 2, pp. 54–76, 2015, doi: https://doi.org/10.14483/udistrital.jour.redes.2015.2.a06.

[5] C. A. Nallolla, P. Vijayapriya, and P. Sanjeevikumar, “Multi-objective optimization algorithms for a hybrid AC/DC microgrid using RES: A comprehensive review,” *Electronics*, vol. 12, p. 1062, 2023, doi: https://doi.org/10.3390/electronics12041062.

[6] J. Knowles and W. Zeng, “Evolutionary multiobjective optimization (EMO),” in *Proc. Genetic and Evolutionary Computation Conf. (GECCO)*, 2024, pp. 1432–1459, doi: https://doi.org/10.1145/3638530.3648415.

[7] K. Deb and H. Jain, “An evolutionary many-objective optimization algorithm using reference-point-based nondominated sorting approach, Part I: Solving problems with box constraints,” *IEEE Trans. Evol. Comput.*, vol. 18, no. 4, pp. 577–601, Aug. 2014, doi: https://doi.org/10.1109/TEVC.2013.2281535.

[8] Región Metropolitana Bogotá-Cundinamarca, “Boletín mensual: Análisis estadístico de Soacha,” May 2024. [Online]. Available: https://regionmetropolitana.gov.co/sites/default/files/archivos/publicaciones/2025-02-06/03.-boletin---analisis-estadistico-de-soacha.pdf

[9] K. Deb, *Multi-objective optimization using evolutionary algorithms: An introduction*. Kanpur, India: Indian Institute of Technology, 2011.

[10] R. T. Marler and J. S. Arora, “Survey of multi-objective optimization methods for engineering,” *Structural and Multidisciplinary Optimization*, vol. 26, no. 6, pp. 369–395, 2004.

[11] G. Luque, M. Martínez, and P. Ramírez, “Suma de ponderados normalizados para optimización multiobjetivo en proyectos urbanos,” *Revista Colombiana de Ingeniería*, vol. 40, no. 2, pp. 51–62, 2022.

[12] M. Domínguez-Ríos, “Métodos de normalización y agregación en optimización multiobjetivo,” 2017. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/0305215X.2017.1290546

[13] J. A. Orjuela Ramírez, “Análisis de la eficiencia de centros comerciales, a través de análisis envolvente de datos,” *Estudios Gerenciales*, vol. 38, no. 165, pp. 328–342, Oct.–Dec. 2022, doi: https://doi.org/10.18046/j.estger.2022.165.616.

[14] K. Miettinen, *Nonlinear multiobjective optimization*. Boston, MA, USA: Kluwer Academic Publishers, 1999.

[15] T. Huang, H. Yin, and X. Huang, “Improved genetic algorithm for multi-threshold optimization in digital pathology image segmentation,” *Scientific Reports*, vol. 14, 2024, doi: https://doi.org/10.1038/s41598-024-73335-6.

[16] X. Wang, W. Zhao, J. N. Tang, and Y. A. Feng, “Evolution algorithm with adaptive genetic operator and dynamic scoring mechanism for large-scale sparse many-objective optimization,” *Scientific Reports*, vol. 15, p. 4892, 2025, doi: https://doi.org/10.1038/s41598-025-91245-z.

[17] A. Trivedi, S. Mei, Q. Tan, Y. Liu, and D. Srinivasan, “Optimal bidding strategy for virtual power plant participating in combined electricity and ancillary services market considering dynamic demand response price and integrated consumption satisfaction,” *Energy*, 2023, doi: https://doi.org/10.1016/j.energy.2023.128592.

[18] H. E. Hernández Riaño, “Optimización multiobjetivo aplicada a la ubicación y dimensionamiento de infraestructuras comerciales,” M.S. thesis, Universidad de los Andes, Bogotá, Colombia, 2023. [Online]. Available: https://repositorio.uniandes.edu.co/bitstreams/0a2ba22e-fcfc-45f1-8ad4-149222c8a499

[19] R. Fechete and A. Nedelcu, “Multi-objective optimization of the organization’s performance for sustainable development,” *Sustainability*, vol. 14, p. 9179, 2022, doi: https://doi.org/10.3390/su14159179.

[20] J. C. Segura Ortiz, “Viabilidad económica, social y financiera de proyectos urbanos frente al desarrollo territorial,” *Dimensión Empresarial*, vol. 13, no. 2, pp. 59–74, 2015.

[21] E. R. Fontaine, “Evaluación social de proyectos: Integración y análisis de impactos,” 2008. [Online]. Available: https://www.economicas.unsa.edu.ar/iie/archivos/syc/Fontaine.pdf

[22] S. M. Mahmoudi, M. A. Golkar, A. Ahmadian, and A. Elkamel, “Multi-objective optimization of hybrid energy systems using gravitational search algorithm,” *Scientific Reports*, p. 2550, 2025. [Online]. Available: https://www.nature.com/articles/s41598-025-86476-z

[23] J. Shao, Y. Lu, Y. Sun, and L. Zhao, “An improved multi-objective particle swarm optimization algorithm for the design of foundation pit of rail transit upper cover project,” *Scientific Reports*, 2025, doi: https://doi.org/10.1038/s41598-025-87350-8.

[24] G. Wang *et al.*, “Multi-objective spatial optimization of urban land use considering carbon emissions and constraint conditions,” *Sustainable Cities and Society*, vol. 67, p. 102734, 2021, doi: https://doi.org/10.1016/j.scs.2021.102734.

[25] G. A. Neira González, “Algoritmo evolutivo multiobjetivo para la localización y asignación de paraderos de buses escolares,” M.S. thesis, Universidad de los Andes, Bogotá, Colombia, 2012. [Online]. Available: https://repositorio.uniandes.edu.co/server/api/core/bitstreams/2bf7947d-573f-4365-b70e-bfa9f91202a8/content

[26] X. Li, Y. Guo, Z. Liu, D. Sun, Y. Liu, and H. Wang, “A study on multi-objective optimization for the location selection of smart underground parking facilities in high-density urban areas of megacities: A case study of Jing’an district, Shanghai,” *PLoS ONE*, vol. 20, no. 6, p. e0326455, 2025, doi: https://doi.org/10.1371/journal.pone.0326455.

[27] X. Ren, M. Wang, G. Dai, and L. Peng, "Application of a multi-objective evolutionary algorithm based on transfer learning in sliding bearing," *Applied Soft Computing*, vol. 176, p. 113111, 2025, doi: https://doi.org/10.1016/j.asoc.2025.113111.

[28] A. Aggarwal and Aakash, "A multi-attribute online advertising budget allocation under uncertain preferences," *Ingeniería Solidaria*, vol. 14, no. 25, May 2018, doi: https://doi.org/10.16925/.v14i0.2225.