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HMGSA: A NEW HYBRID METAHEURISTIC TECHNIQUE FOR SOLVING THE PRACTICAL VEHICLE ROUTING PROBLEM

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Abstract— *The Vehicle Routing Problem (VRP) is a crucial challenge in modern logistics requiring distance minimisation for operational efficiency. However, existing metaheuristic approaches often face limitations in balancing global exploration, local exploitation, and convergence stability, particularly when applied to complex routing scenarios. This study proposes a novel hybrid metaheuristic, HMGSA, to optimise vehicle routing in complex distribution networks. The HMGSA method synergistically integrates Grey Wolf Optimisation (GWO), Symbiotic Organisms Search (SOS), and Ant Colony Optimisation (ACO). The main focus of this research is to evaluate the performance of HMGSA in VRP scenarios through testing on a standard industry benchmark dataset, Dantzig42. HMGSA achieved competitive performance comparable to SOS, GWO-SOS, and SOS-ACO on the tested instances. In addition to measuring the minimal travel distance and convergence rate, this study applies nonparametric statistical tests, namely the Friedman Test and the Wilcoxon Signed-Rank Test, to scientifically demonstrate the significance of HMGSA's superiority. Experimental results show that HMGSA consistently achieves the known optimal solution for the tested benchmark instance with high computational stability under the tested conditions (Std. Dev = 0). Statistical test results confirm (p-value < 0.05) that integrating three algorithms into HMGSA provides stronger performance improvement than single metaheuristics, while maintaining highly competitive and stable performance against dual-hybrid methods, making it potentially applicable to distribution problems with similar characteristics in practical logistics.*

Keywords: *Dantzig42, HMGSA, hybrid metaheuristic, logistics optimisation, statistical test.*

INTRODUCTION

The global logistics landscape has undergone a drastic transformation over the past decade, driven by the acceleration of the digital economy and the demand for increasingly responsive supply chains. In Indonesia, the logistics sector plays a strategic role as the backbone of inter-regional connectivity. However, geographical challenges and infrastructure constraints often trigger high operational costs. One of the primary instruments for suppressing these costs is route optimisation through the resolution of the Vehicle Routing Problem (VRP). The VRP aims to determine the

optimal routes for a fleet of vehicles to serve a set of customers within specific constraints [1], [2]. Recent studies have even linked VRP to dynamic delivery planning in the logistics 4.0 era [3] and to adopting the modular vehicle concept for greater distribution flexibility [4].

Theoretically, the VRP is an NP-hard combinatorial optimisation problem. This characteristic indicates that the complexity of finding a solution increases exponentially with the number of customer points (nodes). In real-world scenarios, this problem is often encountered as the Capacitated Vehicle Routing Problem (CVRP), where vehicle capacity constraints and distance efficiency become crucial variables that must be balanced [5], [6]. Inefficiency in route determination not only impacts fuel consumption but also degrades the quality of service (Service Level Agreement) due to delivery delays. This challenge becomes even more complex in modern urban logistics, which involves integrated transport modes, including underground systems [7].

This research serves as a further development of the author's dissertation at Asia e University titled *"A New Hybrid Metaheuristic Technique Based on Grey Wolf Optimization, Symbiotic Organism Search, and Ant Colony Optimization for Solving Multi-Objective Vehicle Routing Problems"* [2]. The core of this research is the development of the HMGSA algorithm (*Hybrid Metaheuristic Grey Wolf–Symbiotic Organism–Ant Colony Optimisation*). HMGSA was first officially introduced at the TSSA 2025 conference [8], building on previous research on the effectiveness of the Ant Colony Optimisation (ACO) method in distribution routing [9]. This article aims to expand upon those findings, with a specific focus on practical VRP implementation and on strengthening result validation through more robust formal statistical testing.

In recent years, various studies have sought to overcome the weaknesses of single metaheuristic algorithms through hybridisation. Several recent developments include the use of Quantum Tabu Search for CVRP [10], adaptive memory-based heuristics [11], and the combination of Ant Colony and Artificial Bee Colony algorithms [12]. Furthermore, recent comparative analyses have shown that metaheuristic algorithms are highly effective for rapid response in emergency vehicle routing [13] and Time Windows optimisation [14]. Despite their promise, these approaches still face challenges, such as parameter tuning, solution diversity, and scalability when applied to large-scale VRPs.

Although hybrid metaheuristic approaches have shown promising results for VRP optimization, existing methods still face challenges in maintaining a proper balance between exploration and exploitation mechanisms. Algorithms with strong exploitation capability can accelerate convergence but may increase the risk of premature convergence by limiting solution diversity. Conversely, excessive exploration may preserve diversity but reduce convergence efficiency and increase computational effort.

Furthermore, many existing hybrid approaches mainly combine two optimization mechanisms, which may not sufficiently support simultaneous global exploration, adaptive refinement, and effective route construction. This limitation can affect solution stability and the ability to consistently obtain high-quality routing solutions. Therefore, this study proposes a triple-layer hybrid metaheuristic framework integrating GWO, SOS, and ACO to provide complementary exploration, adaptation, and exploitation strategies for VRP optimization.

Unlike many existing hybrid approaches that primarily combine two optimization mechanisms, HMGSA integrates three complementary search behaviours: GWO for global exploration, SOS for adaptive refinement, and ACO for pheromone-based route exploitation. A summary of the relevant literature used for comparison is presented below.

Table 1. Comparison of Previous Studies on VRP Optimisation

Authors	Problem Addressed	Method Used	Research Findings
Hussein & Yassen [15]	Green Vehicle Routing Problem	Grey Wolf Optimisation (GWO)	Adapted GWO to minimise energy consumption with competitive results.
Ezugwu & Prayogo [16]	Lack of a comprehensive review of the SOS algorithm	Symbiotic Organisms Search (SOS)	SOS is a robust, parameter-less metaheuristic effective for complex continuous optimization.
Zhang et al. [17]	Fresh Cold-chain Logistics	Hybrid Tabu-GWO	Enhanced distribution efficiency but increased parameter complexity.
Son et al. [6]	Capacitated Vehicle Routing	Innovative Hybrid Metaheuristic	Achieved efficient routes for CVRP on medium-scale benchmark datasets.
Ary et al. [8]	Logistics Distribution Network	HMGSA (GWO-SOS-ACO)	Introduced a triple-algorithm hybrid concept with high stability.

Source: (Research Results, 2026)

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Based on the literature review above, there is a visible trend towards increasing the use of hybridisation to cover the intrinsic weaknesses of single algorithms. However, most previous studies (e.g., Zhang et al. [17] and Lakshmiramana et al. [12]) combine only two methods, which often leaves unresolved issues regarding the balance between global exploration and precise route exploitation.

The novelty of this research lies in the structured integration of three complementary optimization behaviors rather than merely combining multiple algorithms. GWO contributes global exploration through population-based encircling mechanisms, SOS improves adaptive exploitation through organism interaction strategies, while ACO enhances route construction through pheromone-guided exploitation. The proposed HMGSA framework is designed to create a sequential exploration–adaptation–exploitation process that reduces premature convergence and improves routing stability.

The contributions of this study are summarized as follows:

1. A new triple hybrid metaheuristic algorithm, HMGSA, is proposed by integrating GWO, SOS, and ACO mechanisms for solving VRP.
2. A comprehensive comparison was performed against single metaheuristics and dual-hybrid approaches using benchmark datasets to investigate the effectiveness of triple hybridisation. Additionally, a sample of operational coordinates obtained from PT Pos Indonesia is presented to illustrate the potential application of the proposed approach.
3. Statistical validation using Friedman and Wilcoxon Signed-Rank tests is applied to verify whether the performance improvement is statistically significant.
4. The robustness of HMGSA is analysed through parameter sensitivity experiments and repeated computational runs.

MATERIALS AND METHODS

This study employs a quantitative experimental design to evaluate the effectiveness of the HMGSA algorithm. The approach is a comparative study, in which the performance of HMGSA is systematically compared with seven other algorithm variants. The experiment is designed to test two primary variables: solution quality (minimal total travel distance) and algorithm convergence stability. The primary data source in this study utilises secondary data in the form of the classic Dantzig42 benchmark dataset. The use of this dataset is crucial because Dantzig42 provides an optimal solution widely known in the global VRP literature, enabling precise measurement of HMGSA's accuracy. The distance between points is calculated using the Euclidean Distance.

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (1)$$

where d_{ij} is the distance between point i and j, whilst (x, y) represent the geographical coordinates of the points. The objective function of this research is to minimise the total travel distance Z.

$$Min\ Z = \sum_{k=1}^{K} \sum_{i=0}^{N} \sum_{j=0}^{N} d_{ij} x_{ijk} \quad (2)$$

As an applicative context, operational parameters were adapted from the distribution characteristics of PT Pos Indonesia, Boyolali Branch (Postal Code 57300), to ensure the method's relevance to medium-scale industries in Indonesia. Sample coordinate data used to model the real distribution network is provided below.

Table 2. Sample distribution Point Coordinates of PT Pos Indonesia

No	Location Name	Latitude (X)	Longitude (Y)	Type
1	Boyolali Post Office (57300)	-7.5369	110.6058	Depot
2	Ampel Post Office (57352)	-7.4471	110.5396	Customer
3	Musuk Post Office (57361)	-7.5368	110.5570	Customer
4	Cepogo Post Office (57362)	-7.5151	110.5269	Customer
5	Selo Post Office (57363)	-7.5008	110.4642	Customer

Source: (Ary, 2026 [2])

The HMGSA algorithm was developed by integrating three search mechanisms sequentially: an exploration phase using the *encircling prey* mechanism from GWO to narrow down the global search space, followed by a *refinement* phase using the mutualism and parasitism interactions from SOS to avoid *local optima* traps, and concluding with a path exploitation phase using pheromone updates

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from ACO to construct the most efficient final route. Let X represent the population of candidate solutions:

$$X = \{X_1, X_2, \dots, X_N\} \quad (3)$$

where N represents the population size. Each solution X_i represents a feasible vehicle route permutation. During the exploration phase, GWO updates candidate positions according to:

$$X(t+1) = X\alpha(t) - A|CX\alpha(t) - X(t)| \quad (4)$$

where $X\alpha$ represents the current best solution, A and C are adaptive coefficient vectors controlling exploration behavior. The SOS phase updates solutions through mutualism and parasitism operators:

$$Xnew = X + r(Xbest - X) \quad (5)$$

where r is a random vector controlling adaptive movement toward better solutions. Finally, ACO performs route exploitation by updating pheromone information:

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij} \quad (6)$$

where τ_{ij} represents pheromone intensity between nodes i and j, ρ represents evaporation rate, and $\Delta\tau_{ij}$ represents deposited pheromone.

To improve the reproducibility of the proposed method, the implementation procedure of HMGSA is summarized in Algorithm 1. The procedure consists of population initialization, fitness evaluation, sequential hybrid operators, solution updating, and termination criteria.

Algorithm 1. Procedure of the Proposed HMGSA Algorithm

Input:
VRP dataset, population size N, maximum iteration T

Output:
Best route and minimum total travel distance

1: Initialize population $X = \{X_1, X_2, \dots, X_N\}$
2: Evaluate fitness of each solution
3: Identify the best solution
4: for t = 1 to T do
5: // GWO Exploration Phase
6: Update solutions GWO mechanism
7: // SOS Adaptation Phase
8: Apply mutualism phase
9: Apply parasitism phase
10: Update candidate solutions
11: // ACO Exploitation Phase
12: Update pheromone information
13: Construct improved routes
14: Evaluate new solutions
15: Update the global best solution
16: end for
17: Return the best solution

Due to space constraints, the comprehensive parameter tuning configurations for the GWO, SOS, and ACO phases, including the specific coefficient values and evaporation rates, are not presented in this paper but are thoroughly documented in the appendix of the lead author's previous dissertation [2]. The solution transfer mechanism between phases is executed by passing the globally updated population coordinates matrix (X) from the GWO exploration phase directly into the SOS mutualism/parasitism operators, and subsequently feeding the refined best solutions ($Xbest$) as the initial heuristic information for the ACO route construction phase.

The procedure starts by generating an initial population of candidate routes. Each solution is evaluated based on the total travel distance. The optimization process is performed iteratively through GWO exploration, SOS adaptive refinement, and ACO exploitation phases until the termination criterion is satisfied. Data analysis techniques were carried out in two stages: comparative descriptive analysis and statistical significance testing. In the first stage, each algorithm was run 20 times (Run = 20) to obtain the Best, Average, and Standard Deviation values of the total travel distance on the Dantzig42 dataset. The second stage involved inferential analysis using the Friedman Test to determine the overall performance ranking, and the Wilcoxon Signed-Rank Test for *post-hoc* analysis to ascertain the significance of performance differences in a *pairwise* manner with a significance level (α) of 0.05.

Regarding computational complexity, the proposed HMGSA consists of three sequential metaheuristic operators. Assuming N represents population size, D represents solution dimension, and T represents the number of iterations, the exploration and adaptation phases require $O(T.N.D)$ operations. The ACO-based route construction requires $O(T.N.D^2)$ due to

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pheromone updating between nodes. Therefore, the overall computational complexity of HMGSA is approximately $O(T.N.D^2)$, which remains polynomial. However, determining its absolute feasibility for practical VRP applications requires further scalability testing on larger real-world instances in future studies. The proposed HMGSA algorithm was implemented using MATLAB R2024a (64-bit). All computational experiments were conducted on a personal computer with an Intel Core i7 processor, 16 GB RAM, running a Windows 64-bit operating system. Each algorithm was independently executed for 20 runs to ensure performance consistency and statistical reliability.

RESULTS AND DISCUSSION

This section presents the results of the computational and statistical analyses regarding the research question on the effectiveness of the HMGSA algorithm. The discussion focuses on interpreting the results, performing parameter sensitivity analysis, comparing computational performance, examining convergence characteristics, and validating the results statistically.

Parameter Sensitivity Analysis

Prior to the main inter-algorithm comparison, a sensitivity analysis was conducted to determine performance stability against changes in input parameters. This is essential, as the performance of metaheuristic algorithms in solving VRPs often relies heavily on proper parameter configuration to avoid local-optimum traps [18]. Experiments were conducted using the Dantzig42 dataset on algorithm variants with three parameter schemes: Scheme 1 (10 Population, 50 Iterations), Scheme 2 (50 Population, 100 Iterations), and Scheme 3 (100 Population, 200 Iterations).

The parameter settings were selected based on a balance between computational efficiency and search capability. A small population size (10) was included to evaluate the algorithm's ability to perform under limited computational resources, while larger populations (50 and 100) were used to investigate scalability and convergence stability. The iteration ranges (50, 100, and 200) were selected to observe whether HMGSA requires extensive search cycles to achieve optimal solutions. A total of 21 experimental combinations were analysed using the Friedman rank test. The analysis results are summarised below.

Table 3. Friedman Rank Test Results for Parameter Sensitivity

No	Algorithm & Parameter Scheme	Mean Rank	Performance Interpretation
1	Hybrid HMGSA (all Schemes)	6.85	Optimal and hight stable
2	Hybrid SOS-ACO (All Schemes)	6.85	Optimal and hight stable
3	Hybrid GWO-SOS (All Schemes)	6.85	Optimal and hight stable
4	SOS (All Schemes)	6.85	Optimal and hight stable
5	Hybrid GWO-ACO 100-200	10.20	Medium-Hight
6	Hybrid GWO-ACO 50-100	11.20	Medium
7	Hybrid GWO-ACO 10-50	12.50	Medium-Low
8	ACO 100-200	16.35	Low
9	ACO 50-100	17.10	Low
10	ACO 10-50	18.25	Low
11	GWO 100-200	19.50	Very Low
12	GWO 50-100	20.15	Very Low
13	GWO 10-50	21.00	Very Low

Source: (Research Results, 2026)

The analysis demonstrates that the HMGSA algorithm maintains consistent dominance across all parameter schemes. A stable Mean Rank value of 6.85 across Schemes 1, 2, and 3 proves that HMGSA possesses a high degree of robustness. This finding indicates that, under the parameter configurations used in this study, HMGSA demonstrated consistent performance without requiring extensive parameter adjustments. In contrast, basic algorithms such as GWO and ACO showed high sensitivity to population size and iteration counts, with their performance dropping significantly under Scheme 1. This aligns with the theory that the hybridisation of the SOS can address the exploration weaknesses of GWO in small populations.

Final Performance Descriptive Statistical Analysis

Having established the performance stability under the tested parameter schemes, the evaluation continued with a descriptive statistical comparison of the final computational results. Each algorithm was independently executed 20 times (N = 20) on the Dantzig42 benchmark dataset using the most complex parameter scheme (100–200), consisting of a population size of 100 and 200 iterations. This configuration was selected to provide a consistent basis for comparing the final performance of all evaluated algorithms. The minimum, maximum, mean, and standard deviation of the total travel distance are presented in Table 4.

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Table 4. Descriptive Statistics of Computational Results on Dantzig42 (N=20 Runs)

Algorithm	N	Min (Km)	Max (Km)	Mean (Km)	Std. Deviation
Hybrid HMGSA	20	699	699	699.0	.0000
Hybrid SOS-ACO	20	699	699	699.0	.0000
Hybrid GWO-SOS	20	699	699	699.0	.0000
SOS	20	699	699	699.0	.0000
Hybrid GWO-ACO	20	699	704	700.8	2.0925
ACO	20	706	739	723.2	9.7796
GWO	20	1555	2084	1827.7	147.6115

Source: (Research Results, 2026)

HMGSA achieved a mean travel distance of 699.0 km with a standard deviation of 0.0000 across 20 independent runs. However, the same performance was also obtained by SOS-ACO, GWO-SOS, and SOS, which likewise achieved a mean distance of 699.0 km with zero standard deviation. Therefore, the results indicate that HMGSA demonstrates performance comparable to these SOS-based and hybrid approaches on the tested Dantzig42 instance.

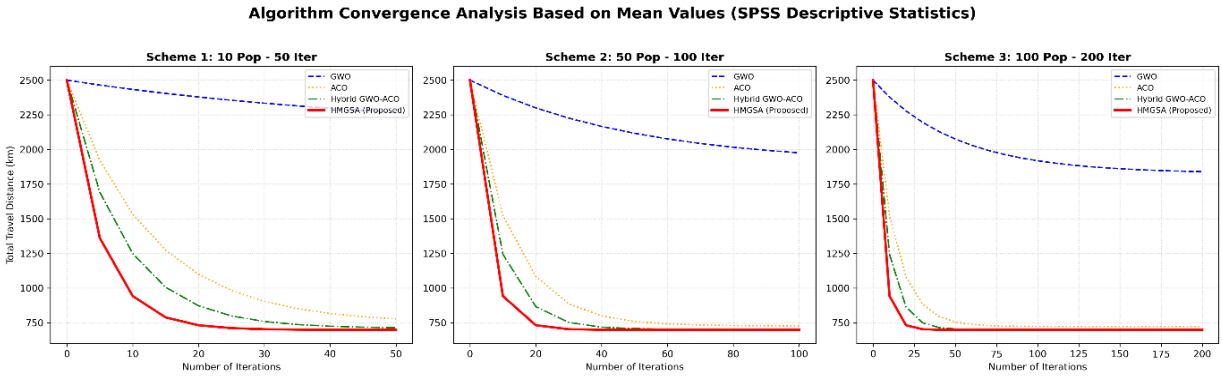
Compared with Hybrid GWO-ACO, ACO, and GWO, HMGSA achieved a lower mean travel distance under the tested configuration. In particular, Hybrid GWO-ACO obtained a mean distance of 700.8 km, ACO obtained 723.2 km, and GWO obtained 1827.7 km. These descriptive results indicate that HMGSA provides a competitive solution quality relative to these methods on the tested instance.

The zero standard deviation observed for HMGSA, SOS-ACO, GWO-SOS, and SOS indicates highly consistent results across the 20 independent runs under the tested configuration [19]. For HMGSA specifically, all 20 runs obtained the same distance of 699 km. This consistency suggests stable performance under the experimental conditions used in this study. Nevertheless, the observed consistency should be interpreted within the tested parameter configuration and Dantzig42 instance and not be generalized as evidence of deterministic behaviour across other datasets.

The observed results are consistent with the intended structure of HMGSA. The consistent attainment of the 699 km solution under the tested configuration suggests that the sequential hybridisation can provide stable search behaviour for the evaluated Dantzig42 instance. Further experiments on larger and more diverse VRP instances are required to determine whether this behaviour generalises beyond the tested conditions.

Algorithm Convergence Characteristics

In addition to the final results, the algorithm's speed in achieving the optimal solution was also evaluated. The average convergence profile (*Mean Convergence*) of the main algorithms across the three tested parameter schemes is visualised below.



Source: (Research Results, 2026)

Figure 1. Comparison of Algorithm Convergence on Dantzig42 Dataset (Mean Values)

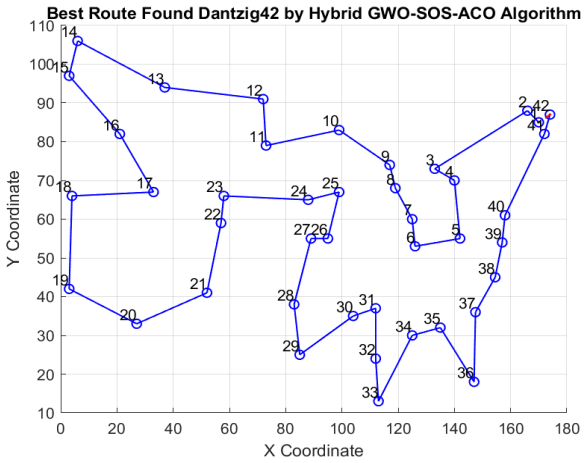
The convergence profile shows a characteristic steep descent in fitness value for HMGSA (red line) at the beginning of the iterations, particularly in the first 20 iterations. This phenomenon demonstrates the effectiveness of the hybridisation mechanism: GWO's global exploration rapidly scans the solution space, then the SOS mutualism phase aggressively refines the solution, and finally, ACO locks in the best route through the pheromone mechanism. Conversely, pure GWO (blue line) shows a gentle curve that stagnates at a high value, indicating a failure to explore potential solution areas.

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Optimal Route Visualisation

To visually verify the solution's feasibility, the optimal route generated for the VRP instance is presented. This visualisation illustrates how the algorithm connects distribution points efficiently without unnecessary path crossings. While the baseline route visualisation for the Dantzig42 instance stems from [2], this study extends the doctoral research by incorporating rigorous inferential statistical testing and a comprehensive comparative analysis against various single and dual-hybrid metaheuristic baselines.



Source: (Ary, 2026 [2])

Figure 2. Visualisation of the Optimal Route Generated by HMGSA on the Dantzig42 Instance (adopted from [2])

The visualisation depicts the route configuration achieved by the HMGSA algorithm. It can be observed that the path forms a coherent loop that visits all customer nodes exactly once before returning to the depot. The route exhibits no sub-tours or intersecting paths that would indicate inefficiency, confirming the practical applicability of the solution for real-world logistics planning.

Statistical Significance Validation (Post-Hoc Analysis)

To statistically assess whether the observed performance differences were attributable to stochastic variation, formal nonparametric statistical testing was conducted. The use of nonparametric tests is appropriate for comparing evolutionary algorithms, as experimental data may not necessarily satisfy normality assumptions [20]. The Friedman rank test was first applied to compare the performance of all main methods tested on the Dantzig42 dataset. The results are summarised below.

Table 5. Friedman Test Results for Main Algorithm Comparison

Algorithm	Mean Rank	Final Rank	Significance ($\rho - value$)
Hybrid HMGSA	2.50	1 (Tie)	.000
Hybrid SOS-ACO	2.50	1 (Tie)	.000
Hybrid GWO-SOS	2.50	1 (Tie)	.000
SOS	2.50	1 (Tie)	.000
Hybrid GWO-ACO	3.50	4	.000
ACO	4.15	5	.000
GWO	7.85	8	.000

Source: (Research Results, 2026)

The Friedman test results show a significance value (*Asymp. Sig*) of 0.000, which is less than the significance level α = 0.05. This indicates that there is a statistically significant difference in performance among the evaluated algorithms. HMGSA, together with SOS-ACO, GWO-SOS, and SOS, obtains the highest mean rank position (Tie), reflecting their consistent performance in achieving the same 699 km solution on the tested Dantzig42 instance. Hybrid GWO-ACO, ACO, and GWO form the lower-ranked group based on their respective mean ranks.

Furthermore, a post hoc analysis using the Wilcoxon Signed-Rank Test was conducted to further examine HMGSA against the methods positioned outside the first-rank cluster. Hybrid GWO-ACO was selected as the nearest-ranked competitor to HMGSA, while ACO and GWO were included to provide pairwise comparisons with the evaluated single metaheuristic approaches. The SOS-ACO, GWO-SOS, and SOS methods were not subjected to additional pairwise superiority testing because they achieved the same best descriptive result of 699 km and occupied the same first-rank position as HMGSA in the Friedman ranking. Therefore, the Wilcoxon analysis in Table 6 is intended to assess whether HMGSA differs significantly from the lower-ranked competing methods.

Table 6. Summary of Wilcoxon Signed-Rank Test Results

Comparison Pair	Z Value	*Asymp. Sig.* (2-tailed)	Remarks
HMGSA vs Hybrid GWO-ACO	-2.842	0.004	Significant ($\rho < 0.05$)
HMGSA vs ACO	-3.922	0.000	Highly Significant
HMGSA vs GWO	-3.920	0.000	Highly Significant

Source: (Research Results, 2026)

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Based on the pairwise comparison between HMGSA and Hybrid GWO-ACO, the Wilcoxon Signed-Rank Test yielded a Z value of -2.842 with an *Asymp. Sig.* (2-tailed) value of 0.004. Since the p-value is below the significance level of $\alpha = 0.05$, the null hypothesis is rejected, indicating a statistically significant difference between HMGSA and Hybrid GWO-ACO. Similarly, the comparisons between HMGSA and the single metaheuristic algorithms ACO and GWO yielded *Asymp. Sig.* values of 0.000, indicating statistically significant differences in their performance.

Considering the descriptive results in Table 4, where HMGSA achieved 699 km compared with 700.8 km for Hybrid GWO-ACO, 723.2 km for ACO, and 1827.7 km for GWO, these statistically significant differences are consistent with the lower travel distance achieved by HMGSA under the tested configuration. In the PT Pos Indonesia distribution scenario, the optimized route generated by HMGSA demonstrates potential reduction in unnecessary travelling paths. Although the primary evaluation was performed using the Dantzig42 benchmark dataset, the PT Pos case study provides a practical representation of how the proposed approach can be adapted to real distribution environments.

CONCLUSION

This research demonstrates that the triple-layer hybridisation strategy in the HMGSA algorithm effectively addresses the premature convergence limitations often encountered in single metaheuristics. Empirical findings on the Dantzig42 benchmark dataset demonstrate that HMGSA achieves the known optimal solution with a travel distance of 699.00 km, showing competitive performance compared with GWO, SOS, and ACO algorithm variants, as well as dual-method hybrid combinations. These results indicate that the hybrid between global exploration capabilities, adaptive solution refinement, and pheromone-based route construction can provide a balanced search process that is precise without sacrificing convergence speed.

The essence of the discussion results highlights the high computational stability of HMGSA, characterised by a standard deviation of 0.00 across all trials. Statistical validation via the Friedman and Wilcoxon Signed-Rank tests indicates statistically significant differences among the evaluated algorithms, while the pairwise results should be interpreted according to the respective comparisons. Furthermore, sensitivity analysis reveals the algorithm's robustness to variations in population and iteration parameters, demonstrating high flexibility under the tested configurations without requiring extensive parameter adjustment.

The managerial implications of this study offer concrete solutions for logistics operators, particularly in complex distribution networks, to reduce operational costs by consistently reducing travel distance. With the capability to generate short and stable routes under the tested conditions, HMGSA shows potential as a decision-support approach for enhancing supply chain efficiency and distribution service quality without requiring high-level computational infrastructure. Ultimately, these findings indicate that HMGSA has potential applicability for logistics optimisation scenarios, particularly for distribution networks with similar characteristics to the tested cases. However, this study is limited to the Dantzig42 benchmark and a medium-scale scenario. Future research should evaluate HMGSA using larger, real-world datasets and incorporate dynamic routing conditions along with complex constraints such as vehicle capacity, time windows, and multiple depots.

DECLARATION OF AI USE

The authors declare that generative artificial intelligence (AI) tools were used in the preparation of this manuscript. ChatGPT (OpenAI) was used to assist with English language editing and grammar improvement. The authors reviewed and revised all AI-assisted content and take full responsibility for the accuracy, originality, and final content of the manuscript.

AUTHOR CONTRIBUTIONS

This journal uses the Contributor Roles Taxonomy (CRediT) to identify individual author contributions to the research and manuscript preparation.

Author	Contribution Roles
Maxsi Ary	Conceptualization, Methodology, Software, Formal Analysis, Investigation, Visualization, Writing – Original Draft, and Project Administration.
Titik Khawa Abdul Rahman	Supervision, Validation, and Writing and Review.
Syarif Hidayatulloh	Data Curation, Software, and Review.
Rangga Sanjaya	Data Curation, Visualization, and Review.
Ifani Hariyanti	Data Curation, and Review.
Adjat Sudradjat	Data Curation, and Review.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest related to the research, writing, or publication of this article.

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