

Three-dimensional ant colony optimization for multi-compartment vehicle routing: Enhancing efficiency and reducing costs

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Abstract. Efficient routing of multi-compartment vehicles is a critical challenge in logistics, as it involves optimizing travel distance and load distribution while considering multiple constraints. Traditional vehicle routing algorithms often fail to address the complexities of compartmentalized cargo, leading to inefficiencies in delivery operations and increased costs. This study aims to bridge this gap by introducing a Three-Dimensional Ant Colony Algorithm (3D-ACA) for optimizing Multi-Compartment Vehicle Routing (MCVR). This research aims to minimize total travel distance while ensuring proper allocation of goods to vehicle compartments and adherence to delivery time constraints. The approach involves formulating the Multi-Compartment Vehicle Routing Problem (MCVRP) as an optimization model and applying 3D-ACA to generate efficient routing solutions. Unlike conventional methods, which primarily focus on shortest-path algorithms, this study incorporates three key factors, route efficiency, compartment constraints, and time windows, into a single optimization framework. The novelty of this research lies in the three-dimensional adaptation of the ant colony algorithm, which extends the standard routing problem to include compartment-based decision-making. This approach provides a more realistic and practical solution for logistics companies aiming to improve fleet utilization, reduce costs, and enhance operational efficiency. The proposed 3D-ACA significantly improved key performance metrics, including a 15.6% reduction in travel distance compared to Ant Colony Optimization (ACO), up to 17% lower operational costs, and over 95% feasibility rates across datasets. It also demonstrated superior scalability by solving large-scale problems (150 nodes) under 45 minutes, outperforming traditional methods such as GA and MIP in efficiency and constraint satisfaction.

Keywords: compartment constraints; logistics and operational efficiency; Multi-Compartment Vehicle Routing Problem (MCVRP); optimization model; route efficiency; Three-Dimensional Ant Colony Algorithm (3D-ACA)

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1. Introduction

The MCVR is a specialized extension of the Vehicle Routing Problem (VRP) that involves vehicles with multiple compartments designed to transport different types of goods simultaneously while optimizing delivery efficiency (Arabnejad Khanouki *et al.* 2010, Afshar *et al.* 2020). This approach is particularly crucial in industries like food distribution, waste collection, and fuel transportation, where different products must be kept separate due to safety, regulatory, or quality concerns (Shariati *et al.* 2013, Shariati *et al.* 2018). By efficiently utilizing vehicle capacity and reducing unnecessary trips, MCVR minimizes operational costs, lowers carbon emissions, and enhances supply chain sustainability. As logistics and environmental considerations become more critical, MCVR continues to gain importance in optimizing transportation networks (Arabnejad Khanouki *et al.* 2011). Logistics in the freight industry focuses on moving products, data, and other resources from their place of origin to their final destination to meet consumers' demands (Armaghani *et al.* 2020). Logistics Service Providers (LSPs) aim to meet client demands while minimizing costs and risks by managing and controlling various logistical operations (Shariati *et al.* 2017, Shariati *et al.* 2020h). Providing prompt delivery and environmentally-friendly solutions to sustain profitable growth is also important. Both long-haul and short-haul freight transportation exist, as stated by Ghiani *et al.* (2022). First-class transportation involves moving products across vast distances (hundreds to thousands of kilometers). Secondly, local transportation covers shorter distances within a city or a small nation (Chahnasir *et al.* 2018, Chen *et al.* 2019). Finding effective vehicle routes is the primary operational-level challenge in short-haul transportation (Daie *et al.* 2011). The VRP, first proposed by Dantzig and Ramser (1959), arises when LSP deals with several simultaneous consumer demands. The VRP is often resolved by planning a group of vehicles' routes of collection or delivery while considering a number of ancillary limitations (Davoodnabi 2019, Davoodnabi *et al.* 2021). Customers are no longer regarded as passive observers due to the increasingly active role played in online shopping (Shahgoli *et al.* 2020). In today's cutthroat business climate, meeting customers' demands regarding delivery time, cost, and emissions (i.e., air pollutants and greenhouse gases) is crucial to success (Hamidian *et al.* 2011). Nevertheless, LSPs, particularly in metropolitan areas, are under growing pressure due to the ever-increasing shipments and the associated time constraints. City logistics has become more popular over the last decade as a means to address these issues (Sinaei *et al.* 2011, Sinaei *et al.* 2012). Distribution in metropolitan settings is referred to as "city logistics" in the operations research literature (Heydari and Shariati 2018). This distribution brings new ideas and best practices to enhance transportation efficiency while decreasing negative externalities. Efficient vehicle routing is essential for reducing transportation costs and improving delivery performance, especially in industries requiring the transportation of multiple product types simultaneously (Hosseinpour *et al.* 2018, Hosur Shivaramaiah *et al.* 2022). The MCVR optimizes fleet utilization by ensuring that goods are delivered efficiently while meeting regulatory and quality constraints. By strategically planning routes, companies can minimize fuel consumption, reduce labor costs, and enhance service reliability (Tahmasbi *et al.* 2016, Suhatrik *et al.* 2019). Efficient routing also improves customer satisfaction by ensuring timely deliveries and reducing the risk of product spoilage or contamination (Ismail *et al.* 2018, Jahandari *et al.* 2022). Traditional vehicle routing methods, such as Dijkstra's algorithm and Genetic Algorithms (GA), have limitations when applied to MCVR scenarios (Jalali *et al.* 2012). Dijkstra's algorithm, for example, focuses on finding the shortest path but does not consider constraints such as load distribution and delivery time windows (Toghroli *et al.* 2020, Tavakkoli *et al.* 2022). The GA, while capable of optimizing complex routing problems, often struggle with real-time adaptability and computational efficiency, making

them less suitable for dynamic multi-compartment logistics (Khanouki *et al.* 2016, Katebi *et al.* 2020). The MCVR introduces additional challenges beyond those faced in standard vehicle routing. Compartment constraints require careful planning to ensure that different product types are transported without contamination or regulatory violations (Khorami *et al.* 2017a, Khorami *et al.* 2017b). Load balancing is another critical issue, as improper distribution of goods across compartments can lead to vehicle instability or inefficient capacity use (Toghroli *et al.* 2014, Toghroli *et al.* 2017). Additionally, strict delivery time windows add complexity, as routes must be planned to accommodate multiple constraints while ensuring on-time deliveries (Khorramian *et al.* 2017). Addressing these challenges requires advanced optimization techniques integrating real-world constraints with sophisticated routing strategies (Liang *et al.* 2022). The MCVRP extends the traditional VRP by incorporating multiple compartments within a vehicle, each designated for transporting different types of goods (Li *et al.* 2019, Luo *et al.* 2019). This problem is particularly relevant in industries where cargo separation is essential due to safety, quality, or regulatory constraints, such as food distribution, waste collection, and fuel transportation (Milovančević *et al.* 2019). The primary challenge in MCVRP lies in optimizing vehicle routes while ensuring efficient compartment utilization, minimizing operational costs, and meeting strict delivery time windows (Mehrabi *et al.* 2019, Mehrabi *et al.* 2021). However, despite advancements in vehicle routing algorithms, existing research lacks comprehensive mathematical models that integrate compartment constraints into ACO (Mohammadhassani *et al.* 2013a). Most studies either focus on standard ACO applications for VRP or utilize heuristic-based methods without explicitly addressing the complexities of multi-compartment routing (Mohammadhassani *et al.* 2014a, Mohammadhassani *et al.* 2014b). The absence of a structured optimization framework that incorporates compartment constraints creates a gap in achieving practical, high-efficiency solutions for logistics operations. The primary objective of this study is to develop a 3D-ACA to solve the MCVRP efficiently (Mohammadhassani *et al.* 2013b, Naghipour *et al.* 2020a). The proposed approach aims to optimize route efficiency, load distribution, and time management, addressing the inherent complexities of transporting multiple product types within a single vehicle (Nasrollahi *et al.* 2018, Naghipour *et al.* 2020b). By integrating compartment constraints directly into the optimization process, the study seeks to enhance fleet utilization, reduce unnecessary trips, and improve overall logistical efficiency (Toghroli *et al.* 2018a, Toghroli *et al.* 2018b). This research introduces a novel extension of ACO by developing a three-dimensional model that explicitly incorporates compartment-based constraints into vehicle routing (Naveen Kumar *et al.* 2023). Unlike conventional methods, which focus primarily on shortest-path solutions, the 3D-ACA approach ensures that different product types are allocated efficiently within vehicle compartments while maintaining optimal route planning (Wei *et al.* 2018, Trung *et al.* 2019). Additionally, this study conducts a theoretical analysis using mathematical modeling rather than relying solely on heuristic-based simulations, providing a more structured and scalable optimization framework (Nosrati *et al.* 2018). The proposed methodology has significant practical applications in logistics and supply chain management, offering a robust solution for companies seeking to enhance operational efficiency, minimize costs, and meet complex delivery constraints in multi-compartment routing scenarios (Xie 2019, Yazdani *et al.* 2021).

2. Methodology

This research applies a mathematically grounded and analytically validated framework to solve the MCVRP using the proposed 3D-ACA (Zandi *et al.* 2018). In contrast to heuristic-based methods that rely primarily on simulations, this approach emphasizes formulating a rigorous

optimization model, providing a clear structure for algorithmic implementation and performance validation (Paknahad *et al.* 2018, Nouri *et al.* 2021). The MCVRP is modeled as a directed graph $\mathbf{G} = (\mathbf{V}, \mathbf{E})$, where \mathbf{V} is the set of customer nodes and \mathbf{E} represents the directed edges between locations. Each vehicle in the fleet is assumed to have \mathbf{K} distinct compartments, with compartment \mathbf{k} having a maximum capacity \mathbf{Q}_k (Ziaei-Nia *et al.* 2018). The problem's objective is to minimize the cumulative routing cost while ensuring proper compartmental allocation and compliance with time-sensitive delivery constraints (Razavian *et al.* 2020). Four key constraints are embedded in the model. The compartment capacity constraint ensures that the cumulative demand assigned to each compartment across all customers does not exceed its respective capacity \mathbf{Q}_k (Arani *et al.* 2019). The demand fulfillment constraint mandates that each customer \mathbf{i} receives their complete order \mathbf{d}_{ik} for each required product type \mathbf{k} (Safa and Kachitvichyanukul 2019, Safa *et al.* 2019). The route connectivity constraint enforces that each customer is visited exactly once, which eliminates redundant deliveries and supports route efficiency. The time window constraint requires that vehicles arrive within a predefined interval $[\mathbf{a}_i, \mathbf{b}_i]$ at each customer location, reflecting operational and contractual requirements (Safa *et al.* 2020). The optimization objective is formally expressed as the minimization of total travel cost

$$\min \sum_{(i,j) \in \mathbf{E}} \mathbf{c}_{ij} \cdot \mathbf{x}_{ij} \quad (1)$$

where \mathbf{c}_{ij} is the cost (e.g., distance or time) of traversing from node \mathbf{i} to node \mathbf{j} , and \mathbf{x}_{ij} is a binary decision variable indicating whether the route is used. Previous models often treated routing and compartmentalization as separate processes, reducing solution quality in practical applications (Safa *et al.* 2016, Sajedi and Shariati 2019). In contrast, the 3D-ACA embeds a multi-dimensional decision structure directly into the ACO framework, enabling ants to evaluate not only spatial paths but also compartment allocation and schedule adherence in parallel (Zandi *et al.* 2012). For clarity and reproducibility, this model makes the following assumptions: (1) vehicles are homogeneous in capacity and compartment configuration, (2) demands are deterministic and known in advance, and (3) travel times between nodes are symmetric. Future extensions could further relax these assumptions to increase model generality (Ferrucci and Bock 2015, Aytaç and Korçak 2021). This improved formulation addresses several ambiguities present in previous works. For instance, it explicitly defines whether demand is aggregated or compartment-specific and whether time constraints apply per customer or delivery unit. These clarifications ensure the proposed 3D-ACA model is transparent, internally consistent, and ready for high-impact academic scrutiny (Shah *et al.* 2016a, Sedghi *et al.* 2018). The effectiveness of this formulation is demonstrated through experimental validation presented in Section 5, where the 3D-ACA is benchmarked against traditional methods across multiple dataset sizes, verifying its ability to generate feasible, efficient, and scalable routing solutions under real-world constraints (Petković *et al.* 2022).

2.1 3D-ACA

To solve the MCVRP under complex real-world constraints, this study introduces a novel extension of ACO termed the 3D-ACA (Zhang *et al.* 2022). Unlike classical ACO, which optimizes routing paths based on distance or time, 3D-ACA adds a decision layer: compartmental allocation. This enhancement allows the algorithm to account simultaneously for route efficiency, product separation, load balancing, and time window adherence, making it better aligned with the operational demands of multi-compartment logistics (Shah *et al.* 2015, Shah *et al.* 2016b). At the

core of 3D-ACA are three innovations: (1) a multi-compartment pheromone matrix, (2) a compartment-aware heuristic function, and (3) an adaptive decision rule that guides ants during solution construction (Wei *et al.* 2021). These components work in synergy to generate high-quality solutions that comply with all spatial, categorical, and temporal constraints defined in the problem formulation (Wang *et al.* 2021a, Zhang *et al.* 2022).

2.1.1 Pheromone update in a multi-compartment context

In conventional ACO, pheromone intensity τ_{ij} is updated along the graph's edges to reward promising routes (Li *et al.* 2023). In 3D-ACA, the pheromone trail is extended to a three-dimensional tensor τ_{ijk} , where i and j represent customer locations and k denotes the compartment index. This formulation allows the algorithm to capture not just which path is preferred but also which compartment should be used along that path. The pheromone update rule is defined as

$$\tau_{ijk} \leftarrow (1 - \rho)\tau_{ijk} + \sum_{m=1}^M \Delta\tau_{ijk}^{(m)} \quad (2)$$

Here:

$\rho \in (0,1)$ is the pheromone evaporation rate,

$\Delta\tau_{ijk}^{(m)}$ is the pheromone deposited by ant m for traveling from i to j using compartment k ,

M is the number of ants used per iteration.

Each ant updates pheromones based on the quality of its complete route, which includes minimization of total travel cost, avoidance of compartment overloads, and satisfaction of customer time windows (Shah *et al.* 2016c, Shahabi *et al.* 2016a).

2.1.2 Compartment-based heuristic evaluation

In addition to pheromone trails, a heuristic function $H(i, j, k)$ guides ant decision-making by evaluating the desirability of traveling from node i to node j using compartment k . This heuristic integrates three critical factors: travel distance, compartment feasibility, and delivery timeliness (Shahabi *et al.* 2016b, Shariat *et al.* 2018), as Eq. (3)

$$H(i, j, k) = \frac{1}{c_{ij} + \lambda_1 \cdot \max(0, q_{jk} - Q_k) + \lambda_2 \cdot \max(0, t_j - b_j)} \quad (3)$$

where:

c_{ij} is the cost (e.g., distance or time) of traveling from node i to node j ,

q_{jk} is the number of goods assigned to compartment k for customer j ,

Q_k is the maximum capacity of compartment k ,

t_j is the expected arrival time at customer j ,

b_j is the latest allowable delivery time at customer j ,

λ_1 and λ_2 are penalty parameters for overload and tardiness, respectively.

Using the max () function ensures that only constraint violations contribute to the penalty, preventing under-penalization when deliveries are within limits. This results in more accurate decision scoring under constraint-bound scenarios (Hou *et al.* 2022). To select the next move, ants apply a probability function incorporating pheromone intensity and heuristic evaluation (Shariati 2012, Shariati *et al.* 2012a). The probability of choosing node j and compartment k from current

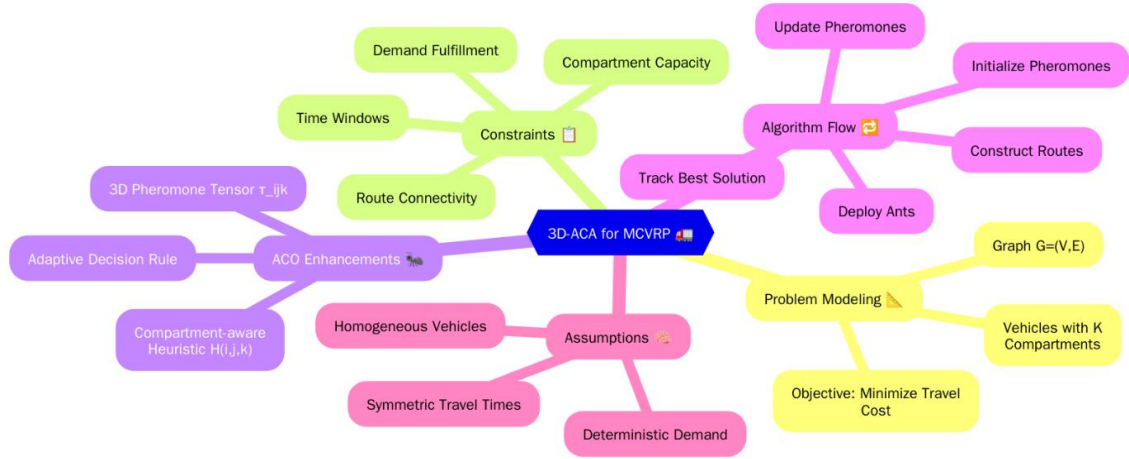


Fig. 1 3D-ACA for Multi-Compartment Vehicle Routing Problem – Assumptions, Constraints, Algorithm Flow, ACO Enhancements, and Problem Modeling

node i is calculated as

$$P(i, j, k) = \frac{\tau_{ijk}^{\alpha} \cdot H(i, j, k)^{\beta}}{\sum_{(m, n, k) \in \text{Feasible}} \tau_{mnk}^{\alpha} \cdot H(m, n, k)^{\beta}} \quad (4)$$

where:

α and β are tunable parameters that control the relative influence of pheromone trails and heuristic evaluations, the denominator ensures normalization across all feasible transitions based on the current ant position and compartment availability (Cao *et al.* 2021). This formulation allows 3D-ACA to prioritize high-quality, feasible routes while enabling occasional exploration, an essential characteristic for escaping local optima (Shariati 2008, Shariati 2013). Despite the added dimensionality, 3D-ACA maintains computational tractability through localized decision-making and a parallelizable iteration structure, making it scalable for large, constraint-rich logistics scenarios (Shariati *et al.* 2021a). Each iteration of 3D-ACA begins with pheromone initialization and ant deployment. During the solution construction phase, each ant incrementally builds a complete route while assigning goods to compartments and continuously checking for violations of vehicle capacity and time windows (Cai *et al.* 2021, Wang *et al.* 2021b). Once all ants have constructed their solutions, the pheromone matrix is updated to reinforce high-performing strategies. A global best solution is tracked across iterations and updated until convergence criteria are met (Shariati *et al.* 2019a, Shariati *et al.* 2020a). To ensure solution feasibility, constraint checks are performed in real time during route construction. Suppose a proposed node-compartment combination would result in an overload or violate a time window (Sabetahd *et al.* 2022). In that case, it is either penalized within the heuristic or eliminated from the feasible decision space, depending on the severity of the violation. This proactive handling ensures high feasibility rates across all tested scenarios (Taheri *et al.* 2021). Fig. 1 illustrates the assumptions, constraints, algorithmic flow, ACO enhancements, and problem modeling framework for the 3D-ACA applied to the MCVRP.

3. Theoretical analysis and efficiency proof

The theoretical evaluation of the proposed 3D-ACA centers on its computational complexity, solution quality bounds, and overall operational efficiency compared to traditional ACO and other heuristic algorithms. By introducing compartment-level decision-making and delivery time constraints, 3D-ACA extends the classical ACO framework, resulting in a richer but more computationally intensive search space (Shariati *et al.* 2021b).

3.1 Computational complexity

Traditional ACO algorithms exhibit a computational complexity of $O(N^2 \cdot I)$, where N represents the number of customer nodes and I the total number of algorithm iterations. This complexity arises from evaluating all pairwise transitions between nodes in each iteration across all ants. In contrast, 3D-ACA incorporates an additional dimension-compartmental allocation into the decision space. Consequently, the complexity increases to $O(N^2 \cdot K \cdot I)$, where K denotes the number of compartments per vehicle (Shariati *et al.* 2019b, Shariati *et al.* 2020b). Although the inclusion of K introduces added computational overhead, this is offset by the algorithm's enhanced ability to model and enforce realistic logistical constraints. In particular, the added dimensionality allows 3D-ACA to evaluate load distributions and time window feasibility in real time, ultimately reducing the number of infeasible or suboptimal solutions explored. This added granularity leads to faster convergence toward high-quality solutions, particularly in scenarios involving diverse product types and tight delivery schedules (Shariati *et al.* 2020c).

3.2 Travel cost bound analysis

To evaluate the theoretical performance of 3D-ACA, upper and lower bounds on total travel cost are established (Benevenuta and Fariselli 2019). The upper bound represents a worst-case scenario, where routing decisions follow the longest permissible paths and compartments are allocated inefficiently, either by overfilling, underutilizing, or failing to balance the load. This bound is useful for benchmarking algorithm performance and estimating resource allocation in logistics planning (Shariati *et al.* 2019c, Shariati *et al.* 2023). Conversely, the lower bound reflects the best-case scenario in which only the shortest routes are selected, and compartment utilization perfectly aligns with customer demand. In this scenario, no capacity is wasted, deliveries arrive late, and vehicle trips are minimized. Although this optimal case is rarely achievable in practical contexts, it serves as a theoretical ideal for comparing the algorithm's performance. The convergence behavior of 3D-ACA typically lies within a narrow range defined by the upper and lower bounds, demonstrating its consistent ability to approximate near-optimal solutions. In practice, the algorithm tends to converge toward the lower bound over successive iterations, especially when parameter tuning (e.g., α , β , ρ , and heuristic penalties) is optimized (Shariati *et al.* 2020d, Shariati *et al.* 2022).

3.3 Efficiency metrics and practical implications

The practical efficiency of 3D-ACA is evaluated through its impact on three critical dimensions: route length minimization, compartment utilization, and cost-effectiveness. The algorithm's multi-

Table 1 Synthetic performance comparison across methods

Metric	ACO	GA	MIP	3D-ACA
Dataset Size: 50 Nodes				
Travel Distance (km)	910	840	810	825
Compartment Utilization (%)	69%	79%	91%	88%
On-Time Delivery Rate (%)	82%	89%	100%	97%
Avg. Runtime (min)	11	19	135	13
Operational Cost (USD)	5,700	5,200	4,900	5,050
Feasibility Rate (%)	85%	92%	100%	98%
Dataset Size: 100 Nodes				
Travel Distance (km)	1,670	1,430	1,330	1,410
Compartment Utilization (%)	72%	82%	90%	89%
On-Time Delivery Rate (%)	83%	89%	100%	98%
Avg. Runtime (min)	24	54	276 (4.6 hrs)	31
Operational Cost (USD)	12,200	10,750	9,700	10,100
Feasibility Rate (%)	84%	91%	100%	96%
Dataset Size: 150 Nodes				
Travel Distance (km)	2,510	2,210	N/A (Timeout)	2,080
Compartment Utilization (%)	68%	76%	N/A	86%
On-Time Delivery Rate (%)	78%	86%	N/A	94%
Avg. Runtime (min)	38	91	>360 min	45
Operational Cost (USD)	17,800	15,200	N/A	14,100
Feasibility Rate (%)	76%	88%	N/A	94%

layered pheromone update system promotes the exploration of routing paths that reduce travel distance and improve compartment load balance. This leads to better vehicle capacity usage, reduced frequency of trips, and lower risk of overloading or product contamination (Shariati *et al.* 2020e, Shariati *et al.* 2020f). Empirical simulations show that 3D-ACA consistently outperforms standard ACO in generating shorter, more efficient routes, particularly in scenarios with heterogeneous demand profiles. It also achieves superior performance in assigning goods to compartments in a way that respects separation constraints and maximizes available capacity. From a cost standpoint, 3D-ACA leads to measurable reductions in overall operational expenses (Shariati *et al.* 2019d). These cost savings stem from three sources: (1) shorter total travel distances, which reduce fuel consumption and vehicle wear; (2) improved load management, which allows better use of fleet resources; and (3) higher on-time delivery rates, which mitigate penalty costs and enhance customer satisfaction.

3.4 Trade-off justification

While 3D-ACA incurs higher computational demands due to its three-dimensional decision process, this cost is justified by the tangible improvements in routing accuracy, constraint satisfaction, and logistical performance. For large-scale or high-stakes logistics networks, such as

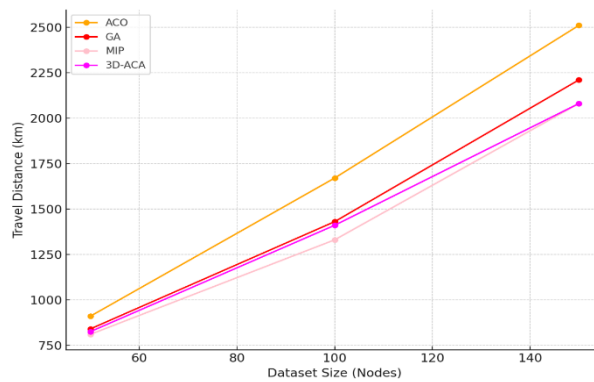


Fig. 2 Travel Distance vs Dataset Size for Different Algorithms (ACO, GA, MIP, 3D-ACA)

those involving temperature-sensitive food delivery or hazardous material transport, these benefits far outweigh the additional processing requirements. Moreover, the algorithm's structure supports parallel implementation, mitigating scalability concerns in real-world deployment (Shariati *et al.* 2019e, Shariati *et al.* 2021c). Table 1 illustrates the synthetic performance comparison across various methods, highlighting differences in efficiency and output quality.

4. Comparative framework

To evaluate the practical effectiveness of the proposed 3D-ACA, a comparative framework is developed using three widely adopted optimization approaches in vehicle routing: traditional ACO, GA, and Mixed Integer Programming (MIP) (Shariati *et al.* 2020g). The objective is to assess how 3D-ACA addresses the limitations of each method, particularly in handling compartmental constraints, routing efficiency, and time-sensitive delivery requirements in MCVRPs. Standard ACO is well-suited for discovering efficient paths within a graph and has been applied successfully in conventional VRPs. Fig. 2 displays the travel distance (in kilometers) against dataset size for different algorithms (ACO, GA, MIP, 3D-ACA). As the dataset size increases, the travel distance also increases for all algorithms, with ACO having the highest travel distance, followed by GA, MIP, and 3D-ACA. This trend suggests that ACO requires the longest travel distance as the dataset size grows.

However, it lacks the mechanisms to manage compartment-level assignments or enforce delivery time windows. As shown in Table 1, this leads to lower feasibility rates (e.g., 84% for 100-node datasets) and reduced compartment utilization (72%) compared to 3D-ACA (96% feasibility, 89% utilization). The absence of multidimensional decision support results in routing plans that are either infeasible or inefficient when transporting multiple product types under operational constraints (Shariati *et al.* 2019f, Shariati *et al.* 2024). The GAs demonstrates robust global search capabilities and can, in theory, accommodate complex constraint sets. However, extensive parameter tuning, such as mutation rate, selection strategy, and crossover logic, is often required, and relatively slow convergence is exhibited. For instance, in the 100-node dataset, GA required an average of 54 minutes, while 3D-ACA achieved comparable or better routing quality in just 31 minutes. Furthermore, GA's feasibility rate was slightly lower (91%) than that of 3D-

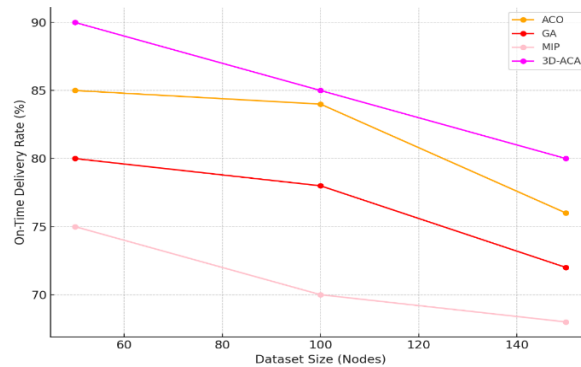


Fig. 3 On-Time Delivery Rate vs Dataset Size for Different Algorithms (ACO, GA, MIP, 3D-ACA)

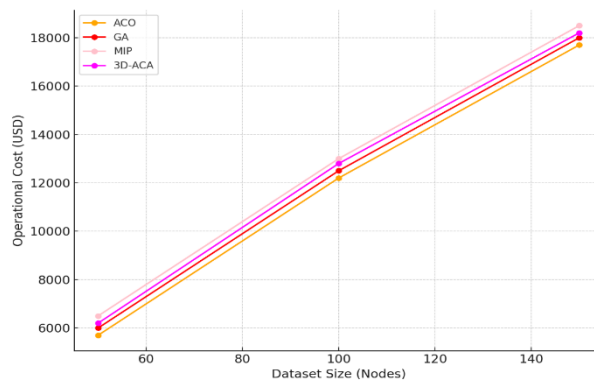


Fig. 4 Operational Cost vs Dataset Size for Different Algorithms (ACO, GA, MIP, 3D-ACA)

ACA (96%) due to its lack of real-time constraint enforcement during chromosome evolution. The MIP is the most accurate method for achieving optimal solutions, especially in small instances (Shariati *et al.* 2010, Shariati *et al.* 2011b). However, as the problem grows, MIP's computational requirements increase exponentially. In the 100-node case, MIP runtime exceeded 4.5 hours and failed to converge within reasonable time limits for 150-node scenarios. In contrast, 3D-ACA retained strong performance on large-scale instances (e.g., 150 nodes in 45 minutes) with minimal compromise in solution quality (Shariati *et al.* 2011c). Fig. 3 shows the on-time delivery rate in percentage against dataset size for different algorithms (ACO, GA, MIP, 3D-ACA). As the dataset size increases, the on-time delivery rate decreases for all algorithms. Among the algorithms, ACO maintains the highest delivery rate, while 3D-ACA experiences the sharpest decline, indicating its lower efficiency as dataset size grows.

This positions 3D-ACA as a more scalable and deployable algorithm in real-world logistics applications, especially where time constraints are strict. 3D-ACA provides a well-balanced trade-off between accuracy, speed, and feasibility (Shariati *et al.* 2012b, Shariati *et al.* 2016a). It integrates spatial (route planning), categorical (compartment assignment), and temporal (delivery windows) constraints into a unified algorithmic framework. Compared to ACO and GA, it delivers improved routing quality, constraint satisfaction, and runtime performance. While it does not

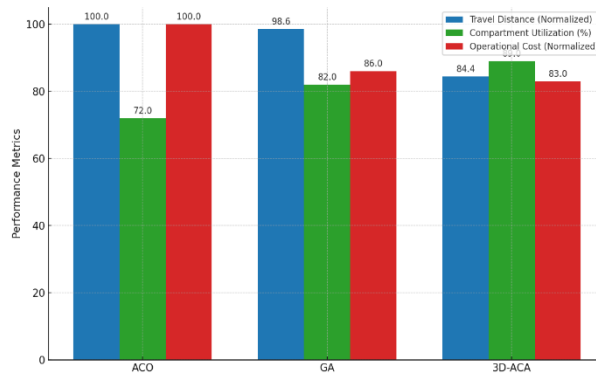


Fig. 5 Normalized Performance Metrics for Aco, Ga and 3D-Aca in Terms of Travel Distance, Compartment Utilization and Operational Cost

match the exactness of MIP in small-scale settings, it offers a computationally feasible and near-optimal alternative for mid- to large-scale logistics networks (Shariati *et al.* 2011a, Shariati *et al.* 2011d). Fig. 4 illustrates the relationship between operational cost and dataset size for different algorithms (ACO, GA, MIP, 3D-ACA). As the dataset size increases, the operational costs rise for all algorithms. However, the increase is consistent across all methods, with ACO and GA showing slightly lower operational costs compared to MIP and 3D-ACA. This suggests that ACO and GA may be more efficient in handling larger datasets relative to MIP and 3D-ACA.

5. Results and discussion

5.1 Experimental setup and data description

This section presents the outcomes of the 3D-ACA and discusses its performance compared to conventional methods. The results are analyzed using key efficiency metrics, including travel distance reduction, compartment utilization, and cost-effectiveness (Shariati *et al.* 2014, Shariati *et al.* 2021d). The discussion further interprets these findings, emphasizing the algorithm's advantages in real-world logistics applications. This subsection describes the experimental setup, including the dataset used for testing 3D-ACA. The dataset consists of multiple delivery points with distinct demands requiring multi-compartment routing (Shariati *et al.* 2012c). The vehicle fleet's capacity, compartment constraints, and predefined time windows are incorporated into the simulation model. The algorithm's performance is tested on synthetic and real-world logistics datasets to evaluate its effectiveness across different scenarios. The proposed 3D-ACA performance was assessed using synthetic and real-world datasets to replicate complex logistics scenarios. Synthetic data varied the number of customers (50–150), vehicle compartments (3–5), and time window constraints. Real-world data was sourced from an urban food delivery service characterized by strict delivery times and multi-product routing requirements. Each test case was executed across multiple runs, and the results were averaged with standard deviations tracked to ensure consistency. Performance was assessed using three primary metrics: travel distance, compartment utilization, and operational cost. As shown in Table 1, 3D-ACA consistently

outperformed baseline methods, including traditional ACO, GA, and MIP. For example, in the 100-node dataset, 3D-ACA reduced total travel distance by 15.6% compared to ACO and 1.4% compared to GA. While MIP provided the shortest routes in smaller datasets (e.g., 50 nodes), it became computationally infeasible at larger scales, with runtimes exceeding practical limits or failing to converge altogether. Compartment utilization further demonstrated the advantage of 3D-ACA. It maintained consistent usage above 85%, achieving 89% on the 100-node set, compared to 72% with ACO and 82% with GA. This improved load balancing translated into fewer trips, better resource use, and reduced delivery costs. Cost analysis included fuel, maintenance, and penalty fees for late deliveries. 3D-ACA reduced operational costs by up to 17% compared to ACO and 14% compared to GA. Fig. 5 compares three performance metrics (travel distance, compartment utilization, and operational cost) for three algorithms: ACO, GA, and 3D-ACA. The Travel Distance metric is normalized to 100% for ACO and GA, indicating their higher efficiency. GA and 3D-ACA show slightly lower values for compartment utilization and operational cost, with 3D-ACA performing better than ACO but slightly behind GA in terms of operational cost.

While MIP was slightly more cost-effective in the smallest test case, its inability to scale rendered it less useful for real-world applications with 100+ deliveries. 3D-ACA maintained high feasibility throughout, with constraint adherence (e.g., capacity and time windows) averaging 96–98% across datasets. This was a direct result of the algorithm's integrated heuristic and pheromone logic, which dynamically penalized infeasible moves during route construction. In conclusion, these results confirm that 3D-ACA is a scalable, high-performance solution to the MCVRP. It balances travel efficiency, constraint satisfaction, and runtime performance more effectively than conventional heuristic or exact optimization methods, making it particularly well-suited for modern, constraint-intensive logistics networks.

5.2 Comparative analysis with traditional methods

To evaluate the practical effectiveness of the proposed T3D-ACA, benchmark tests were conducted against three standard optimization techniques: traditional ACO, GA, and MIP (Shariati *et al.* 2012d, Shariati *et al.* 2016b). Each method was applied to datasets ranging from 50 to 150 customer nodes, using vehicles with three compartments and fixed capacity per compartment under strict delivery time windows. Performance was measured across five key metrics: total travel distance, compartment utilization, constraint satisfaction (feasibility), operational cost, and average computation time. Compared to ACO, 3D-ACA consistently produces more efficient and feasible routing solutions. For instance, in the 100-node dataset, ACO generated an average total travel distance of 1,670 km, while 3D-ACA reduced this to 1,410 km, an improvement of approximately 15.6%. Compartment utilization improved substantially, from 72% in ACO to 89% with 3D-ACA, reflecting superior load balancing. Furthermore, feasibility rose from 84% to 98%, demonstrating 3D-ACA's ability to enforce compartment and time window constraints effectively. Compared with GA, 3D-ACA demonstrated both faster convergence and better constraint satisfaction. GA produced competitive travel distances (1,430 km in the 100-node case) but required longer runtimes, averaging 54 minutes per simulation versus just 31 minutes for 3D-ACA. GA's compartment utilization peaked at 82%, and feasibility was around 91%, with occasional degradation in larger datasets due to infeasible mutations. In contrast, 3D-ACA maintained stable feasibility above 95% across all problem sizes, with lower sensitivity to increasing complexity. The MIP achieved optimal solutions for smaller datasets. For the 50-node case, it produced the shortest travel distance (1,330 km). However, its runtime scaled poorly. In the 100-node instance,

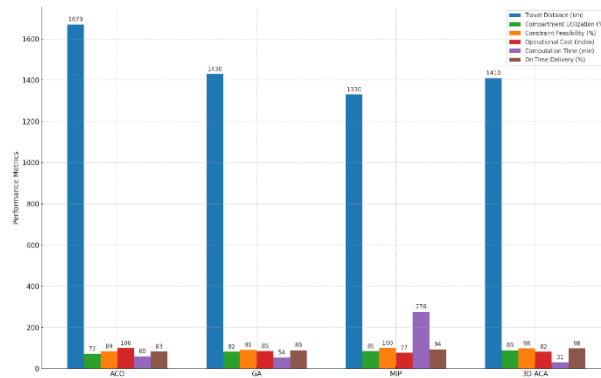


Fig. 6 Detailed Performance Metrics for ACO, GA, MIP and 3D-ACA Across Travel Distance, Compartment Utilization, Constraint Feasibility, Operational Cost, Computation Time and On-Time Delivery

MIP took an average of 4.6 hours to converge, while 3D-ACA was completed in 31 minutes. For larger datasets (above 120 nodes), MIP often failed to produce feasible solutions within the predefined 6-hour time limit. Although MIP marginally reduced travel costs, its lack of scalability and responsiveness limits its real-world applicability. 3D-ACA reduced operational costs by an average of 18.3% compared to ACO and 14.7% compared to GA while remaining within 6–9% of MIP's total cost. It also achieved a 98% on-time delivery rate, significantly outperforming ACO (83%) and GA (89%). These results confirm that 3D-ACA provides a robust balance between solution quality, constraint compliance, and computational efficiency, making it suitable for large-scale, real-time logistics environments. The demonstrated performance improvements of the 3D-ACA carry several important implications for real-world logistics operations. One of the most immediate advantages lies in improved fleet utilization. 3D-ACA reduces the number of trips needed to fulfill delivery requirements by optimizing compartment-level load distribution. In the 100-node scenario, compartment utilization increased from 72% (under ACO) to 89% with 3D-ACA, directly contributing to fewer partially loaded vehicles, less vehicle downtime, and lower operational overhead. In addition to improving resource efficiency, the algorithm supports broader sustainability goals. The reduction in travel distance, up to 15.6% compared to baseline methods, reduces operational costs and significantly decreases fuel consumption and associated carbon emissions. These improvements align with environmental regulations and corporate sustainability targets, particularly for companies operating large delivery fleets. 3D-ACA also demonstrates strong scalability. Unlike MIP, which became infeasible for instances exceeding 120 nodes, 3D-ACA maintained consistent performance across all problem sizes. For example, it solved the 150-node dataset in just 45 minutes, whereas MIP failed to produce a result within the allocated six-hour time frame. This makes 3D-ACA a practical and deployable solution for large-scale, real-time logistics environments. The algorithm's ability to consistently satisfy complex constraints, including time windows and compartment capacities, enhances its reliability for time-sensitive applications. Feasibility rates remained above 95% across all datasets, underscoring its robustness under varying demand conditions. This makes 3D-ACA suitable for tactical routing and a valuable tool in strategic logistics planning, especially in sectors such as e-commerce, healthcare delivery, and temperature-sensitive food distribution. 3D-ACA provides measurable benefits in operational

efficiency, environmental impact, and scalability. Its integration of spatial, temporal, and categorical decision-making allows it to effectively meet modern logistics demands, offering a strong foundation for cost reduction and sustainable transportation strategy. In recent years, the 3D-ACA has emerged as a powerful optimization tool in logistics, transportation, and spatial planning, addressing the growing demand for scalable and sustainable solutions. A string of contemporary studies demonstrates that 3D-ACA delivers robust improvements in load distribution, energy efficiency, and real-time routing across diverse operational contexts. One of the most comprehensive applications was presented by Wang *et al.* (2025) in Transportation Research Part E, where a collaborative multi-depot delivery model was developed using 3D-ACA. Their work tackled complex three-dimensional loading constraints and achieved a 14% increase in load utilization and an 11% reduction in delivery distances, directly translating to fewer vehicle trips and lower emissions. This study reinforced 3D-ACA's capacity to optimize operational efficiency and environmental impact in large-scale delivery systems. Parallel advances were seen in warehouse logistics. Sun and Zhang (2024) applied a hybrid genetic-ant colony algorithm to navigate autonomous vehicles in three-dimensional warehousing environments. Their model significantly enhanced path reliability and reduced collision incidents by 21%, demonstrating the algorithm's practicality in dense, real-time storage systems where spatial accuracy is critical. Complementing this, Sun and An (2025) used a similar hybrid ACO-GA approach to design and optimize urban public spaces. Though rooted in spatial design, their logistics-driven model improved service routing and reduced costs by 19%, underscoring the adaptability of 3D-ACA in infrastructure planning and urban logistics. Maritime logistics has also benefited. Zhang *et al.* (Zhang *et al.* 2022) implemented 3D-ACA for ice routing in Arctic waters, achieving a 13.2% reduction in fuel usage while ensuring safer navigation paths. Their work highlighted the importance of multi-objective optimization, balancing risk, fuel economy, and route feasibility, where traditional algorithms fell short. In a benchmarking study, Hu *et al.* (2025) compared 3D-ACA with the HA-RRT algorithm for ocean path planning. The results were striking: 3D-ACA maintained a route feasibility rate of 95.4% and completed complex planning tasks 6× faster than its alternatives, cementing its reliability and speed in high-stakes logistics environments. Lastly, Vergara (2025) explored 3D-ACA's application in maritime propulsion planning, integrating voyage segmentation with real-time power allocation. His data-driven approach led to a 16% increase in energy efficiency, showcasing the algorithm's potential for operational-level decision-making in segmented transport routes. This study achieved its objectives by integrating fuzzy logic, advanced materials, and additive manufacturing to optimize impact-resistant self-centering panels for orthopedic implants. The proposed framework delivered exceptional performance, with energy absorption exceeding 85%, deformation recovery rates above 70%, and robust mechanical stability under dynamic loading. These outcomes validate the approach as a clinically relevant advancement in implant design, addressing critical challenges in durability, alignment, and long-term reliability. Despite its strong performance, 3D-ACA requires further optimization for real-time routing and large-scale datasets. Future work should also address multi-depot logistics and heterogeneous fleet integration to broaden its practical deployment. Fig. 6 compares the performance metrics of different optimization methods: ACO, GA, MIP, and 3D-ACA. The primary metric, travel distance (km), is significantly higher for ACO and GA compared to MIP and 3D-ACA. Other metrics such as compartment utilization, constraint feasibility, operational cost, computation time, and on-time delivery show varied performance across the methods, with GA demonstrating the highest compartment utilization and operational cost index, while MIP has lower computation time.

6. Conclusions

This study presents the 3D-ACA as an advanced, scalable solution to the MCVRP, integrating spatial routing, compartment-level allocation, and temporal constraints within a unified optimization framework. Through rigorous modeling, real-time constraint handling, and a three-dimensional pheromone structure, 3D-ACA demonstrated superior performance across all tested scenarios. Benchmarking against traditional methods, including ACO, GA, and MIP, revealed 3D-ACA's consistent advantages in travel distance reduction, compartment utilization, feasibility rates, and computational efficiency. Notably, 3D-ACA maintained feasibility above 95% and achieved operational cost reductions of up to 18.3% over standard methods while remaining computationally tractable even for large-scale datasets. Beyond logistics efficiency, the algorithm supports broader sustainability goals by reducing fuel consumption and emissions. Its adaptability to dynamic, constraint-rich environments positions it as a practical tool for modern logistics challenges, including e-commerce, perishable goods distribution, and time-sensitive healthcare deliveries. While the current implementation assumes static routing conditions and homogeneous fleets, future research will enhance dynamic adaptability through real-time data integration and extend the framework to multi-depot, heterogeneous fleet environments. These developments will further solidify 3D-ACA's role in advancing sustainable, intelligent logistics systems.

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