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Optimizing transport routing in the supply chain using the Ant Colony Optimization in MATLAB

Alireza Mahmoodi Fard[1,*], Negar Mozaffarghadirli[2]

[1]National University of Skill-Enghelab Eslami Technical and Vocational College, Tehran, Iran.
[2]Department of Industrial Engineering, Abrar University, Tehran, Iran.

***Corresponding Author:**
alireza10.m10@gmail.com

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ABSTRACT

In recent years, numerous efforts have focused on lowering transportation costs through various vehicle routing problem models. The increasing expenses in transportation have led many to seek ways to cut these costs by implementing vehicle routing systems. This study explores the transportation routing problem within the supply chain. The vehicle routing problem involves vehicles leaving a warehouse, visiting a group of customers, and then returning to the warehouse. Each vehicle has a fixed capacity, and each customer has a specific demand that must be completely fulfilled. The challenge lies in selecting the customers for each vehicle and designing routes according to vehicle routing problem rules, aiming to minimize the total distance traveled, the overall early and late times, and ultimately the total cost. As the vehicle routing problem is intricate and falls under the NP-Hard category, metaheuristic methods are used to address it. This research suggests employing the Ant Colony Optimization to tackle the vehicle routing problem, with the objective of finding an optimal solution using MATLAB software.

Keywords: Vehicle Routing, Ant Colony Optimization, Supply Chain, Optimization, Transportation, MATLAB Software

Introduction

In the contemporary landscape of commerce and goods distribution, optimizing transportation operations within the supply chain is crucial. As these industries grow and become more complex, transportation routing problems emerge as key challenges in supply chain management. These problems evolve into intricate optimization tasks due to the interplay of various factors such as time constraints, capacity limits, fluctuating demands, and numerous locations and transportation resources.

In recent decades, the intensely competitive industrial world has driven companies and manufacturers to fulfill customer demands for a wide array of high-quality products at reasonable prices. Achieving this is a central goal of supply chain management, as competition among companies fundamentally translates to competition among their individual components [1].

The Vehicle Routing Problem (VRP) is a critical and expensive aspect of logistics, receiving considerable attention today due to its real-world applications in industrial contexts. Initially introduced by Dantzig and Ramser, it is vital in transportation, distribution routing, and logistics [2].

VRP involves vehicles that fulfill customer demands by traveling from a warehouse to customers and then returning to the warehouse after serving all customers. Adding constraints and assumptions to these problems has resulted in various versions and broadened its applications across different fields. This research aims to offer robust solutions for VRPs under conditions of known demand quantities using metaheuristic algorithms such as Ant Colony Optimization (ACO) while ensuring optimal results. In this study, demand for each customer is known, eliminating uncertainty. The specified demand amount is met when the vehicle,

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starting from Tehran, the capital of Iran, reaches the customer, after which it moves on to the next customer. The proposed method's objective function includes both the cost of serving customers and the travel cost between customers and the warehouse.

For NP problems, no quick and practical solutions have been discovered within a reasonable time frame to date, and it is improbable that such solutions will emerge in the future. These problems encompass several thousand distinct issues with various applications. It has been established that finding a fast solution for just one of these problems would enable the resolution of the others. These problems are inherently complex and lack swift solutions. (By fast solution, we refer to a polynomial relationship between the time required to solve the problem and the size of its inputs) [3].

This problem has wide-ranging applications, especially in the industrial and service sectors, as enhancing efficiency in goods transportation significantly lowers their final cost. This improvement enables industrial and service companies to be more competitive, deliver their products to buyers at lower prices, expand their market presence, and achieve higher profits. The real-world significance of this problem has made it a central concern in everyday life [4].Additionally, as noted, the vehicle routing problem (VRP) is categorized as a hard problem, and no precise algorithms with polynomial complexity exist for it. This has driven a growing interest in heuristic and metaheuristic methods alongside exact methods for solving VRP. Particularly in the last decade, with the advancement in personal computer speeds, the use of these methods has become prevalent. Numerous methods have been proposed for this problem, some of the most notable being Tabu Search [5], Simulated Annealing [6], Ant Colony Algorithm [7], Memetic Algorithm [8], Scatter Search [9], a combination of Nearest Neighbor with Tabu Search [10], the Pseudo Magnetic Algorithm [11], the Reduced Variable Neighborhood Algorithm [12], the Adaptive Large Neighborhood Search [13], and the Variable Neighborhood Algorithm [14].

These applications have led researchers to develop many algorithms to solve this problem, which can generally be classified into two categories: exact and approximate algorithms. The first category, used for small-scale problems, finds the optimal solution in a very long time. It is important to note that heuristic and approximate algorithms themselves are further divided into two subcategories: heuristic and metaheuristic algorithms.

Literature Review

An algorithm for addressing a particular variant of the vehicle routing problem, involving a set of stations and utilizing advanced metaheuristic techniques, has been proposed. In this scenario, stations receive shipments from a producer and then use vehicles to deliver these shipments to customers within a designated region. This algorithm is designed specifically for certain conditions of the vehicle routing problem and does not address the general case of simultaneous pickup and delivery [15].

The authors have explored the vehicle routing problem with simultaneous pickup and delivery for vehicles with various characteristics, employing the Tabu Search algorithm to tackle the issue. The algorithm also includes automatic parameter adjustments, making it easier to implement. However, this approach does not account for the optimal number of vehicles required, and the proposed evolutionary algorithm is not well-suited for complex problems involving a multi-modal objective function [16]. The effectiveness of metaheuristic algorithms in solving the vehicle routing problem has been extensively reviewed and compared [17].

The vehicle routing problem has numerous real-world applications. A 2017 study in transportation and distribution clarified various areas, including the transport of people and goods, transport services, and waste management. While the reduction in distance for individual routes is modest, the overall distance savings become more pronounced when considering the total distance traveled by all buses on a daily or monthly basis. The time coefficient also shows a slight decrease with the reduction in route distances [18].

Vanstein, Wagen, and Gonawan, in their book, inform both academics and professionals about the usefulness of existing mathematical models for solving routing problems and highlight research opportunities for academic scholars [69]. researchers introduced a path-based approach to develop practical routes for servicing a set of customers without needing intermediate refueling stops. This solution method combines a VRP with an exploratory technique for small to medium-sized samples, and the authors assert that their approach outperforms known exact methods [19].

A hybrid evolutionary algorithm (HEA) was proposed to address the multi-depot green vehicle routing problem, incorporating a variable neighborhood search and a hybrid evolutionary algorithm. This HEA features multiple adjacent operators, a path-based crossover operator, and a population update strategy based on distance and quality. Environmental considerations are now a significant focus in supply chain management, alongside reducing transportation costs [20].

In their book, Derbel and colleagues presented new systems for addressing vehicle routing problems using green logistics development tools. Logistics and e-commerce companies aim to minimize distribution costs, typically by solving vehicle routing problems [21]. Delivery scheduling and vehicle routing are essential for supply chain operations, which is why this topic was emphasized in 2020. These factors become constraints or variables in the problem, leading to the creation of various VRP types that researchers formulate, study, and solve [22].

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The transportation sector negatively impacts the economy, environment, and citizens' quality of life. In 2021, key performance indicators were introduced to quantify these negative effects across economic, environmental, and social sustainability dimensions. Comprehensive experiments and sensitivity analyses were conducted using newly generated samples adapted from existing VRP benchmarks [23].

Researchers analyzed a new green vehicle routing problem to determine how connected and automated vehicles can be scheduled to meet customer demands while minimizing carbon emissions, proposing a mathematical model for this purpose [24].

Electric vehicle technology promises to lower costs and environmental impacts of logistics operations. Consequently, extensive research is being conducted in this area, including a 2021 study that discussed fundamental changes in the EVRP, presented a mathematical formulation for several simplified problem versions, and detailed the developed solution approaches [25].

Intelligent transportation is increasingly important, and the classical vehicle routing problem, a common issue in intelligent transportation, has received more attention recently. A 2022 study tackled this topic by applying the bee colony algorithm to address time efficiency and warehouse collaboration challenges. Ultimately, a co-evolutionary strategy in warehouse integration was proposed to develop a comprehensive solution [26].

Methodology

Ant Colony Optimization (ACO)

The Ant Colony Optimization addresses the Traveling Salesman Problem (TSP) by having ants lay down a chemical substance called pheromone on their paths as they move towards food sources or return to their colony. These pheromones act like signals, helping other ants find their way based on the paths previously traveled [27]. After rain, the pheromones become visible by turning white, prompting other ants to follow these marked routes [28]. At first, ants choose routes randomly, but over time, the pheromone levels on some paths increase due to random variations, drawing more ants to these paths. This process reinforces the selection of these routes among the ants [29].

Mathematical Model

Consider G = (V, A) as a complete graph where V = {1 , 2 ,… , n} represents the set of demand points, and A denotes the set of arcs or paths connecting these points in the network. Each vertex i = 1, 2,…, n corresponds to customers with specific non-negative demands $q_i \geq 0$. Additionally, vertex 0 represents the origin. A non-negative cost is associated with each arc, representing the travel cost from point i to point j (where t_{ij} is the length of the arc or the travel time between vertices i and j. If the cost $C_{ij} = C_{ji}$ is established for all i and j, then the problem becomes a Vehicle Routing Problem (VRP). A closed path that visits all vertices of the graph exactly once is called a tour or cycle, whereas a closed path that includes only a subset of the vertices (a subset of the vertices) is called a subtour. To prevent the creation of multiple subtours, the problem includes constraints to eliminate subtours using the MTZ method [28, 29].

The objective function of the problem (1) minimizes the total travel cost of the vehicles. Constraint (2) ensures that each node or demand point is serviced by only one vehicle. Constraint (3) guarantees that if a vehicle enters a node, it must

$$\text{Min } Z = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{v=1}^{NV} C_{ij}X_{ij}^{V} \quad (1)$$

St.

$$\sum_{i=1}^{n}\sum_{v=1}^{NV} X_{ij}^{V} = 1 \qquad \forall j \in \{2.3 \dots . n\} \quad (2)$$

$$\sum_{i=1}^{n} X_{ip}^{v} - \sum_{j=1}^{n} X_{pj}^{v} = 0 \qquad p = \{1. \dots . n\}. \forall v \quad (3)$$

$$\sum_{i=1}^{n}\left[\sum_{j=1}^{n} d_i X_{ij}^{V}\right] \leq Cap \qquad v = 1.2 \dots . NV \quad (4)$$

$$\sum_{j=2}^{n} X_{1j}^{V} \leq 1 \qquad v = 1.2 \dots . NV \quad (5)$$

$$u_{iv} - u_{iv} + d_j \leq M\left(1 - x_{ijv}\right) \qquad \forall i. j = 2.3 \dots . n \quad \forall_v = 1 \dots NV \quad (6)$$

$$x_{ij}^{v} \in (0.1) \cdot u_{ij} \geq 0 \quad (7)$$

Implementation

In the MATLAB software, the transportation routing problem was solved using Ant Colony Optimization resulting in an optimal solution. The algorithms achieved the best travel cost (the shortest distance between nodes) after 100 iterations (IT). By specifying the number of Function Evaluations (NFE), the algorithms aimed to reach the optimal travel cost between nodes. The algorithms worked to calculate the optimal number of vehicles required for the problem by solving and reaching the best solution.

also leave that node, thus maintaining route continuity. Constraint (4) pertains to the maximum capacity of the vehicles. Constraint (5) ensures that each vehicle must start and end its service at the origin, otherwise, it is considered inactive. Relation (6) addresses the elimination of subtours using the MTZ method. Constraint (7) defines the binary variable.

The locations of the nodes in the routing problem are as follows: our central warehouse is located in Tehran, the capital of Iran, and our customers, who have various demands, are located in other cities across Iran.

Their geographical locations are listed by latitude and longitude in Table (1).

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Conclusion

As previously mentioned, the vehicle routing problem (VRP) is a significant and practical issue in the real world, particularly in reducing costs and increasing the efficiency of supply distribution systems for companies and organizations. Due to its wide range of applications and diversity, it has always been a focus of researchers.

In this study, the vehicle routing problem is addressed with the objective of minimizing the total distance traveled by vehicles, thereby reducing transportation costs. A mathematical model for this problem is also presented, in which the constraint of returning to the initial warehouse is removed. Consequently, vehicles are not required to return to the starting warehouse, allowing for scenarios where the starting and ending warehouses can be different. To solve the proposed model, considering its NP-Hard nature, a metaheuristic algorithm has been employed. The proposed algorithm used is the Ant Colony Optimization (ACO) algorithm. The results obtained from solving the model and the efficiency of the proposed algorithm are presented.

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