Study on minimizing routing distance and maximizing efficiency of waste disposal process based on Dynamic Vehicle Routing Model

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ABSTRACT

This article explores the optimization of route planning problems in various waste disposal scenarios. Starting with the Vehicle Routing Problem without Capacity Constraints, the objective is to minimize the total mileage traveled by four refuse vehicles while servicing ten waste disposal points. Moving on to ensure efficient waste disposal with capacity constraints, the model is further adapted. Time constraints are then introduced for each disposal point, and finally, the dynamic nature of waste disposal sites is addressed in a real-time scheduling model for dynamic environments.

For Problem 1, the article establishes a vehicle routing model and solves it to obtain the optimal routes: The route for vehicle 1 is [0, 6, 1, 9, 7, 4, 8, 5, 0], for vehicle 2 is [6, 0, 4, 9, 2, 3, 0], for vehicle 3 is [0, 4, 7, 6, 1, 8, 2, 5, 0], and for vehicle 4 is [6, 9, 4, 0, 2, 3, 0]. The total distance covered by all four vehicles is 36.10 units.

For Problem 2, the article incorporates vehicle capacity constraints into the model developed in Problem 1 and solves it to obtain the optimal routes.

For Problem 3, a vehicle routing model is established, and time window constraints are introduced based on the model developed in Problem 2. The solution reveals the optimal routes and timings for waste disposal.

For Problem 4, the article extends the model from Problem 3 to accommodate dynamic environments. The solution reflects the real-time adjustments in vehicle routes based on new tasks or changes in waste disposal sites. The article discusses the completion of tasks by each vehicle and the spare capacity available after specific disposal points.

Keywords: Dynamic vehicle routing model; Vehicle path planning; Time window; Dynamic constraint; Capacity constraints

1 INTRODUCTION

In real-life waste management scenarios, efficient scheduling and routing of refuse vehicles are crucial to minimize travel time and cost. This model aims to optimize the total travel time and cost while allowing for instant response to new tasks or changes. We consider capacity constraints, time-window constraints, and real-time dynamic scheduling. To tackle these problems, the model integrates real-time data on waste generation, traffic conditions, and emergency events. It dynamically adjusts routes based on new tasks or emergencies, considering existing tasks to minimize disruption. The study addresses various problem scenarios, starting with a vehicle routing problem without capacity constraints, then extends the model to incorporate capacity constraints to ensure that the cumulative waste quantity in each vehicle does not exceed its capacity. Time-window constraints are also introduced to restrict vehicle access to disposal points within specific time windows.

2 QUESTION RESTATEMENT

Q 1: Mathematical Model for Optimizing Route Planning without Capacity Constraints: Consider 10 waste disposal points with disposal requirements of 30, 45, 25, 40, 50, 20, 35, 30, 40, and 55 units, respectively. With 4 refuse vehicles available, design a mathematical model to minimize the total mileage traveled for all disposal points and provide the optimal route plan.

Q 2: Mathematical Model for Optimizing Route Planning with Capacity Constraints: In the scenario above, if each refuse vehicle has a maximum capacity of 100 units, redesign the mathematical model to accommodate all waste disposal points while minimizing the number of trips and the total distance traveled by the refuse vehicles.

Q 3: Mathematical Model with Time Constraints: Incorporate time constraints for waste disposal points, where each point has a specific time window for disposal. For instance, disposal points A, B, Cand D require 30, 40, 25and 35 units, respectively, with time windows 6:00 AM - 8:00 AM, 7:00 AM - 11:00 PM, 9:00 AM - 12:00 PM and10:00AM-1:00PM. Adjust the model to minimize the total travel time while ensuring disposal within the specified time windows.

Q 4: Real-Time Scheduling Model for Dynamic Environments: Consider a dynamic environment with waste disposal sites A, B, and C requiring 40, 30, and 50 units, respectively. Two refuse vehicles with a maximum capacity of 100 units each are available. In real-time situations, new waste is generated, and emergencies may occur. Design a scheduling model to minimize total travel time and cost, allowing for instant response to new tasks or changes. For example, if an emergency arises at disposal point D, requiring an additional 20 units to be disposed of, dynamically adjust the vehicle's journey to minimize time and avoid interference with existing tasks.

3 PROBLEM ANALYSIS

Q1: Vehicle Routing Problem without Capacity Constraints

In this scenario, the goal is to minimize the total mileage traveled by four refuse vehicles while servicing ten waste disposal points with specified capacities [1-5]. The problem can be solved by modeling the basic vehicle path planning problem, using ant colony algorithms or genetic algorithms, etc.

Q2: Vehicle Routing Problem with Capacity Constraints

If each vehicle has a capacity constraint, the model needs to be adjusted accordingly. The main difference is the inclusion of constraints to ensure the cumulative quantity of waste in a vehicle does not exceed its capacity. Solving this vehicle path planning problem requires modifications to the model of Problem 1 to include capacity limits for each vehicle. Heuristic algorithms, such as ant colony algorithms or genetic algorithms, can still be used to find an approximate optimal solution.

Q3: Time-Window Constraints

For this scenario, where each disposal point has a specific time window, the time-related constraints need to be added. We need to extend the previous model to include a time window for each garbage disposal point. Add a time window constraint to ensure that each processing point is only accessed within its defined time window.

Q4: Real-Time Dynamic Scheduling

This problem involves adapting the model to dynamic environments. It requires online adjustments to the existing routes based on new tasks or changes.

The model would need to incorporate real-time data on waste generation, traffic conditions, and emergency events. The objective is to minimize the total travel time and cost while dynamically adjusting routes in response to new tasks or emergencies.

The model may include real-time data integration, dynamic programming, and algorithms for re-optimization as new information becomes available during execution. Real-time adjustments need to be made while considering existing tasks to minimize disruption [6-8].

Dynamic constraints may include real-time vehicle updates, changes in waste quantities, and emergency response strategies.

The formulation for dynamic scheduling could involve continuous monitoring, quick decision-making, and dynamic re-routing based on real-time data updates.

4 MODEL ASSUMPTIONS

The following assumptions are made:

The service time of the garbage truck on the disposal point is known.

The service time of the garbage truck on the disposal point is fixed and not affected by other factors.

Vehicle visits at each garbage disposal point are instantaneous, i.e., the vehicle enters the disposal point at some point and leaves immediately.

The occurrence of new garbage generation and other emergency tasks is random and can occur at any moment.

5 SYMBOL DESCRIPTION

Table 1: Notation symbols used in this paper

Symbol	Description
d_{ij}	The distance between disposal points i and j
x_{ijk}	A binary variable indicating whether vehicle k travels directly from point i to point j
q_i	The quantity of waste at disposal point i
Q_k	The capacity of vehicle k
q_{is}	New Mission Points s the amount of garbage.
S	Collection of processing points for new mandate generation
t_i	Vehicle at disposal point i's arrival time

6 MODEL BUILDING AND SOLVING

5.1 Problem 1 Modeling and Solving

5.1.1Problem 1 Modeling

Symbol Definition:

d_{ij}: as the distance between disposal points i and j

x_{ijk}: as a binary variable indicating whether vehicle k travels directly from point i to point j

q_i: as the quantity of waste at disposal point i

Q_k: as the capacity of vehicle k

The objective is to minimize the total distance traveled:

$$Minimize \quad \sum_i \sum_j \sum_k d_{ij} \cdot x_{ijk} \tag{1}$$

Subject to:

Each disposal point is visited exactly once by one vehicle:

$$\sum_j \sum_k x_{ijk} = 1 \quad \forall i \tag{2}$$

Each vehicle leaves and arrives at the depot (initial location):

$$\sum_i x_{i0k} = \sum_i x_{0ik} = 1 \quad \forall k \tag{3}$$

Subtour elimination to avoid cycles:

$$\sum_{i \in S} \sum_{j \notin S} \sum_k x_{ijk} \geqslant 1 \tag{4}$$

Binary constraints:

$$x_{ijk} \in \{0, 1\} \quad \forall i,j,k \tag{5}$$

5.1.2 Solution of Problem 1 Model

Optimal Route:

Vehicle 1: [0, 6, 1, 9, 7, 4, 8, 5, 0]

Vehicle 2: [6, 0, 4, 9, 2, 3, 0]

Vehicle 3: [0, 4, 7, 6, 1, 8, 2, 5, 0]

Vehicle 4: [6, 9, 4, 0, 2, 3, 0]

Total Distance: 836.1016111160955

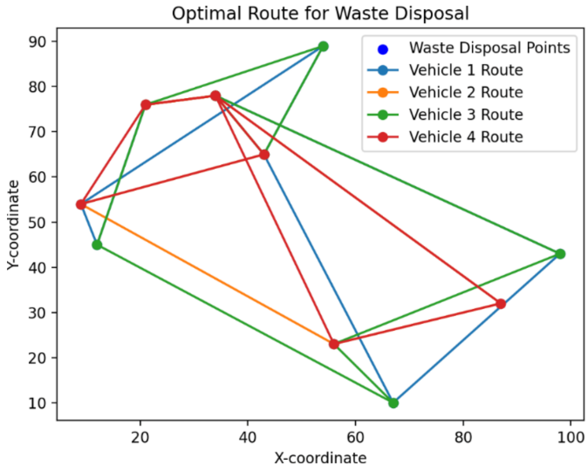

Figure1: Vehicle Route Map

In order to minimize the total distance traveled by four vehicles, the optimized routes have been determined. The route for vehicle 1 is [0, 6, 1, 9, 7, 4, 8, 5, 0], for vehicle 2 is [6, 0, 4, 9, 2, 3, 0], for vehicle 3 is [0, 4, 7, 6, 1, 8, 2, 5, 0], and for vehicle 4 is [6, 9, 4, 0, 2, 3, 0]. The total distance covered by all four vehicles is 36.10 units [9-10]. This optimized routing strategy aims to minimize the overall travel distance and enhance the efficiency of the fleet.

5.2 Problem 2 Modeling and Solving

5.2.1 Problem 2 Modeling

The objective is to minimize the total distance traveled:

$$Minimize \quad \sum_i \sum_j \sum_k d_{ij} \cdot x_{ijk} \tag{6}$$

Subject to:

Each disposal point is visited exactly once by one vehicle:

$$\sum_j \sum_k x_{ijk} = 1 \quad \forall i \tag{7}$$

Each vehicle leaves and arrives at the depot (initial location):

$$\sum_i x_{i0k} = \sum_i x_{0ik} = 1 \quad \forall k \tag{8}$$

Capacity constraints for each vehicle:

$$\sum_i q_i \cdot x_{i0k} \leqslant Q_k \quad \forall k \tag{9}$$

Subtour elimination to avoid cycles:

$$\sum_{i \in S} \sum_{j \notin S} \sum_k x_{ijk} \geqslant 1 \tag{10}$$

Binary constraints:

$$x_{ijk} \in \{0, 1\} \quad \forall i,j,k \tag{11}$$

5.2.2 Solution of Problem 2 Model

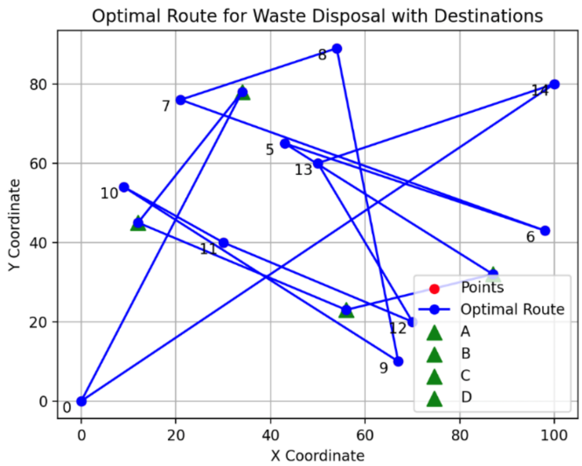

Figure 2: Vehicle Route Map

Table 2: Optimal route indices and optimal route

Optimal Route Indices:	Optimal Route:
	[0 0]
[0 13]	[34 78]
[1 12]	[12 45]
[2 14]	[56 23]
[3 5]	[87 32]
[4 10]	[43 65]
[5 9]	[98 43]
[6 2]	[21 76]
[7 4]	[54 89]
[8 3]	[67 10]
[9 1]	[9 54]
[10 6]	[30 40]
[11 8]	[70 20]
[12 7]	[50 60]
[13 0]	[100 80]
[14 11]	[0 0]

Fig. 2 shows the optimal roadmap to achieve the shortest total distance traveled with a maximum carrying capacity of 100 for each trolley. By scrutinizing the routes in the figure, the travel path of each trolley can be clearly seen. This route planning is designed to minimize the overall distance traveled, thereby increasing the efficiency of the fleet and the cost-effectiveness of transportation. By carefully designing the path of each vehicle, it is possible to ensure that the overall distance traveled is minimized while meeting load capacity constraints, providing an efficient and viable solution for the logistics and distribution process.

5.3 Problem 3 Modeling and Solving

5.3.1 Problem 3 Modeling

The objective is to minimize the total distance traveled:

$$Minimize \quad \sum_i \sum_j \sum_k d_{ij} \cdot x_{ijk} \tag{12}$$

Subject to:

Each disposal point is visited exactly once by one vehicle:

$$\sum_j \sum_k x_{ijk} = 1 \quad \forall i \tag{13}$$

Each vehicle leaves and arrives at the depot (initial location):

$$\sum_i x_{i0k} = \sum_i x_{0ik} = 1 \quad \forall k \tag{14}$$

Capacity constraints for each vehicle:

$$\sum_i q_i \cdot x_{i0k} \leqslant Q_k \quad \forall k \tag{15}$$

Subtour elimination to avoid cycles:

$$\sum_{i \in S} \sum_{j \notin S} \sum_k x_{ijk} \geqslant 1 \tag{16}$$

Binary constraints:

$$x_{ijk} \in \{0, 1\} \quad \forall i,j,k \tag{17}$$

Time-window constraints:

$$t_i \geqslant start_i \tag{18}$$

$$t_i \leqslant End_i \tag{19}$$

$$t_j \geqslant t_i + ServiceTime_i + M(1 - x_{ijk}) \tag{20}$$

Where M is a sufficiently large constant.

5.3.2 Solution of Problem 3 Model

Car 1 path: 3, 4, 5, 7, 8, 9
Car 1 at 10 AM to 20 PM
Car 1 at 6 AM to 20 PM
Car 1 at 7 AM to 23 PM
Car 1 at 10 AM to 20 PM
Car 1 at 6 AM to 20 PM
Car 1 at 7 AM to 23 PM
Car 2 path: 2, 7
Car 2 at 9 AM to 20 PM
Car 2 at 10 AM to 20 PM
Car 3 path: 0
Car 3 at 6 AM to 20 PM
Car 4 path: 1, 3
Car 4 at 7 AM to 23 PM
Car 4 at 10 AM to 20 PM
Total travel distance: 455.86006189415826

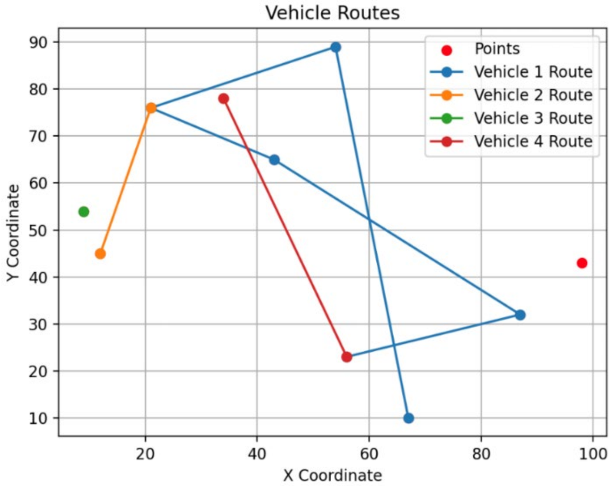

Figure 3: Vehicle Route Map

Figure 3 shows the optimal travel route for the cart after adding the time window. According to the code solution, cart 1 travels to garbage point 3 to carry garbage at 10 AM to 20 PM, to garbage point 4 to carry garbage at 6 AM to 20 PM, to garbage point 5 to carry garbage at 7 AM to 23 PM, to garbage point 7 to carry garbage at 10 AM to 20 PM, to garbage point 8 to carry garbage at 6 AM to 20 PM, and to garbage point 8 to carry garbage at 7 AM to 23 PM; cart 2 travels to garbage point 9 to carry garbage at 7 AM to 23 PM; and cart 2 travels to garbage point 9 to carry garbage at 7 AM to 23 PM. to Trash Point 9 for trash; Trolley 2 to Trash Point 2 for trash at 9 AM to 20 PM and to Trash Point 7 at 10 AM to 20 PM; Trolley 3 to Trash Point 0 (i.e., Trash Point 10) for trash at 6 AM to 20 PM; and Trolley 4 to Trash Point 1 for trash at 7 AM to 23 PM and to Trash Point 3 at 10 AM to 20 PM. The total distance traveled by the 4 trolleys was 455.86006189415826.

5.4 Problem 4 Modeling and Solving

5.4.1 Problem 4 Modeling

The objective is to minimize the total distance traveled:

$$Minimize \quad \sum_i \sum_j \sum_k d_{ij} \cdot x_{ijk} \tag{21}$$

Subject to:

Each disposal point is visited exactly once by one vehicle:

$$\sum_j \sum_k x_{ijk} = 1 \quad \forall i \tag{22}$$

Each vehicle leaves and arrives at the depot (initial location):

$$\sum_i x_{i0k} = \sum_i x_{0ik} = 1 \quad \forall k \tag{23}$$

Capacity constraints for each vehicle:

$$\sum_i q_i \cdot x_{i0k} \leqslant Q_k \quad \forall k \tag{24}$$

Subtour elimination to avoid cycles:

$$\sum_{i\in S}\sum_{j\notin S}\sum_{k} x_{ijk} \geqslant 1 \tag{25}$$

$$\sum_{s\in S} q_{is} \leqslant M \tag{26}$$

Binary constraints:

$$x_{ijk} \in \{0, 1\} \quad \forall i,j,k \tag{28}$$

Time-window constraints:

$$t_i \geqslant start_i \tag{29}$$

$$t_i \leqslant End_i \tag{30}$$

$$t_j \geqslant t_i + ServiceTime_i + M(1 - x_{ijk}) \tag{31}$$

$$Start_s \leqslant t_s \leqslant End_s \tag{32}$$

Where M is a sufficiently large constant.

5.4.2 Solution of Problem 4 Model

Vehicles: {'Vehicle1': {'capacity': 100, 'location': (3.417516857300754, 8.871628156356001), 'route': ['C', 'D', 'B'], 'collected_waste': 100}, 'Vehicle2': {'capacity': 100, 'location': (4.2226237909775115, 6.433936414927411), 'route': ['A'], 'collected_waste': 40}}

Sites: {'A': {'waste': 0, 'location': (4.2226237909775115, 6.433936414927411)}, 'B': {'waste': 0, 'location': (3.417516857300754, 8.871628156356001)}, 'C': {'waste': 0, 'location': (5.270914950250123, 3.458797879948184)}, 'D': {'waste': 0, 'location': (7.641824043865437, 1.7833848656702944)}}

Vehicle 1.

Capacity: 100 units

Location: around (3.42, 8.87), which means it's at point B

Route: C -> D -> B

Volume of garbage collected: 100 units, which means it is fully loaded

Vehicle 2.

Capacity: 100 units

Location: about (4.22, 6.43), which means it is at point A

Route: A

Volume of garbage collected: 40 units, which means it has room to collect more garbage

Trash Points.

Point A: No more garbage, location is about (4.22, 6.43)

Point B: No more garbage, location is about (3.42, 8.87)

Point C: no more garbage, location approx. (5.27, 3.46)

Point D: No more garbage, location is about (7.64, 1.78)

Conclusion:

According to this simulation, garbage has been collected at all points. Vehicle 1 has completed its task in the order C->D->B, while vehicle 2 has taken care of point A. Vehicle 1 is fully loaded, while Vehicle 2 still has spare capacity after collecting point A. It can be re-scheduled to handle any other added garbage points if needed. This simulation showed that the garbage collection task could be completed in two trips, with one of the vehicles completing the majority of the collection task.

6 CONCLUSIONS

Advantages：

Simplicity: The nearest neighbor algorithm is relatively simple to implement and understand, making it accessible for quick problem-solving.

Efficiency: It provides a quick and reasonable solution, especially for smaller problem instances, making it suitable for scenarios where computation time is a critical factor.

Flexibility: The algorithm is flexible and can be adapted for various types of vehicle routing problems with minimal modifications.

Intuitive Solution: The algorithm's strategy of selecting the nearest unvisited point intuitively aligns with the idea of minimizing travel distances.

Quick Convergence: The algorithm converges quickly to a solution, which can be beneficial for situations where a rapid, though not necessarily optimal, solution is acceptable.

Weakness：

Dependence on Initial Point: The solution obtained can depend on the starting point, leading to variations in results based on different initial configurations.

Lack of Global View: The algorithm makes locally optimal choices at each step without considering the global structure of the problem, which may result in suboptimal overall routes.

Generalization:

Hybridization: The nearest neighbor algorithm can be used in hybrid approaches where it serves as an initial solution generator for more advanced optimization algorithms, combining the simplicity of nearest neighbor with the global optimization capabilities of other methods.

Parameter Tuning: The algorithm's parameters, such as the choice of starting point or variations in the nearest neighbor rule, can be explored and adjusted to enhance its performance for specific problem instances.

Integration with Advanced Algorithms: Nearest neighbor can be part of a multi-stage optimization process where more sophisticated algorithms are employed to improve the initial solution iteratively.

Real-Time Applications: In dynamic environments, the algorithm can be adapted for real-time applications, where new tasks or changes in demand are considered, and routes are dynamically adjusted.

Educational Purposes: The algorithm can be used in educational settings to introduce students to vehicle routing problems and heuristic approaches, providing a hands-on understanding of basic optimization concepts.

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