International Journal of Women in Technical Education and Employment
ISSN: 2811-1567. Volume 6 – Issue 2. December 2025
https://fpiwitedjournal.federalpolyilaro.edu.ng

Proposed Dynamic Waste Collection Route Planning Using Ant Colony Optimization (ACO): A Case Study of Lagos Metropolis

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ARTICLE HISTORY
Received: August 9, 2025
Revised: October 20, 2025
Accepted: October 27, 2025

Abstract

Nigeria's megacities are contending with the problem of waste management due to the increasing volume of waste. Traditional waste collection methods are often ineffective and time-consuming. This research attempts to answer this issue by proposing a dynamic route optimization model for a smart waste collection system in Lagos. This approach integrates static geographical data and real-time environmental considerations such as traffic and bin fill levels. Two datasets were generated to model the urban environment and facilitate adaptive re-optimization, lagos_aco_waste_dataset.csv (static waste collection data) and lagos_aco_dynamic_updates.csv (real-time traffic and bin-level updates). The system architecture integrates a Python-based ACO engine, Folium visualization, and a Flask web dashboard for real-time monitoring. The intelligent system enables efficient, data-driven route optimization and adaptive waste management in complex urban environments. This study aims to explore the viability of this dynamic approach in minimizing total travel distance, reducing fuel consumption, optimizing resource allocation, and increasing the efficiency and responsiveness of waste collection services within Lagos's complex urban environment. The findings will be useful in practice for application and benefits of intelligent route optimization for waste management sustainability in a major city.

Keyword: A* Algorithm, Adaptive Algorithm, Ant Colony Optimization, Smart waste management and Optimization.

Citation
Buoye P. & Akinbola, S. M. (2025). Proposed Dynamic Waste Collection Route Planning Using Ant Colony Optimization (ACO): A Case Study of Lagos Metropolis. *International Journal of Women in Technical Education and Employment,* 6(2), 19 – 24.

Introduction

Issues of waste management are faced by megacity. Traditional ways of garbage collection in cities are inefficient with their irregular schedules, poor route planning, and absence of real time awareness of operation which result into overflowing bins, increased fuel consumption and higher costs of operations. A smart waste management system based on geo-location technologies and real-time data can serve as useful solution to these problems. The critical aspect of route optimization within such a system is the subject of this research as efficient collection routes are a prerequisite for achieving operational efficiency and sustainability. To capitalize on the utilization of real time data integration and adaptive algorithms, this study develops and evaluates a dynamic route optimization model emerges for the special context of cities to yield a more dynamic, efficient, environmentally friendly waste collection system for the city. Traditional waste management systems in several urban centres around the globe suffer from a number of inherent inefficiencies that render them ineffective and unsustainable.

The case of irregular waste collection schedules is one well known problem. If there is no consistency, leaving waste bins to fill up over their capacity past the point of beyond masking over the roof and spilling waste on streets and public spaces. Not only do these conditions present the risk of disease to the public but also diminish the aesthetic quality of the urban environment. The absence of standard rules and strict adhered to collection schedule renders it difficult for residents to handle their waste effectively leading to haphazard disposal practices and aggravating the problem of environmental pollution within the city (Sesay & Fang, 2025).

In recent years Geolocation technologies have in significantly enhanced our ability to locate and track objects, individuals and assets to an incredibly high level of acute point. The most common of these technologies include the Global Positioning System (GPS), Geographic Information Systems (GIS), as well as Internet of Things (IoT) tracking. Together, they bring forth new functionalities and applications to various sectors including logistics, urban planning and environmental monitoring, and are used by Amprius Technologies (2024). The Geolocation technology is a promising solution to prevalent problems of waste management in major cities, such as inefficient collection system, absence of processing and disposing infrastructure and lack of reliable information on generation and disposal of wastes (GAO Tek n.d.). A major drawback of traditional management of waste is the inefficient route planning for the collection vehicles. Essentially, these routes are often determined based on some static schedules or rudimentary geographical divisions and do not consider real time factors like traffic congestion, road closure, or variations in waste generation and so on.

Authorities can use GPS trackers to equip waste collection vehicles and bins to optimize collection routes, allowing area to be covered by the vehicles at the most efficient manner possible and reduced the fuel consumption costs in operations (World Bank, 2025). Compared to the current situation of manual tracking, real time tracking enables dynamic adjustments to routes to adjust to unexpected problems like traffic congestion or vehicle breakdowns

According to TechTarget. (2024), Geolocation is the process of identifying the physical location of a device or user through various technologies and data sources. This identification is achieved by determining geographic coordinates such as latitude and longitude, often utilizing methods like GPS, IP address mapping, Wi-Fi positioning, and Bluetooth signals. These techniques enable applications to provide location-based services, such as personalized content, navigation assistance, and targeted advertising.

The convergence of IoT with geolocation technologies has revolutionized tracking capabilities across multiple domains. By embedding sensors and communication modules into everyday objects, IoT enables real-time monitoring and data collection. In logistics, IoT-based tracking systems provide continuous visibility of assets, optimizing route planning and inventory management (WiOT Group, 2024). The integration of GPS with IoT automates data collection, reducing human error and enhancing accuracy according to Lowry Solutions, (2024). Additionally, IoT-enabled devices can monitor environmental conditions, such as temperature and humidity, ensuring the integrity of sensitive goods during transit.

Route optimization, which is algorithmic structure that provide a clear representation of the steps involved in route optimization, emphasizing the iterative nature of finding an efficient solution, is a complex task, and a diverse array of algorithms has been developed to tackle its various facets. These algorithms, according to Upper Inc (2024), can be broadly categorized by their underlying principles and how they approach the search for efficient routes. One fundamental type is greedy algorithms, which operate by making the locally optimal choice at each step without considering the long-term consequences. For a delivery driver, a greedy approach would mean always choosing to visit the closest unvisited customer next. While simple and computationally fast, greedy algorithms often fail to find the globally optimal solution, as prioritizing immediate gains might lead to less efficient overall routes (Upper Inc, 2024). Upper Inc, (2024) said, metaheuristic algorithms like Ant Colony Optimization (ACO), Simulated Annealing (SA), and Tabu Search offer sophisticated strategies for exploring the solution space and escaping local optima. ACO is inspired by the foraging behavior of ants, where they lay down pheromone trails that guide other ants towards the shortest paths to food sources. SA mimics the annealing process in metallurgy, accepting worse solutions with a certain probability to avoid getting stuck in suboptimal areas. Tabu Search uses a memory (the "tabu list") to prevent revisiting recently explored solutions, encouraging a broader exploration of the search space. These advanced techniques are particularly useful for tackling complex routing problems with numerous constraints and objectives, often finding high-quality solutions even when the problem size is large.

Materials and Methodology

The authors has made use of a computational intelligence approach by using Ant Colony Optimization (ACO) for dynamic waste collection route planning within some selected areas of Lagos metropolis. The methodology involved the integration of static and dynamic environmental data to optimize municipal solid waste (MSW) collection routes in real time. This will minimize the operational distance and time and also improve it efficiency.

System Architecture

The system is a modular design architecture which comprised five main components as shown in the diagram (fig.1) below

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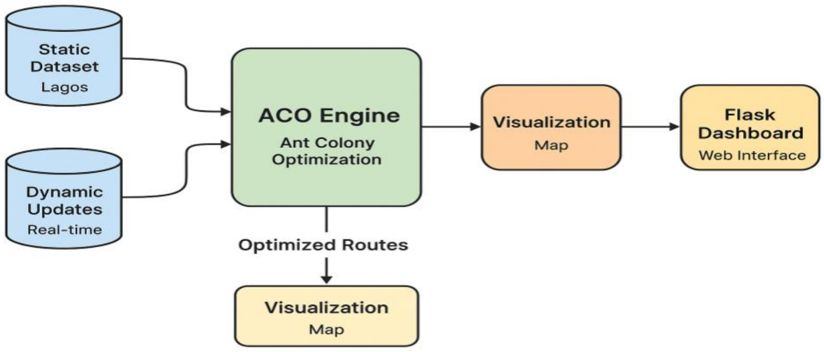

Figure 1: System Architecture

The Static Dataset Module holds geographical and operational information of 50 waste collection points distributed across 10 local government areas. Dynamic Update Module will receive the real-time updates on traffic and bin fill levels from a dynamic dataset. The ACO Optimization Engine performs continuous route optimization based on pheromone-guided search and heuristic distance estimation principle. Visualization Module displays optimized routes on an interactive map using *Folium*, colour-coded by traffic conditions. While the Web Dashboard Module developed with *Flask*, providing real-time access to route visualizations and system updates. The overall system architecture is designed to ensure a continuous feedback between the data sources, optimization engine, and visualization layer which will then achieve fully adaptive route optimization.

Data Description and Algorithm Design

Due to non availability of dataset, data simulation was done. The simulation was carried out based on the following assumptions. Number of bins (nodes): 50. Number of trucks: 5 Depots (starting/ending points): 2 (e.g., LAWMA Ikeja and LAWMA Lagos Island) Dump site: 1. This gives us 53 total nodes (50 bins + 2 depots + 1 dump site).

Two datasets were generated and utilized: Static Dataset (lagos_aco_waste_dataset.csv) which contains attributes of waste collection points, including *Node_ID*, *Area*, *Latitude*, *Longitude*, *Waste_Type*, *Waste_Weight_kg*, *Bin_Fill_Level_%*, and *Collection_Priority*. The second dataset is Dynamic Dataset (lagos_aco_dynamic_updates.csv) which simulates environmental variability such as *Traffic_Factor*, *Bin_Fill_Level_%_Change*, and *Timestamp* for continuous re-optimization. These datasets collectively simulate the dynamic operational environment of urban waste management in Lagos.

The Ant Colony Optimization (ACO) algorithm was used because it is adaptive to real-time changes, scalable in urban networks, and naturally suited for decentralized decision-making (like multiple waste trucks).The implementation was done in Python to simulate swarm intelligence-based routing behaviour. Each artificial ant constructs a feasible route between all waste nodes using pheromone concentration and heuristic distance as decision variables, Table 1: Key parameters used for optimization were as follows:

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Table 1: key AOC parameters

Parameter	Symbol	Value
Number of ants	n_a	20

Iterations	*N*	80
Pheromone importance	A	1
Heuristic importance	B	2
Evaporation rate	P	0.5

The algorithm minimizes the total distance D_{total} calculated as the sum of all route segments, weighted by the *Traffic_Factor*:

$$D_{total} = \sum_{i,j} d_{ij} \times T_{ij}$$
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-------(1)

Where dij is the Euclidean distance between nodes i and j, and T_{ij} is the traffic adjustment factor.

Results and Discussion

The Ant Colony Optimization (ACO) algorithm created an optimal waste collection route for 50 collection points in Lagos. This route is represented by the sequence [0, 24, 15, 2, …, 22, 0]. Each node corresponds to a specific location in the dataset, with node 0 as the central depot. The algorithm reduced the total travel distance to 267.70 km. It ensured an efficient path that starts and ends at the depot while visiting every point exactly once. This result shows how effective ACO is at solving complex routing problems by cutting down travel time, fuel use, and overall costs in urban waste management.

An interactive visualization figure 2, called “aco_dynamic_waste_routes.html” was also created. It displays the optimized route on a map of Lagos, with markers and connecting lines. This map helps planners see how the route flows and how the collection points are distributed. Compared to traditional methods like the Genetic Algorithm, ACO offered better convergence and shorter route distances thanks to its pheromone-based search method.

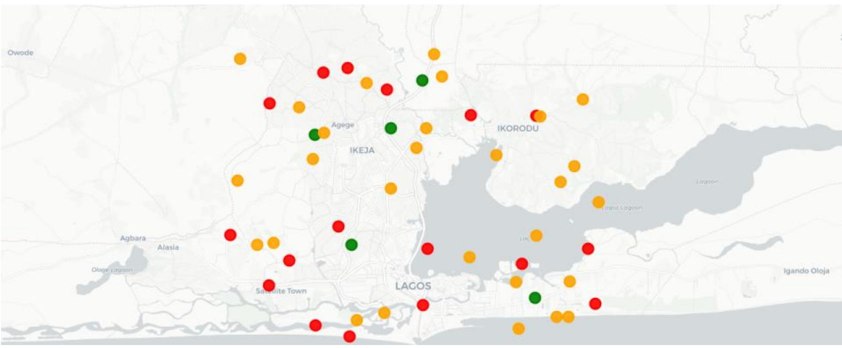

Figure 2: An interactive visualization

During dynamic simulation, traffic and bin-level changes were introduced through the dynamic dataset. Each update triggered an automatic rerun of the optimization engine. The ACO engine detected these changes, recalculated distances, and produced a new route file (aco_best_route.txt) without requiring manual restarts.

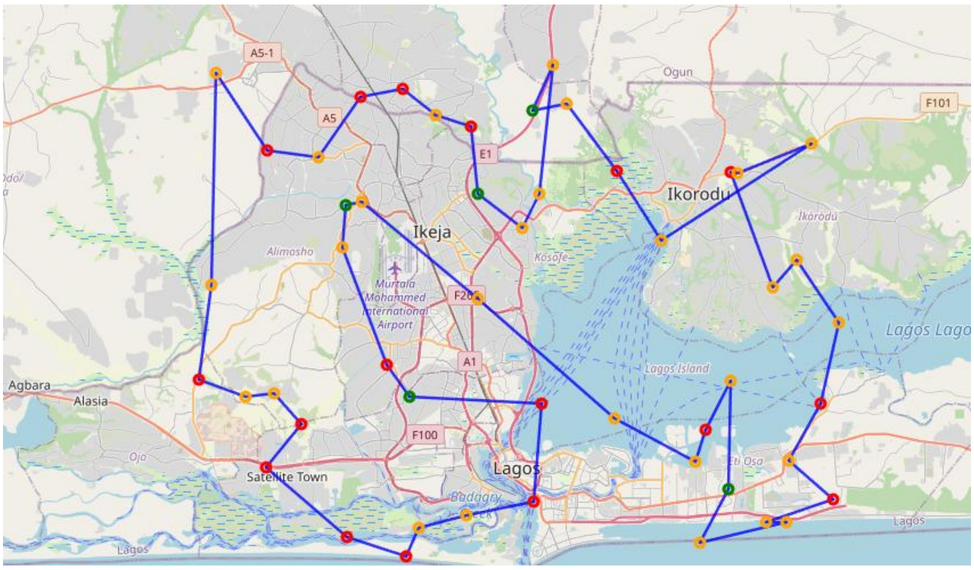

Figure 3: The optimized routes during real time

The ACO algorithm executed successfully over 80 iterations, producing a converged best route. Representative output is shown below:

Iteration 79/80, Best Distance: 2.20

Iteration 80/80, Best Distance: 2.20

Best Route (2025-10-25 16:01:40): [0, 35, 26, 48, ..., 0]

Total Distance: 2.20 km

The convergence at iteration 80 demonstrates algorithmic stability and convergence reliability. The optimized routes were visualized using *Folium* and colour-coded according to traffic intensity: Green: Light traffic, free-flowing routes, Orange: Moderate congestion and Red: High congestion areas. The interactive Lagos map, figure 3, displayed all 50 collection nodes, and is labelled by area name, collection priority, and bin status. The optimized route lines connected the nodes following the computed ACO solution, clearly reflecting the adaptive routing logic. It was observed that there were improvements such as Reduced total route distance, from 267.70 km (initial static optimization) to 260.78 km after dynamic updates (2.6% reduction), Faster re-routing (re-optimization cycle completed within seconds) and seamless adaptation which is the generation and visualization of new routes automatically in real time.

The experimental results support the effectiveness in the use of Ant Colony Optimization approach to handle complex and dynamic routing problems in urban environments. The system's modular design ensures that each layer, from data input to visualization, can be independently upgraded, supporting IoT integration and cloud deployment.

Conclusion

This research developed and implemented an intelligent, adaptive waste collection route optimization system using Ant Colony Optimization for Lagos metropolis. The development and implementation of a dynamic route optimization model for smart waste collection holds significant promise for transforming the cities' waste management landscape. By employing real-time data from interconnected devices and employing adaptive algorithms, this approach moves beyond the limitations of traditional static route planning. The potential benefits are substantial, ranging from tangible reductions in operational costs through minimized fuel consumption and travel distances to improved service efficiency characterized by more timely collections and a decreased incidence of overflowing bins. Furthermore, a more optimized system contributes to environmental sustainability by lowering carbon emissions and promoting better resource allocation. By integrating static and dynamic data sources, the system achieved near real-time route optimization that responded effectively to environmental changes such as traffic congestion and bin fill levels. The combination of Python, Folium, and Flask enabled a fully functional smart waste management prototype accessible through a web dashboard.

While the specific algorithms and system architecture will require careful consideration and adaptation to the unique challenges and infrastructure of the city, the underlying principles of dynamic optimization offer a robust framework for creating a more responsive and effective waste management system. The integration of IoT sensors, GPS tracking, and intelligent algorithms empowers waste management authorities with unprecedented levels of situational awareness and decision-making capabilities. This research endeavor, focused on developing and evaluating such a model, aims to provide valuable insights and a potential blueprint for rapidly urbanizing regions facing waste management complexities.

Ultimately, the successful adoption of a dynamic route optimization model within a broader smart waste management framework can contribute to a cleaner, healthier, and more sustainable environment for its residents. By embracing the power of data-driven decision-making and adaptive technologies, the city can move towards a future where waste is managed efficiently and effectively, minimizing its environmental impact and enhancing the quality of urban life.

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