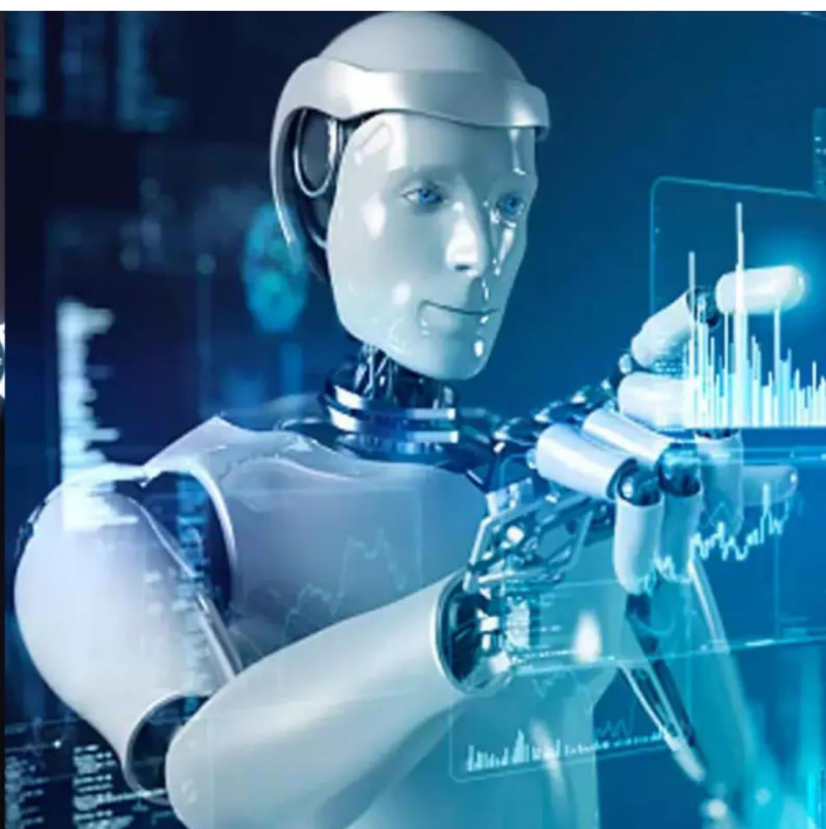




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An Intelligent IoT-Based Garbage Monitoring and Route Optimization Framework Using Graph Theory, Max Priority Queue, and Dijkstra's Shortest Path Algorithm

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ABSTRACT: Rapid urbanization has increased the demand for efficient municipal waste management systems. Conventional waste collection methods rely on fixed schedules, resulting in unnecessary vehicle movement, overflowing bins, increased fuel consumption, and higher operational costs. This paper proposes **An Intelligent IoT-Based Garbage Monitoring and Route Optimization Framework Using Graph Theory, Max Priority Queue, and Dijkstra's Shortest Path Algorithm**. The proposed framework integrates ultrasonic sensors, Arduino Uno, ESP8266 Wi-Fi modules, and GPS technology to monitor garbage levels and transmit real-time data to a centralized server. The road network is modeled using Graph Theory, where garbage bins are represented as vertices and roads as weighted edges. A Max Priority Queue prioritizes bins based on garbage fill level, waiting time, and complaint count, while Dijkstra's Shortest Path Algorithm generates the optimal collection route. The framework also supports dynamic route updates whenever new bins reach the predefined threshold. By combining IoT with intelligent scheduling and graph-based optimization, the proposed system reduces travel distance, fuel consumption, and collection time while improving operational efficiency. The framework provides a scalable solution for smart waste management and future smart city applications.

KEYWORDS: Internet of Things (IoT), Smart Waste Management, Graph Theory, Max Priority Queue, Dijkstra's Shortest Path Algorithm, Route Optimization, Smart City.

I. INTRODUCTION

The rapid growth of urban populations has significantly increased the generation of municipal solid waste, creating major challenges for city administrations. Traditional waste collection systems follow fixed schedules without considering the real-time status of garbage bins, often leading to overflowing bins, unnecessary vehicle movement, increased fuel consumption, and higher operational costs. These limitations highlight the need for intelligent and adaptive waste management solutions. The Internet of Things (IoT) enables real-time monitoring of garbage bins through sensors and wireless communication, allowing collection decisions to be based on actual bin status rather than predefined schedules. In addition, Graph Theory provides an efficient representation of the road network, Max Priority Queue prioritizes bins according to urgency, and Dijkstra's Shortest Path Algorithm determines the most efficient collection route.

This paper proposes an intelligent IoT-based garbage monitoring and route optimization framework that integrates real-time sensing, graph-based road modeling, priority-based scheduling, and shortest-path routing into a unified system. The proposed framework aims to improve waste collection efficiency, reduce travel distance and fuel consumption, support dynamic route updates, and provide a scalable solution for smart city waste management.

II. LITERATURE REVIEW

Recent advancements in Internet of Things (IoT) technology have significantly improved smart waste management systems by enabling real-time monitoring of garbage bins. Several researchers have proposed IoT-based solutions using ultrasonic sensors, wireless communication, and GPS for monitoring waste levels and notifying municipal authorities when bins become full. However, most of these systems primarily focus on monitoring and lack intelligent route optimization for waste collection.

Gopal Krishna Shyam et al. [1] developed an IoT-based waste monitoring system that improved garbage level detection and notification but did not address optimized vehicle routing. Monika K. A. et al. [2] proposed a smart dustbin system for automatic garbage monitoring; however, it lacked priority-based scheduling and route optimization. Parkash and Prabu [3] introduced an IoT-enabled waste management framework using GPS and wireless communication, but the collection process followed conventional scheduling methods. Vinoth Kumar et al. [4] proposed a smart garbage monitoring system that improved collection efficiency through real-time monitoring, yet it did not integrate advanced data structures or shortest-path algorithms. Researchers have also applied Dijkstra's Shortest Path Algorithm [5] for route optimization in transportation and logistics. Graph Theory has been widely used to represent road networks, while Max Priority Queue scheduling efficiently handles high-priority tasks. Nevertheless, only limited research combines IoT-enabled monitoring, Graph Theory, Max Priority Queue scheduling, and Dijkstra's Shortest Path Algorithm into a unified waste management framework.

Therefore, this work proposes an integrated framework that combines real-time IoT monitoring, intelligent priority-based scheduling, graph-based road modeling, and optimized route planning to improve waste collection efficiency and support scalable smart city applications.

III. RESEARCH GAP

Existing IoT-based waste management systems mainly focus on garbage monitoring or route optimization independently. Most lack intelligent priority-based scheduling and dynamic route updates based on real-time bin status. There is a need for an integrated framework that combines IoT monitoring, Graph Theory, Max Priority Queue scheduling, and Dijkstra's Shortest Path Algorithm to achieve efficient and adaptive waste collection.

Objectives

1. To develop an IoT-based smart garbage monitoring system using ultrasonic sensors, Arduino Uno, ESP8266, and GPS.
2. To represent the waste collection network using Graph Theory for efficient route modeling.
3. To prioritize garbage bins using a Max Priority Queue based on fill level, waiting time, and complaint count.
4. To optimize waste collection routes using Dijkstra's Shortest Path Algorithm.
5. To improve waste collection efficiency through real-time monitoring and dynamic route updates.

IV. PROPOSED FRAMEWORK

The proposed framework integrates IoT technology with Graph Theory, Max Priority Queue scheduling, and Dijkstra's Shortest Path Algorithm to improve municipal waste collection. Each garbage bin is equipped with an ultrasonic sensor, Arduino Uno, ESP8266 Wi-Fi module, and GPS unit to continuously monitor the garbage fill level and transmit real-time data to a centralized server.

The server processes the received data and identifies garbage bins that exceed the predefined threshold. These bins are prioritized using a Max Priority Queue based on fill level, waiting time, and complaint count. The road network is represented as a weighted graph, where garbage bins are modeled as vertices and roads as weighted edges. Dijkstra's Shortest Path Algorithm is then applied to generate the shortest collection route for waste collection vehicles. Whenever additional bins reach the threshold, the framework dynamically updates the priority queue and recalculates the optimized route. This integrated approach reduces travel distance, fuel consumption, and collection time while improving the efficiency and scalability of smart waste management systems.

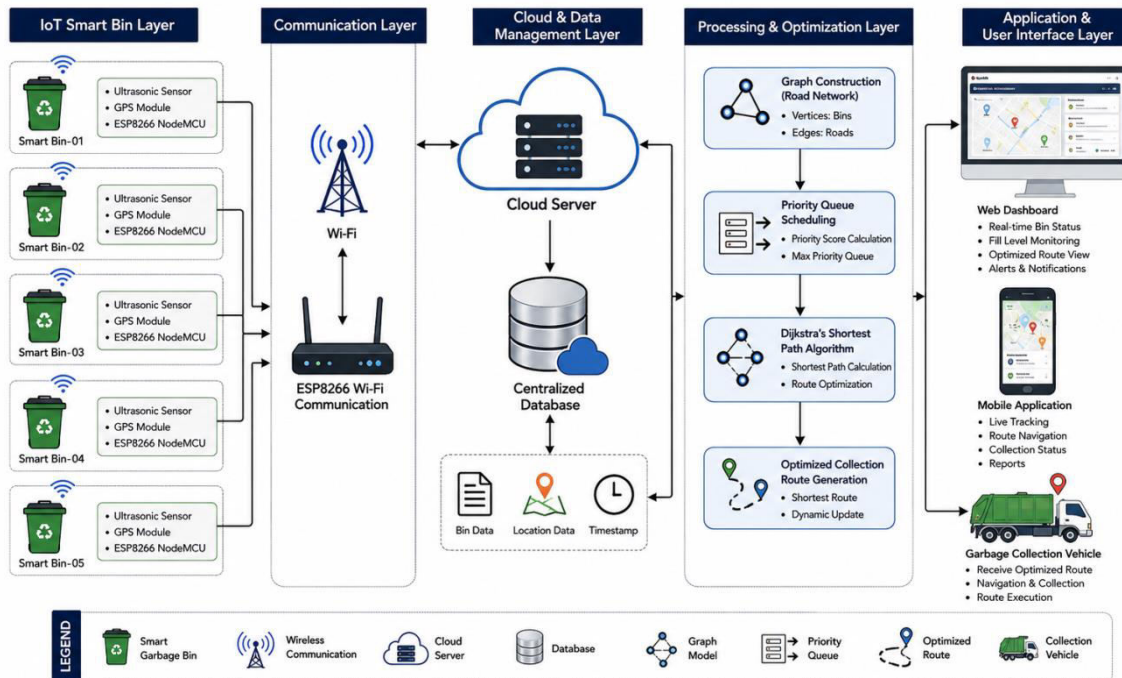


Fig. 1. System Architecture of the Proposed Intelligent IoT-Based Garbage Monitoring and Route Optimization Framework.

Mathematical Model

The proposed framework models the waste collection network as a weighted graph.

Weighted Graph:

$$[1] \quad (1) \quad G = (V, E)$$

where

- V = Set of garbage bins (vertices)
- E = Set of roads connecting the bins (edges)

IoT Data Model: Each garbage bin is represented as

$$[2] \quad (2) \quad B_i = (F_i, T_i, C_i, L_i)$$

where

- F_i = Garbage Fill Level
- T_i = Waiting Time
- C_i = Complaint Count
- L_i = GPS Location

Priority Score: The priority score of each garbage bin is calculated as

$$[3] \quad (3) \quad P_i = \alpha F_i + \beta T_i + \gamma C_i$$

subject to

$$[4] \quad (4) \quad \alpha + \beta + \gamma = 1$$

where α , β , and γ are weighting factors assigned to fill level, waiting time, and complaint count.

Route Optimization: The shortest collection route is obtained by minimizing the total travelling distance.

$$[5] \quad (5) \quad \min \sum w(u,v)$$

subject to

$$[6] \quad (6) \quad P_i \geq P_{th}$$

Only garbage bins with a priority score greater than or equal to the threshold are selected for route optimization using Dijkstra's Shortest Path Algorithm.

Algorithm Design

The proposed framework consists of four major algorithms that work together to improve waste collection efficiency.

Algorithm 1: Graph Construction

The road network is modeled as a weighted graph where garbage bins are represented as vertices and roads are represented as weighted edges. This graph serves as the basis for route optimization.

Algorithm 2: Max Priority Queue Scheduling

Garbage bins are assigned a priority score based on garbage fill level, waiting time, and complaint count. Bins exceeding the predefined threshold are inserted into a Max Priority Queue, ensuring that high-priority bins are serviced first.

Algorithm 3: Dijkstra's Shortest Path Algorithm

The weighted graph and prioritized garbage bins are used to compute the shortest collection route. Dijkstra's Algorithm identifies the minimum-distance path from the collection vehicle to all selected garbage bins, reducing travel distance and fuel consumption.

Algorithm 4: Dynamic Route Update

The system continuously receives real-time sensor data. Whenever a new garbage bin reaches the threshold, the priority queue is updated and Dijkstra's Algorithm is executed again to generate an optimized collection route.

Complexity Analysis:

The computational complexity of the proposed algorithms is analyzed to evaluate their time and space requirements. Table summarizes the complexity of each algorithm.

 ALGORITHM	 TIME COMPLEXITY	 SPACE COMPLEXITY
 Graph Construction	$O(V + E)$	$O(V + E)$
 Max Priority Queue Scheduling	$O(n \log n)$	$O(n)$
 Dijkstra's Shortest Path Algorithm	$O((V + E) \log V)$	$O(V)$
 Dynamic Route Update	$O(k(V + E) \log V)$	$O(V + E)$

V - Number of garbage bins (vertices)

E - Number of roads (edges)

n - Number of garbage bins processed

k - Number of dynamic route update events

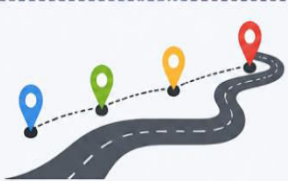


Table 1. Time and Space Complexity of the Proposed Algorithms

Hardware and Software Requirements

HARDWARE REQUIREMENTS		SOFTWARE REQUIREMENTS	
Component	Description / Specification	Software / Tool	Description / Specification
 Ultrasonic Sensor (HC-SR04)	Measures garbage fill level in the bin (Range: 2 cm – 400 cm)	 Arduino IDE	For writing and uploading code to Arduino microcontroller
 Arduino Uno (ATmega328P)	Microcontroller for sensor data processing and control	 Python 3.x	For server-side programming, data processing and algorithm implementation
 ESP8266 Wi-Fi Module	Wireless communication module for sending data to server	 MySQL	Database for storing bin status, location, and system data
 GPS Module (NEO-6M)	Provides real-time location of garbage bin	 Web Application (HTML, CSS, JavaScript, PHP)	For user interface, real-time monitoring, and route visualization
 Power Supply (5V DC)	Provides power to electronic components	 Google Maps API	For map integration and location tracking
 Smart Dustbin Unit	Integrated unit consisting of all hardware components	 Jupyter Notebook (Optional)	For algorithm testing, simulation and analysis
 GPS Enabled Vehicle	Used by waste collection vehicle for route navigation	 Operating System (Windows 10/11)	Platform for development and system execution

Table 2. Hardware and Software Requirements

Working Methodology

The proposed framework performs intelligent waste collection through the following steps:

1. **Data Collection:** Ultrasonic sensors continuously measure the garbage fill level, while GPS modules identify the location of each smart garbage bin.
2. **Data Transmission and Storage:** The Arduino Uno processes the sensor data, and the ESP8266 module transmits the information to a cloud server, where it is stored in a centralized database.
3. **Threshold Evaluation:** The server continuously checks whether the garbage fill level has reached the predefined threshold. If the threshold is not reached, the system continues monitoring. Otherwise, the waste collection process is initiated.
4. **Priority-Based Scheduling:** Garbage bins exceeding the threshold are assigned priority scores based on fill level, waiting time, and complaint count, and are inserted into a Max Priority Queue.
5. **Route Optimization:** The road network is represented using Graph Theory, and Dijkstra's Shortest Path Algorithm computes the shortest route for garbage collection vehicles.
6. **Dynamic Route Update and Monitoring:** Whenever additional garbage bins become full, the priority queue and optimized route are updated dynamically. Municipal authorities monitor the entire process through a web or mobile application.

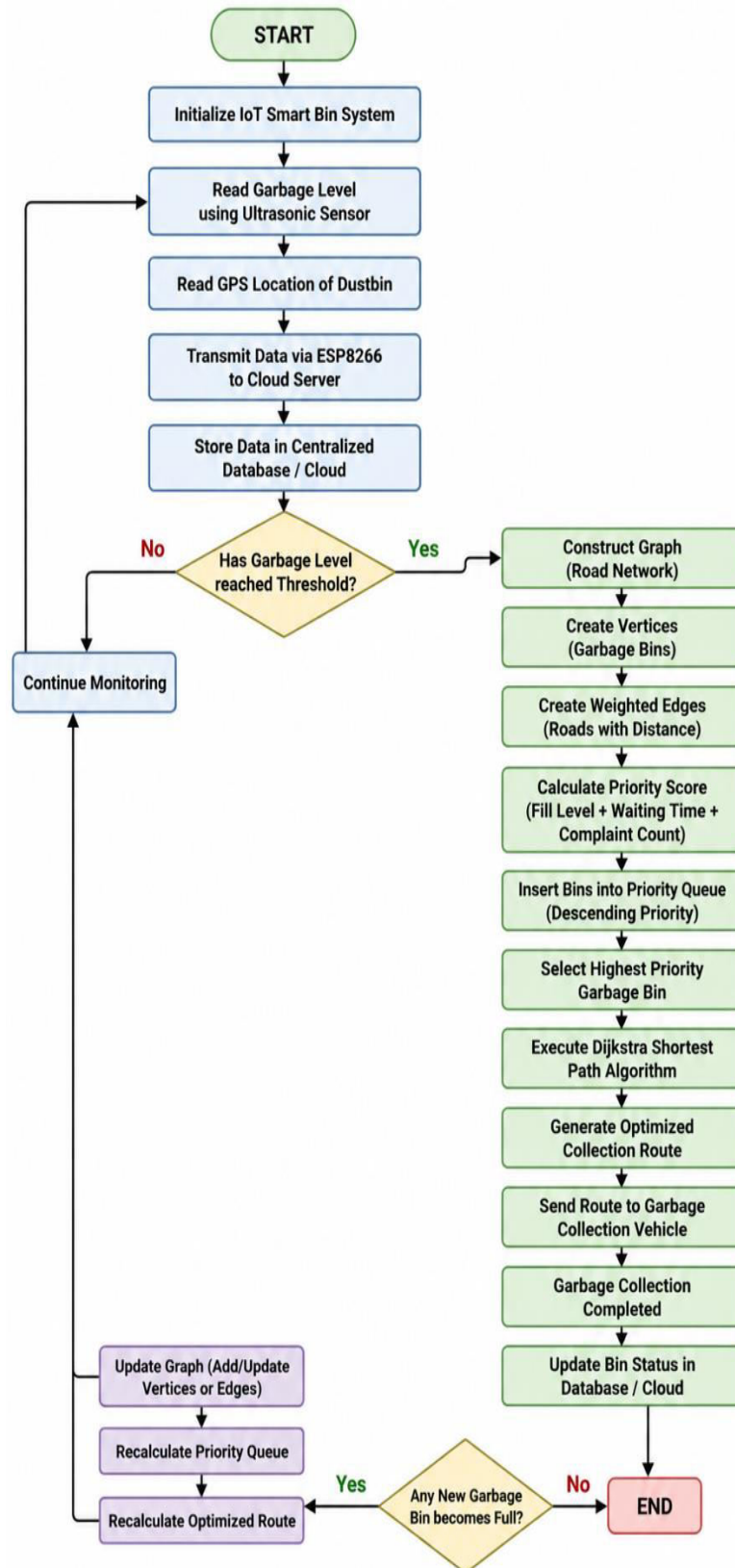


Fig. 2. Flowchart of the Proposed Waste Collection Framework

System Output

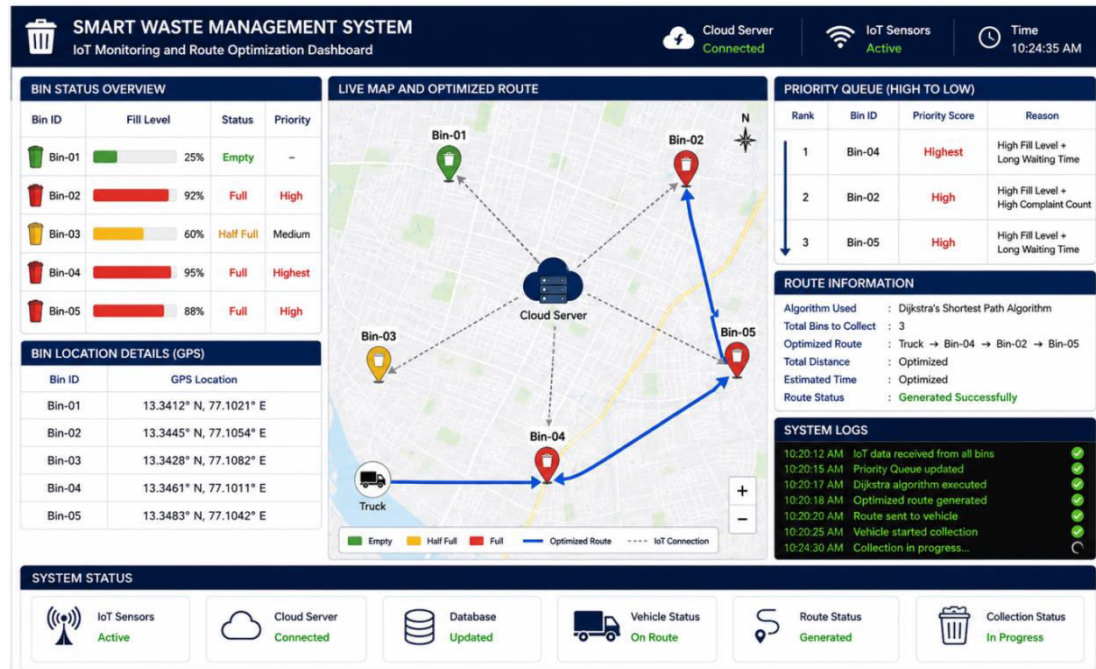


Fig. 3. System Output Dashboard

Fig. 3 illustrates the output dashboard of the proposed intelligent waste management framework. The dashboard displays garbage bin status, optimized collection routes, and priority-based scheduling information.

V. CONCLUSION

The proposed Intelligent IoT-Based Garbage Monitoring and Route Optimization Framework integrates IoT technology with Graph Theory, Max Priority Queue, and Dijkstra's Shortest Path Algorithm to improve municipal waste collection. The framework enables real-time monitoring of garbage bins, prioritizes waste collection based on urgency, and computes optimized collection routes. This integrated approach reduces travel distance, fuel consumption, and collection time while improving operational efficiency. The proposed framework offers a scalable and practical solution for smart city waste management.

VI. FUTURE SCOPE

1. Integrate Machine Learning algorithms to predict garbage generation patterns and optimize collection schedules.
2. Incorporate real-time traffic and weather information for adaptive route optimization.
3. Extend the framework to support multi-vehicle route optimization for large-scale smart city deployments.
4. Develop a cloud-based mobile application for real-time monitoring, reporting, and decision-making.

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