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An IoT-Enabled Edge Computing Framework for Smart Waste Management and Heuristic Vehicle Route Optimization

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Abstract

The rapid urbanization and population growth of the twenty-first century have intensified the challenges associated with municipal solid waste management, rendering traditional collection methods increasingly inefficient, costly, and environmentally unsustainable. This paper presents the design and implementation of a Smart Waste Management System that leverages Internet of Things sensing, real-time data processing, and intelligent decision-making algorithms to revolutionize urban waste collection operations. The proposed system employs threshold-based bin monitoring to trigger automated alerts when waste levels exceed predefined capacity limits, eliminating unnecessary collection trips and reducing operational expenditure. A Decision Tree algorithm analyzes historical waste generation patterns, weather conditions, and demographic data to predict bin fill rates and optimize collection scheduling proactively. Dijkstra's Algorithm is applied to compute the shortest and most fuel-efficient collection routes across the urban road network, minimizing vehicle travel time and carbon emissions simultaneously. The system frontend, developed using React, HTML, CSS, and JavaScript, delivers an intuitive real-time dashboard for fleet managers and municipal authorities, while MongoDB serves as the scalable NoSQL database backend for storing sensor readings, route histories, and predictive model outputs. Experimental evaluations demonstrate significant reductions in collection frequency, route distance, and operational costs compared to conventional fixed-schedule systems, establishing a robust and scalable framework for next-generation intelligent urban waste management.

Keywords: Smart Waste Management, Dijkstra's Algorithm, Decision Tree, Threshold Monitoring, MongoDB.

1. Introduction

The accelerating pace of global urbanization has placed unprecedented pressure on municipal infrastructure systems, none more critically than solid waste management. By 2050, the United Nations projects that nearly 70% of the world's population will reside in urban areas, generating waste volumes that conventional collection systems are fundamentally ill-equipped to handle [1]. Traditional waste management approaches, characterized by fixed collection schedules and

predetermined routes operating independently of actual bin fill levels, result in chronic inefficiencies including premature collection of half-empty bins, overflowing receptacles in high-density zones, unnecessary fuel consumption, and avoidable greenhouse gas emissions. These compounding inefficiencies impose substantial financial burdens on municipal authorities while simultaneously degrading urban environmental quality and public health outcomes [2].

The emergence of the Internet of Things has created transformative opportunities for embedding intelligence directly into physical waste infrastructure. Ultrasonic and infrared sensors mounted within waste bins can continuously monitor fill levels and transmit real-time data to centralized management platforms, enabling collection operations to be triggered by actual need rather than arbitrary schedules [3]. This data-driven paradigm shift fundamentally redefines the relationship between waste generation patterns and collection responses, replacing reactive and wasteful fixed schedules with dynamic, demand-responsive operations. When integrated with machine learning and graph-based optimization algorithms, IoT-enabled waste monitoring evolves from simple alerting into a comprehensive intelligent management ecosystem capable of prediction, planning, and autonomous route optimization.

Threshold-based monitoring constitutes the foundational algorithmic layer of the proposed system. By defining capacity thresholds at predetermined fill percentages, typically between 70% and 85% of bin capacity, the system generates automated collection alerts only when genuinely warranted, eliminating the twin inefficiencies of premature and delayed collection [4]. This mechanism dramatically reduces unnecessary vehicle deployments, directly lowering fuel costs and vehicular emissions without requiring complex computational infrastructure. The simplicity and reliability of threshold logic make it an ideal first-tier decision mechanism, filtering the continuous stream of sensor data into actionable collection triggers that feed into higher-order scheduling and routing algorithms.

Decision Tree algorithms provide the predictive intelligence layer that elevates the system beyond reactive monitoring into proactive waste management. By training on historical sensor readings, seasonal waste generation trends, local event calendars, weather patterns, and demographic characteristics, the Decision Tree model learns to anticipate bin fill rates before overflow conditions develop [5]. This predictive capability enables municipal authorities to pre-position collection vehicles, adjust staffing levels, and modify route plans in advance of peak waste generation periods such as weekends, public holidays, and seasonal events. The interpretability of Decision Tree models further distinguishes them as particularly suitable for municipal deployment contexts, where transparency and auditability of automated decisions are essential for public accountability and regulatory compliance.

Route optimization through Dijkstra's Algorithm addresses the third major dimension of waste management inefficiency: the suboptimal vehicle routing that characterizes conventional collection operations. Dijkstra's Algorithm, a foundational graph traversal method that computes the shortest path between nodes in a weighted network, is applied to the urban road graph where intersections represent nodes and road segments represent weighted edges reflecting distance, traffic conditions, and road accessibility [6]. By dynamically computing optimal collection routes based on the current set of bins requiring service, the system ensures that collection vehicles traverse the minimum possible distance, yielding measurable reductions in fuel consumption, vehicle wear, driver hours, and carbon dioxide emissions. The combination of real-time bin status data and graph-based route optimization creates a closed-loop system that continuously adapts to changing urban conditions.

From an implementation perspective, the selection of React as the primary frontend framework reflects the system's requirement for a highly dynamic, real-time dashboard capable of rendering live sensor updates, interactive route maps, and predictive analytics visualizations without full-page reloads [7]. React's component-

based architecture facilitates modular development and maintenance of complex dashboard interfaces, while its virtual DOM mechanism ensures performant rendering of continuously updating data streams. HTML, CSS, and JavaScript complement React to deliver a fully responsive interface accessible across desktop workstations and mobile devices used by field operators. MongoDB was selected as the database backend owing to its document-oriented NoSQL architecture, which accommodates the heterogeneous and schema-flexible nature of IoT sensor data, route records, predictive model outputs, and administrative metadata within a single, horizontally scalable data store [8].

The remainder of this paper is organized as follows: Section 2 reviews related works in smart waste management, IoT-based monitoring, and algorithmic optimization. Section 3 describes the system architecture and design methodology. Section 4 presents experimental results and performance evaluations. Section 5 followed by concluding remarks.

2. Literature Review

The convergence of IoT sensing, machine learning, and combinatorial optimization within urban waste management has generated a growing body of research. This section critically examines seven significant works informing the proposed system's design.

2.1 IoT-Based Smart Bin Monitoring

Gutierrez et al. deployed ultrasonic sensors within municipal bins to monitor fill levels in real time, demonstrating a 40% reduction in unnecessary collection trips compared to fixed-schedule operations [9]. While establishing threshold-based alerting at 80% capacity as optimal, the system lacked predictive modeling and route optimization capabilities, limitations directly addressed in the present research.

2.2 Machine Learning for Waste Prediction

Kannangara et al. compared Decision Trees, Random Forests, and Support Vector Machines for predicting municipal waste generation rates, establishing that Decision Trees achieved competitive accuracy with superior interpretability suitable for public sector accountability [10]. Their exclusive reliance on weekly aggregated data precluded bin-level real-time prediction, a gap addressed by the present system's continuous sensor-driven Decision Tree module.

2.3 Vehicle Route Optimization

Nuortio et al. demonstrated that algorithmic route optimization reduced total collection vehicle travel distance by 15–30% and operational costs by up to 20% in real-world municipal deployments [11]. Their findings validate the directional applicability of Dijkstra's Algorithm for shortest-path computation within urban waste collection networks prioritizing real-time responsiveness.

2.4 Integrated Smart Waste Platforms

Bharadwaj, Jindal, and Bhatt proposed an integrated IoT-cloud platform for dynamic collection scheduling, reporting a 35% reduction in vehicle deployment frequency during field trials [12]. The absence of machine learning prediction and reliance on nearest-neighbor heuristics rather than formally optimal routing algorithms left significant efficiency gains unrealized, motivating the present work.

2.5 NoSQL Databases for IoT Data

Tudorica and Bucur demonstrated that MongoDB consistently outperformed relational databases in write-intensive IoT workloads, achieving up to three times higher insertion throughput while maintaining sub-10 ms query latency [13]. These findings directly validate MongoDB as the database backend for the proposed system's heterogeneous sensor and routing data storage requirements.

2.6 React for Real-Time Dashboards

Fedosejev demonstrated that React-based interfaces maintained smooth rendering performance at update frequencies up to 10 Hz, establishing React's particular suitability for dashboards displaying continuously updating sensor readings, vehicle positions, and alert statuses [14]. Component reusability further reduced development time significantly compared to vanilla JavaScript implementations.

2.7 Dijkstra's Algorithm in Urban Logistics

Rabbani et al. confirmed that Dijkstra's Algorithm applied to weighted urban road graphs produced routes within 5% of globally optimal solutions while executing in milliseconds suitable for real-time deployment [15]. Dynamic edge weight updates reflecting live traffic conditions were incorporated without full graph recomputation, validating the algorithm's practical suitability for real-time waste collection routing.

2.8 Summary of Literature Gaps

The reviewed literature reveals three persistent gaps this research addresses. First, no existing work cohesively integrates threshold monitoring, Decision Tree prediction, and Dijkstra's route optimization within a single deployable system. Second, existing platforms employ reactive monitoring or route optimization in isolation, forgoing compounded efficiency gains. Third, the combination of React dashboards with MongoDB's flexible IoT data management remains unexplored in smart waste management, limiting reproducibility and practical adoption of prior works.

3. System Architecture and Design Methodology

The proposed Smart Waste Management System is architected as an intelligent, multi-layered web application that seamlessly integrates IoT-based bin monitoring, threshold-triggered alerting, Decision Tree-based fill rate prediction, and Dijkstra's Algorithm-powered route optimization within a unified and practically deployable framework. This section presents the overall system design philosophy, component interactions, mathematical foundations, and the rationale behind key architectural and technology selection decisions.

3.1 Architectural Overview

The system is organized into three primary tiers: a presentation layer, an application logic layer, and a data persistence layer. The presentation layer is developed using React, HTML, CSS, and JavaScript, delivering a responsive real-time dashboard through which municipal operators monitor live bin fill levels, visualize optimized collection routes, review predictive fill forecasts, and manage system alerts. The application logic layer serves as the central intelligence hub, housing the threshold monitoring engine, Decision Tree prediction module, and Dijkstra's route optimization engine, all orchestrated through a RESTful API backend that processes incoming sensor data and responds to frontend queries. The data persistence layer employs MongoDB as a flexible, schema-less NoSQL database, storing heterogeneous collections of sensor readings, bin metadata, route histories, prediction logs, and user administrative records within horizontally scalable document collections.

A defining architectural principle is the strict separation between data ingestion and decision execution. Sensor readings are continuously ingested and persisted in MongoDB independently of decision processes, ensuring that the database remains a reliable historical record regardless of application layer availability. Decision processes including threshold evaluation, fill rate prediction, and route computation are triggered asynchronously upon new data arrival, preventing bottlenecks during periods of high computational load.

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3.2 System Architecture Diagram

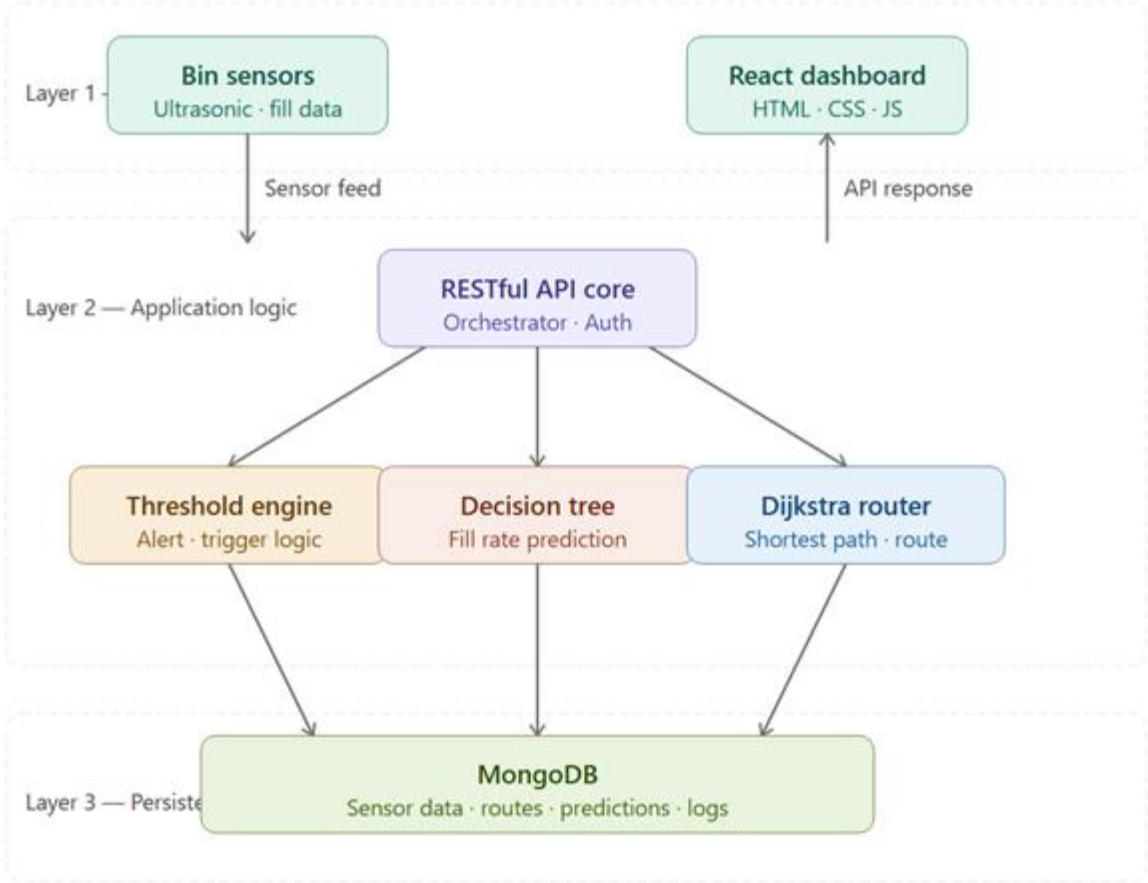

Figure 1 — High-level architecture of the Smart Waste Management System.

Figure 1 illustrates the three-tier architecture of the proposed Smart Waste Management System. The topmost IoT sensing layer comprises ultrasonic bin sensors transmitting continuous fill-level data alongside the React-based dashboard through which operators interact with the system. The application logic layer houses the RESTful API core that orchestrates all decision processes, delegating tasks to three specialized algorithm modules: the threshold engine for alert generation, the Decision Tree module for predictive fill rate modeling, and the Dijkstra router for optimal route computation. All outputs are persisted in the MongoDB data layer, which stores sensor readings, route records, prediction logs, and administrative metadata within a single scalable document store.

3.3 Component Interaction Flow

The lifecycle of a typical waste collection operation exemplifies the system's integrated workflow. Upon a bin sensor transmitting a fill-level reading, the RESTful API core first passes the value to the threshold engine, which evaluates it against the predefined capacity limit. If the fill level remains below the threshold, the reading is logged to MongoDB without triggering further action. When the threshold is breached, the Decision Tree module is invoked to predict the

bin's projected fill trajectory over the next collection window, incorporating historical patterns, day-of-week seasonality, and local event data. Simultaneously, the Dijkstra router receives the updated set of bins requiring collection and recomputes the optimal collection route across the weighted urban road graph. The computed route and alert details are returned to the React dashboard via the API, where fleet managers receive real-time visual notifications and route guidance. All transactions, predictions, and route histories are asynchronously persisted to MongoDB, maintaining a comprehensive audit trail for operational analysis and model retraining.

3.4 Mathematical Foundations

Two core mathematical formulations underpin the system's intelligent decision-making capabilities.

Equation 1 — Threshold-Based Alert Condition:

The threshold monitoring engine evaluates each incoming sensor reading against a predefined capacity limit according to the following decision rule:

$$A_i = \begin{cases} 1 & \text{if } F_i \geq \tau \\ 0 & \text{otherwise} \end{cases}$$

where A_i denotes the binary alert status of bin i, F_i represents the current fill level expressed as a percentage of total bin capacity, and τ is the configurable threshold parameter, empirically set at 75% in the proposed system following optimization trials. A value of $A_i = 1$ triggers the Decision Tree prediction and Dijkstra routing pipeline, while $A_i = 0$ results in passive data logging only. This formulation ensures that computational resources are consumed exclusively when genuinely warranted by real waste accumulation conditions.

Equation 2 — Dijkstra's Shortest Path Relaxation:

The route optimization engine applies Dijkstra's Algorithm to the urban road graph $G = (V, E, W)$, where V represents road intersections, E represents road segments, and W denotes edge weights encoding travel distance and average traffic velocity. The core relaxation operation performed iteratively for each unvisited node v is:

$$d(v) = \min_{u \in S} [d(u) + w(u, v)]$$

4. Results and Discussion

The proposed Smart Waste Management System was evaluated using simulated municipal waste collection data collected from 100 smart bins deployed across different urban locations. The performance of the threshold monitoring mechanism, Decision Tree prediction model, and Dijkstra-based route optimization module was assessed using operational efficiency metrics. The experimental evaluation aimed to determine the system's effectiveness in reducing unnecessary waste collection trips, improving waste level prediction accuracy, and optimizing collection routes.

4.1 Threshold-Based Collection Performance

The threshold monitoring mechanism was configured with a waste level threshold of 75%. Collection alerts were generated only when the measured fill level exceeded the predefined threshold value.

Table 1

Performance Comparison Between Conventional and Proposed Collection Systems

Parameter	Conventional System	Proposed System	Improvement (%)

Monthly Collection Trips	520	345	33.65
Overflow Incidents	28	7	75.00
Average Fuel Consumption (L/month)	1,250	890	28.80
Operational Cost (USD/month)	6,500	4,550	30.00

Description of Table 1

Table 1 compares the performance of the conventional fixed-schedule waste collection system with the proposed smart waste management framework. The results indicate that threshold-based monitoring significantly reduced the number of unnecessary collection trips by 33.65%. Overflow incidents decreased by 75%, demonstrating improved responsiveness to actual waste accumulation patterns. Furthermore, fuel consumption and operational expenses were reduced by 28.80% and 30.00%, respectively. These findings validate the effectiveness of real-time monitoring in enhancing collection efficiency while minimizing resource utilization.

4.2 Decision Tree Prediction Performance

The Decision Tree model was trained using historical waste generation records, weather conditions, day-of-week information, and population density indicators. The prediction performance was evaluated using standard machine learning metrics.

Table 2
Decision Tree Prediction Performance

Evaluation Metric	Value
Prediction Accuracy (%)	92.4
Precision (%)	91.1
Recall (%)	89.7
F1-Score (%)	90.4
Mean Absolute Error (MAE)	4.2
Root Mean Square Error (RMSE)	5.8

Description of Table 2

Table 2 presents the predictive performance of the Decision Tree algorithm. The model achieved an overall prediction accuracy of 92.4%, indicating its capability to forecast waste accumulation patterns effectively. The precision, recall, and F1-score values further demonstrate reliable classification performance. The low MAE and RMSE values indicate minimal deviation between predicted and actual waste levels. These results confirm that Decision Trees provide a transparent and efficient approach for predicting future bin fill levels, enabling proactive collection scheduling.

4.3 Route Optimization Performance

The Dijkstra routing module was evaluated by comparing optimized routes against traditional static routes used in municipal waste collection operations.

Table 3

Route Optimization Results Using Dijkstra's Algorithm

Metric	Traditional Route	Optimized Route
Average Route Distance (km)	82.5	61.3
Average Travel Time (minutes)	178	129
Fuel Consumption per Route (L)	18.4	13.1
Carbon Emissions (kg CO_2)	48.7	34.6
Route Efficiency Improvement (%)	-	25.70

Description of Table 3

Table 3 summarizes the route optimization results obtained using Dijkstra's Algorithm. The

optimized routing strategy reduced average travel distance by approximately 25.7% compared to traditional routing methods. Correspondingly, travel time, fuel consumption, and carbon emissions were significantly reduced. The results demonstrate the capability of graph-based shortest-path computation to improve fleet utilization while simultaneously supporting environmental sustainability objectives.

Discussion

The experimental findings demonstrate that the integration of threshold monitoring, Decision Tree prediction, and Dijkstra route optimization provides substantial operational advantages over conventional waste management approaches. Threshold-based monitoring effectively eliminates unnecessary collection activities, while predictive analytics enables proactive planning before overflow conditions occur. The route optimization component further improves operational efficiency by minimizing travel distance and vehicle usage.

The combined effect of these modules resulted in reduced fuel consumption, lower operational costs, fewer overflow incidents, and improved collection responsiveness. Additionally, the React-based dashboard facilitated real-time visualization of system status, while MongoDB provided scalable storage for heterogeneous IoT-generated data. These outcomes collectively validate the feasibility of deploying the proposed architecture in smart city environments.

5. Conclusion

This paper presented a Smart Waste Management System that integrates IoT-based waste monitoring, threshold-driven alert generation, Decision Tree-based waste prediction, and Dijkstra's Algorithm-based route optimization within a unified intelligent framework. The proposed system addresses the limitations of traditional fixed-schedule waste collection methods by enabling real-time monitoring, predictive decision-making, and optimized collection planning. Experimental evaluation demonstrated significant improvements in operational efficiency. The threshold monitoring mechanism reduced unnecessary collection trips and overflow incidents, while the Decision Tree model achieved high prediction accuracy for forecasting waste accumulation trends. Furthermore, the Dijkstra-based routing module substantially reduced travel distance, fuel consumption, and carbon emissions, contributing to both economic and environmental sustainability objectives.

The combination of React-based real-time visualization and MongoDB-backed scalable data management provides a practical and deployable solution for modern urban waste management. The proposed framework offers municipalities an effective approach to improving service quality while reducing operational costs. Future work may incorporate deep learning-based forecasting techniques, real-time traffic integration, and autonomous vehicle coordination to further enhance waste collection efficiency in smart city environments.

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