

Problem Statement: Smart Waste Bin Network (Virtual IoT Design Challenge)

1. System Architecture

The Smart Waste Bin Network is designed as a comprehensive, end-to-end IoT solution that transforms urban waste management. The system continuously monitors the fill levels of distributed waste bins in real time, allowing collection teams to focus their efforts on bins that actually need emptying. This approach not only conserves operational resources but also reduces unnecessary emissions and improves the cleanliness of city environments.

Sensors and Microcontroller

Each waste bin is equipped with a suite of sensors to ensure accurate, reliable measurements. The primary sensor is an ultrasonic module, positioned within the bin to measure the distance between the lid and the trash. This allows the system to determine the current fill level with high precision. However, since environmental factors like dirt or uneven surfaces can sometimes affect ultrasonic readings, a load cell serves as a secondary measure. By weighing the contents of the bin, the load cell provides redundancy.

The ESP32 microcontroller is chosen for its energy efficiency and integrated Wi-Fi, the ESP32 is ideal for IoT deployments, delivering robust performance while maintaining low power consumption. In large-scale, city-wide implementations, connectivity is further enhanced with LoRa modules, extending communication range far beyond standard Wi-Fi making it possible to reach bins in remote locations without the need for dense infrastructure.

Data Communication

Reliable, scalable communication is essential for a distributed network of this scale. The system leverages LoRaWAN for city-wide deployments, which offer long-range, low-power data transmission critical for maintaining connectivity between hundreds or thousands of bins spread across urban and suburban zones. In densely populated areas where Wi-Fi coverage is strong, the system can switch to Wi-Fi to maximize data rates and reduce operational costs.

Cloud and Edge Computing

Data collected from the bins is first processed locally on the ESP32 microcontroller. This edge processing step acts as a first filter, smoothing out anomalies and reducing noise in the data, which minimizes unnecessary transmissions and conserves bandwidth. Only validated, relevant data is sent to the cloud, where it is securely stored and aggregated.

In the cloud, advanced analytics engines analyse incoming data streams to identify trends, predict maintenance needs, and optimize collection strategies. The system automatically flags bins approaching capacity, detects sensor anomalies, and integrates historical data to forecast future fill patterns. This centralized intelligence allows municipalities to make informed decisions based on both current and predictive insights.

Dashboard & Visualization

All real-time and history data flows into a web-based dashboard, offering a unified view of the entire network. The interface is visual, using color-coded indicators green for empty, yellow for partially filled, and red for full bins to provide instant situational awareness. Municipal staff can easily sort bins by zone, status, or urgency, and interactive maps enable identification of high-priority areas. The dashboard also supports customizable alerts and reporting, empowering administrators to monitor system health, track collection efficiency, and generate documentation for ongoing optimization.

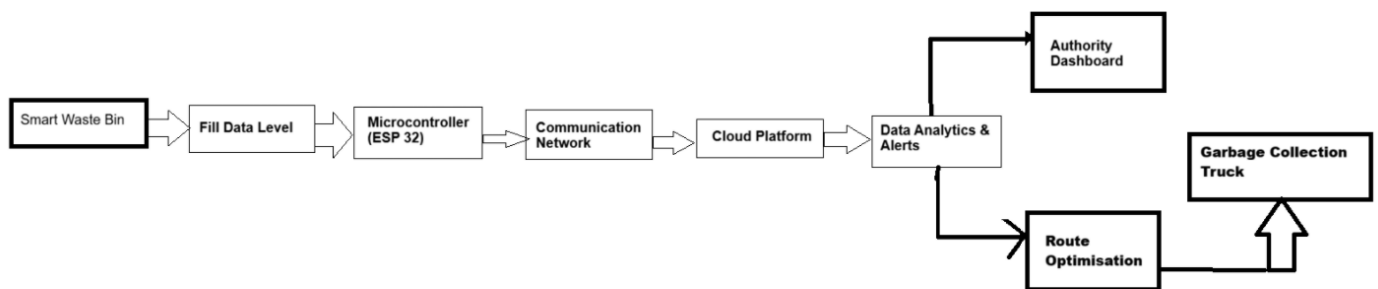


Figure 1

System Architecture

2. Data Flow Design

The system is engineered for efficiency, ensuring that data moves swiftly and reliably from sensor to actionable insight.

The data flow is as follows:

1. Sensors within each bin gather real-time measurements of fill level and weight.
2. The ESP32 microcontroller processes this raw data, calculates the fill percentage, and applies local filters to remove outliers.
3. Cleaned and validated data is transmitted to the cloud
4. The cloud infrastructure collects and organizes all incoming data, building a comprehensive historical record for each bin.

5. Automated analytics modules continuously scan these records, identifying bins that require immediate attention based on configurable thresholds.
6. When a bin approaches or exceeds a set fill level, the system instantly generates alerts, notifying staff or triggering automated responses.
7. The dashboard updates in real time, ensuring that users always have access to the latest information and can respond proactively.
8. Route optimization algorithms draw on the latest bin data, dynamically adjusting collection schedules and routes to maximize operational efficiency.

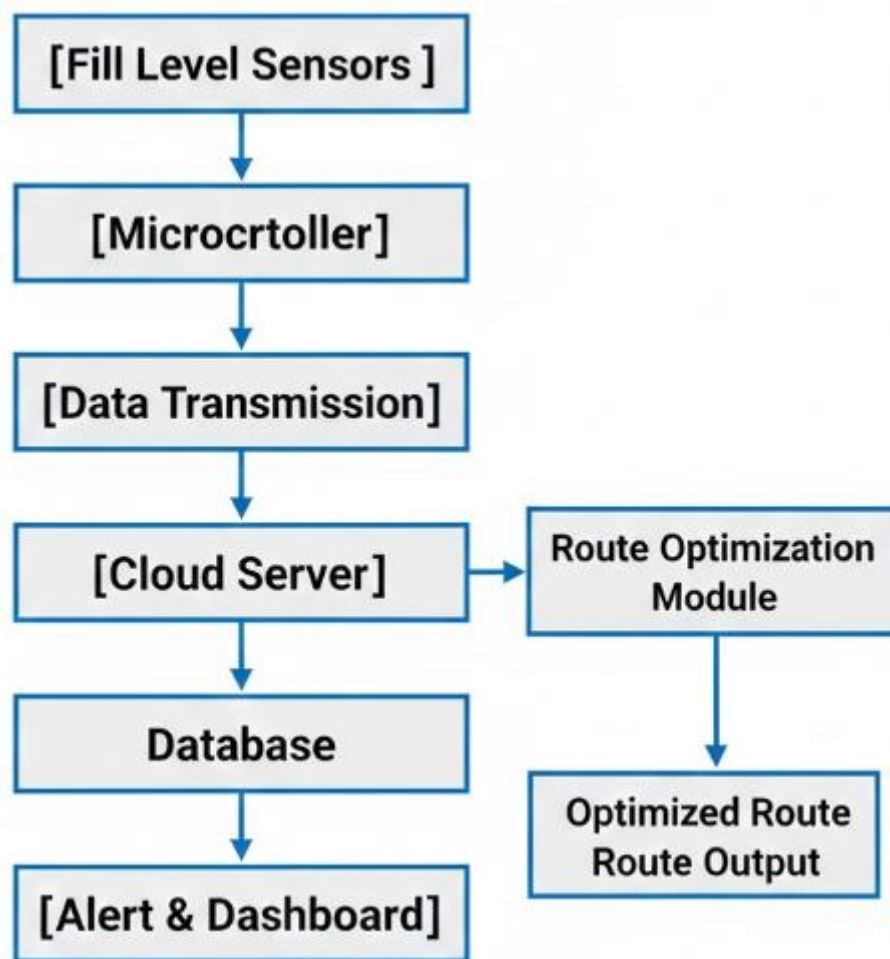


Figure 2

Dataflow Design

3. Route Optimization Strategy

By leveraging real-time data, the system intelligently streamlines the waste collection process, eliminating unnecessary trips and reducing operational costs.

The decision-making logic operates as follows:

- Only bins that are at least 80% full are added to the collection list, ensuring that resources are focused where they are most needed.
- Bins are automatically grouped by geographic zone, minimizing travel distances and preventing inefficient routing.
- If a bin surpasses a critical threshold such as 90% capacity it is prioritized at the top of the pickup schedule, reducing the risk of overflow and associated public health or environmental concerns.
- Advanced routing algorithms, such as Dijkstra's shortest path and clustering techniques, are employed to plot the most efficient routes. These algorithms consider both the proximity of bins and the current status of each collection vehicle.
- The system is also aware of each truck's capacity, ensuring that routes are balanced and vehicles are not overloaded, which could otherwise lead to safety issues or wasted trips.
- As the system receives new data, it dynamically updates routes and priorities, adapting instantly to changes in bin status or unexpected events.

Over time, the system's analytics can reveal patterns and seasonal trends, enabling even greater optimizations and smarter city planning.

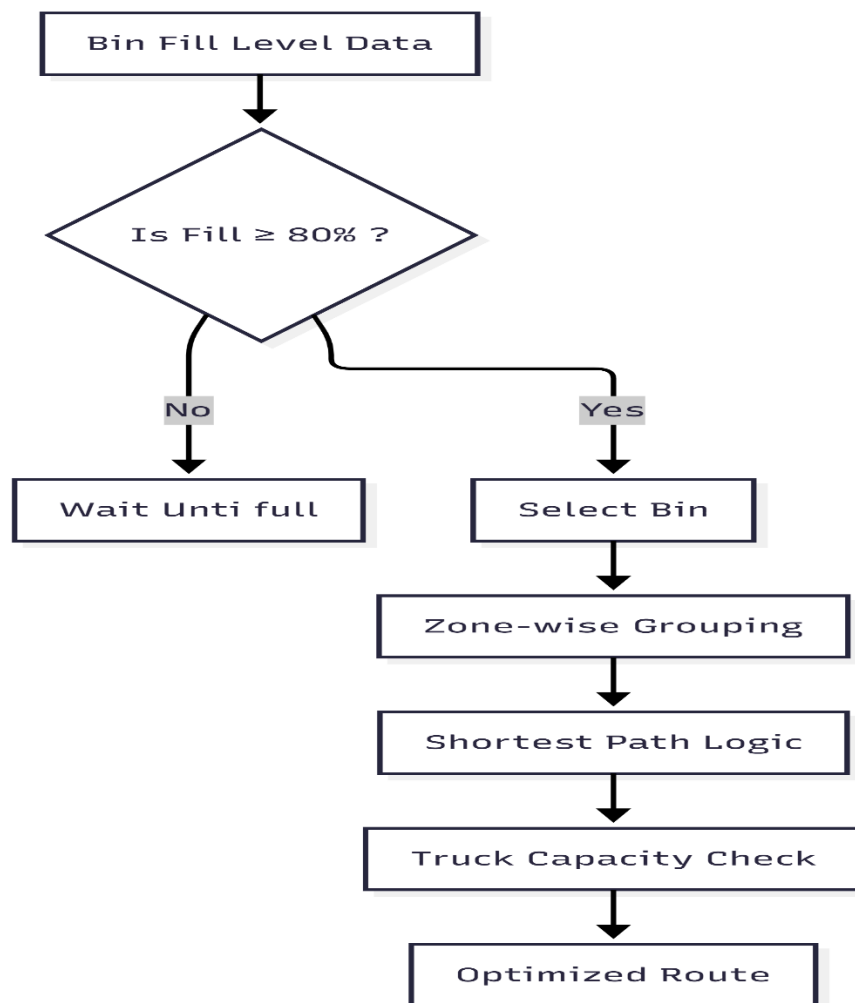


Figure 3

Route Optimization

4. Power Management Plan

Since these waste bins rely on battery power, maximizing energy efficiency is critical for both sustainability and long-term operation. Careful management not only preserves battery life but also minimizes maintenance demands, making the system more practical and cost-effective at scale

Energy Optimization Techniques

To ensure efficient energy use, the sensors inside each bin are programmed to wake periodically such as every 15 or 30 minutes to check fill levels, rather than remaining active around the clock. This interval-based sensing conserves power when the bin is idle. The ESP32 microcontroller, known for its low-power capabilities, spends the majority of its time in deep sleep mode, consuming minimal energy and only activating the system when necessary. Data transmissions are event-driven bins only send updates to the cloud when there is a significant change, like a sudden fill or emptying event, rather than on a fixed schedule. This approach reduces unnecessary wireless communication, which is typically one of the largest sources of power drain.

For data transmission, technologies like LoRaWAN selected for low power requirements and long-range coverage, enabling reliable connectivity without frequent battery replacements. To extend autonomy even further, solar panels can be integrated to recharge batteries, especially in outdoor environments. With solar charging, bins in open locations can operate for years before needing manual intervention, making the system both eco-friendly and self-sustaining.

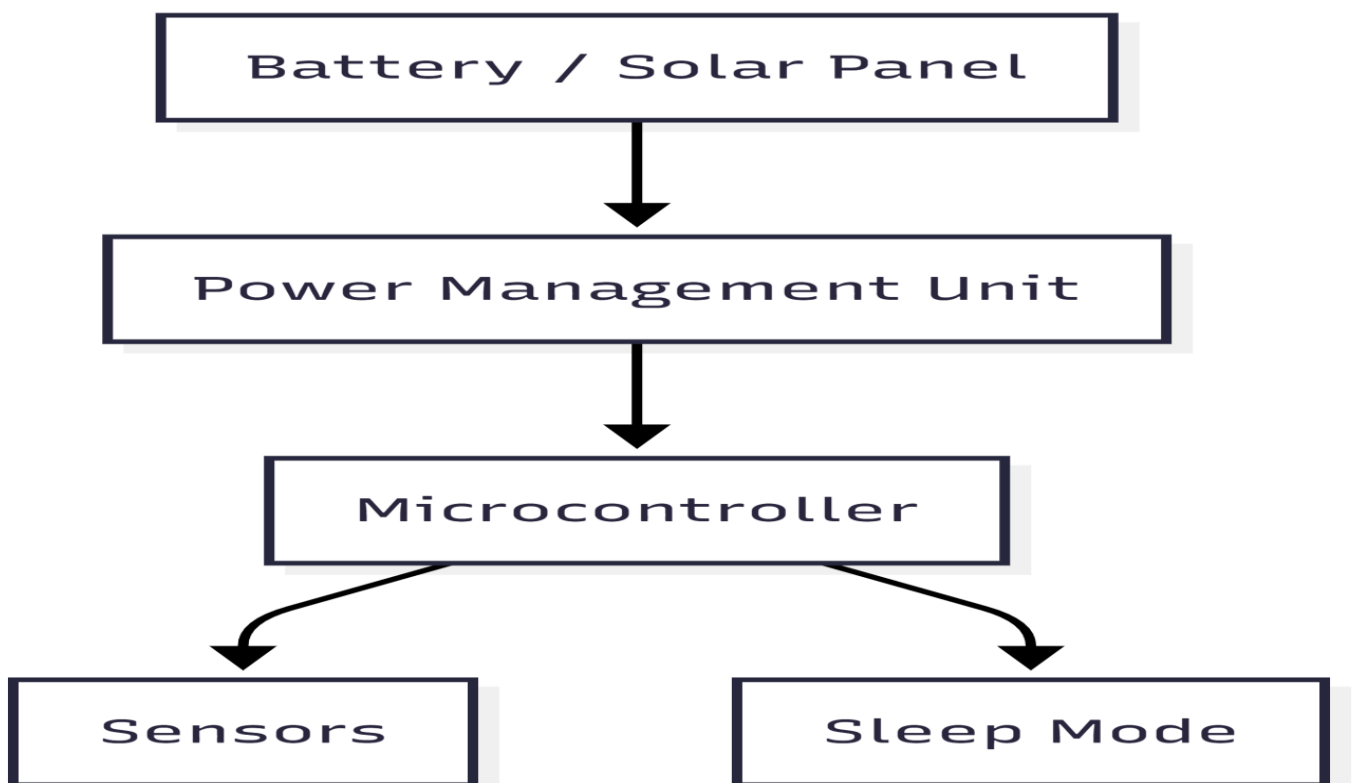


Figure 4

Power Management

5. Reliability & Fault Handling

Real-world deployments are unpredictable, so the system is engineered with robustness in mind. Environmental factors, sensor drift, communication outages, and hardware malfunctions are all anticipated and addressed to maintain reliable operation.

False Reading Mitigation

To minimize false or inaccurate readings, the system employs multiple sensor types typically combining ultrasonic distance sensors with weight sensors. By cross validating data from both, the system can identify discrepancies and compensate when one sensor provides suspect values. Statistical techniques, such as averaging multiple readings and discarding outliers, further improve accuracy. Regular, automated calibration routines ensure sensors remain accurate over time, adapting to environmental changes like temperature or humidity that could otherwise affect measurements.

Fault Handling

When connectivity to the cloud is lost, bins store their data locally, buffering measurements until the network is restored to prevent information loss. In cases where a sensor malfunctions or gives inconsistent data, automated alerts are sent to maintenance personnel, enabling rapid response and minimizing downtime. The system also includes manual override capabilities, allowing maintenance teams to intervene directly through local controls or a dedicated app, ensuring continued service even if automation fails.

6. Scalability & Network Considerations

Scalability Strategy

Cloud-based infrastructure forms the backbone of the system, allowing easy addition of new bins without significant changes to the core software or hardware. Deployments are typically phased, rolling out bins by neighbourhoods or zones, which simplifies logistics and makes it easier to monitor and manage each area individually. The system supports multiple waste collection vehicles operating simultaneously across different routes, enabling efficient city-wide operations and reducing the risk of bottlenecks.

Network Topology

A star network topology is used, where each bin communicates directly with a central gateway or the cloud, rather than relaying messages through neighbouring bins. This approach reduces complexity, lowers the risk of cascading failures, and simplifies troubleshooting. Star topology also helps keep individual bin power consumption low, since bins don't have to forward messages for others. While mesh networks can extend range in some scenarios, their higher power requirements and increased management complexity make them less suitable for battery-powered waste bins deployed in urban settings.

7. Cost & Feasibility Discussion

Approximate Cost per Bin

The overall hardware cost per bin remains low. Sensors and microcontrollers, such as the ESP32, are inexpensive due to widespread adoption and mass production. Communication modules compatible with LoRaWAN or NB-IoT are moderately priced but provide reliable, energy-efficient connectivity. The power system—primarily batteries, with optional solar panels—adds little to the total cost. As a result, the combined setup is affordable enough for large-scale municipal deployments without straining budgets.

Approximate Cost Details:

Component	Purpose	Approx. Cost (INR)
Ultrasonic Sensor	Fill-level measurement	₹150 – ₹250
Weight Sensor (Load Cell)	Redundant validation	₹250 – ₹400
Microcontroller (ESP32)	Data processing & communication	₹400 – ₹600
Communication Module (LoRa / NB-IoT)	Long-range data transmission	₹600 – ₹1,200
Power Supply (Battery Pack)	Bin power source	₹300 – ₹500
Solar Panel (Optional)	Battery recharging	₹500 – ₹800
Protective Enclosure & Mounting	Weather resistance	₹300 – ₹500
Miscellaneous (Wires, PCB, casing)	Integration	₹200 – ₹300
Total Estimated Cost		₹2,700 – ₹4,550

All cost values are approximate and provided for conceptual feasibility analysis. Actual deployment costs may vary depending on scale, vendor selection, and infrastructure availability.

Service	Description	Approx. Cost (INR/Year)
Network Subscription	LoRa/NB-IoT connectivity	₹200 – ₹400
Maintenance	Battery replacement, sensor calibration	₹300 – ₹600
Cloud Services	Data storage & analytics hosting	₹200 – ₹400
Total Annual Operation		₹700 – ₹1,400

Trade-Offs

Choosing higher-precision sensors slightly increases the upfront expense but pays off by significantly reducing the likelihood of false alarms and unnecessary dispatches. Opting for low-bandwidth communication protocols like LoRa or NB-IoT keeps energy consumption and operating costs down, though this limits the volume and frequency of data transmission an acceptable compromise for waste monitoring, where real-time updates aren’t always critical. Cloud-based data processing enables efficient scaling while avoiding the infrastructure and maintenance costs associated with local servers.

Feasibility

The system is designed for phased implementation, allowing cities to start small and expand as needs and budgets permit. Integration with existing waste management practices and municipal software ensures a smooth transition without requiring a complete overhaul of current operations. Over time, data driven route optimization and more efficient collection schedules lead to measurable cost savings, reduced environmental impact, and improved public cleanliness, justifying the initial investment and supporting further expansion.