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Development of a Smart Waste Management System for Route Optimization and Adaptive Demand Management in Dubai

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Abstract

Effective waste management is one of the major elements of urban sustainability, more so in rapidly growing cities like Dubai. This paper presents an overview of the development of a Smart Waste Management System (SWMS) that integrates Geographic Information System (GIS) technology with waste route optimization algorithms and adaptive demand management strategies. The system has four major components: (1) a mobile field application to add and modify collection points in real time; (2) a route optimization module that minimizes travel distance and CO_2 emissions while accounting for real-world constraints; (3) an interactive dashboard for decision-makers to monitor analytics, visualize routes, and make real-time adjustments; and (4) a navigator app for truck drivers to follow optimized routes seamlessly. Furthermore, the system includes a new adaptive waste demand management module, which dynamically updates the demand for each collection point using real-time usage data, rather than being based on static assumptions of capacity. The effectiveness of the system was tested on a sample of 110 collection bins located in three different areas in Dubai. Preliminary results indicate that route optimization alone has achieved a reduction of 19.1% in CO_2 emissions, and further improvement is expected with full implementation of the adaptive demand management module. The findings highlight the potential of intelligent systems to significantly reduce the environmental and financial costs associated with municipal waste collection, paving the way for scalable deployment in other urban environments.

1. Introduction

Effective waste management is a fundamental pillar of urban sustainability, particularly in rapidly expanding metropolitan areas like Dubai. The growth of cities brings about complexities associated with managing the increasing volume of Municipal Solid Waste (MSW) as traditional waste collection systems struggle to adapt to the dynamic nature of urban waste generation, given that they often rely on static schedules and predetermined routes. This system causes an area of inefficiency which not only leads to increased operational costs, but also contributes to higher carbon emissions, traffic congestion, and environmental degradation [1].

With ambitious sustainability goals and smart city initiatives being undertaken in Dubai, it presents an opportunity to explore innovative waste management solutions to contribute to these initiatives [2]. For that, this study introduces the Smart Waste Management System (SWMS), an integrated solution designed to enhance the efficiency and sustainability of municipal waste collection through the application of advanced technologies. This approach will support the needed shift from conventional waste management methods to more intelligent, data-driven approaches.

The SWMS combines Geographic Information System (GIS) technology with route optimization algorithms and adaptive demand management strategies. Its core components include a mobile field application for real-time management of collection points, a route optimization module aimed at minimizing travel distances and carbon dioxide (CO_2) emissions, an interactive dashboard for decision-makers to monitor and adjust operations, and a navigator app for truck drivers to seamlessly follow the optimized routes. The system also incorporates an adaptive waste demand management module that dynamically updates waste collection needs based on real-time data as a replacement for the traditional static capacity assumptions.

In this paper, the development, implementation, and evaluation of the SWMS will be presented with the aim of demonstrating the potential that smart technologies hold in significantly reducing the environmental and financial burdens of traditional waste management practices. Ultimately, the findings contribute to the broader discourse on sustainable urban development and offer insights into scalable solutions for cities worldwide.

2. Literature Review

With the rapid pace of urbanization and population growth, the rates of MSW generation is growing faster than of urbanization itself, which poses significant risk to urban sustainability and positions SWM as a critical issue globally [3]. The World Bank projects that global waste generation will escalate from 2.01 billion tonnes in 2016 to 3.40 billion tonnes by 2050, which quantifies and puts into perspective the urgency for effective waste management strategies that can sustain this demand [4]. This surge in waste production not only strains existing waste management infrastructure but also introduces significant environmental threats, including increased landfill usage, groundwater contamination, and escalating greenhouse gas emissions.

A substantial portion of municipal budgets, estimated at up to 70%, is dedicated to waste collection which is mainly attributed

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to fuel costs and inefficient route planning [5]. Traditional waste collection methods rely on fixed schedules and predetermines routes, which often results in unnecessary trips to bins or collection points that are only partially filled or not yet at their full capacity, This is a source of inefficiency that leads to increased operational costs, fuel consumption, and greenhouse gas emissions [6,7]. These outdated methods also contribute to increased wear and tear on vehicles, higher maintenance costs, and inefficient labor utilization, which highlight the need for optimization techniques that enhance collection efficiency while reducing both financial burdens and environmental impacts.

Optimization models, such as the Vehicle Routing Problem (VRP) and its variant, the Capacitated VRP (CVRP), have been widely employed to improve waste collection routes [8]. Metaheuristic algorithms such as Genetic Algorithms (GAs), Ant Colony Optimization (ACO), and Particle Swarm Optimization (PSO), have all proven to be effective in addressing complex routing problems [9]. However, despite these advancements, data gaps in waste generation patterns limit the effectiveness of optimization efforts. This issue is particularly pronounced in rapidly changing urban environments where waste production patterns can vary significantly. Information and Communication Technologies (ICT) like GIS, GPS, RFID, and GPRS have been instrumental in bridging these gaps to enable more accurate data collection and real-time monitoring of waste generation [10].

SWMS emerged as a transformative solution that integrates IoT technologies, data analytics, and advanced routing algorithms to enhance collection efficiency [11]. Real-world implementations in cities like Amsterdam and Barcelona have demonstrated significant reductions in collection costs by 35% and route efficiency gains of up to 40% [12]. Smart bins equipped with sensors enable real-time monitoring of waste levels to facilitate dynamic route optimization and reducing unnecessary trips [13]. These systems not only improve operational efficiency but also enhance service quality by ensuring timely waste collection and reducing instances of overflowing bins.

The environmental benefits of SWMS are substantial, including a 45.7% reduction in Global Warming Potential, a 52% decrease in vehicle travel distances, and a 46% reduction in resource depletion [14]. These improvements contribute to mitigating the adverse effects of urbanization on climate change and resource consumption. However, there are notable research gaps, particularly in the comprehensive life cycle assessment (LCA) of SWMS, which considers the environmental impacts of electronic components and supporting infrastructure [14]. Moreover, the energy consumption associated with data centers supporting IoT infrastructure raises concerns about the net environmental benefits of smart systems. Additionally, existing optimization models often overlook real-time waste data, leading to inefficiencies in dynamic urban environments where rapid demographic shifts can alter waste production patterns significantly [15].

Addressing these gaps through the development and implementation of innovative systems, such as the SWMS developed in this study, can significantly enhance waste collection efficiency. This paper contributes to the existing body of knowledge by integrating GIS technology with advanced route optimization algorithms and adaptive demand management strategies. The system aims to reduce operational inefficiencies and environmental impacts commonly associated with traditional waste collection methods. The findings from this research will offer valuable insights into scalable smart waste management solutions that can be adapted to other urban environments facing similar challenges.

3. System Design and Overview

The SWMS is designed as an integrated framework that connects various technological components to improve the efficiency, sustainability, and responsiveness of waste collection processes. The architecture of the SWMS is built around five key components: the Mobile Field Application, the Route Optimization Module, the Decision-Maker Dashboard, the Navigator App, and the Adaptive Waste Demand Management Module. Each component plays a unique role while seamlessly interacting with others to form a cohesive system. This section provides a detailed overview of these components, their functions, technologies, and how they contribute to the overall effectiveness of the SWMS.

3.1 Mobile Field Application

The Mobile Field Application, shown in Figure 1, was developed utilizing ArcGIS Field Maps and is designed to streamline the process of adding and managing waste collection points with maximum efficiency and convenience. This application leverages GIS technology to facilitate both on-site and remote data input to make it highly adaptable to the dynamic nature of urban environments.

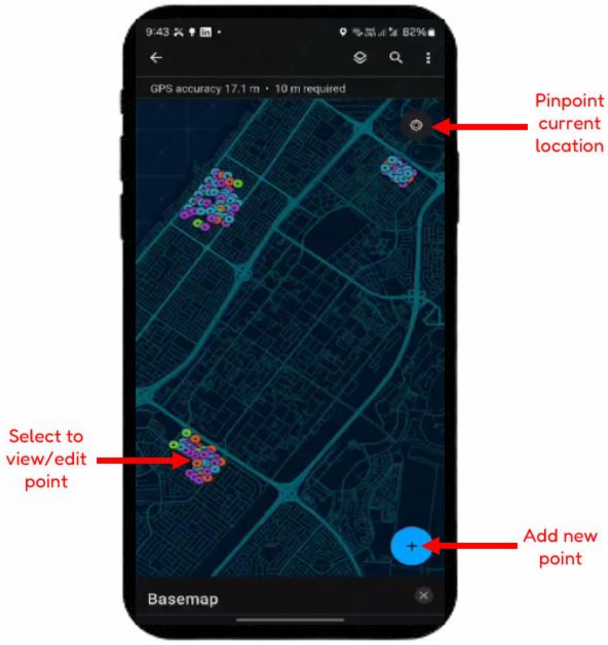


Figure 1: Mobile Field Application interface.

One of the key features of the application is its real-time GPS integration, which allows field operators to automatically detect their current location at a high accuracy when on-site, allowing for precise placement of collection points or waste bin locations. For situations where on-site presence is not feasible, users can manually select pin locations through the interactive map interface, allowing data entry from an office or any remote location. This flexibility supports continuous system updates without requiring physical verification at every site, thus enhancing operational efficiency.

The application is particularly valuable in rapidly expanding urban areas, like Dubai, where new collection points need to be regularly added to accommodate urban growth. When adding a new collection point, users can select from a range of predefined attributes to categorize the waste bin effectively. Options include the bin type (e.g., general waste, recyclables, organic waste), bin capacity, area or any identification number, and priority level based on waste generation rates. Additional metadata, such as the installation date, maintenance status, accessibility conditions, along with any other general remarks can also be recorded to provide comprehensive information for decision-makers.

3.2 Route Optimization Module

The Route Optimization Module within the Smart Waste Management System (SWMS) is powered by RouteSmart for ArcGIS, which is a specialized extension designed to solve complex routing problems with precision and efficiency. RouteSmart is a powerful GIS-based solution that integrates seamlessly with ArcGIS as an add-on to allow for advanced spatial analysis.

At its core, RouteSmart uses sophisticated algorithms to generate the most efficient collection routes with a focus on finding the right balance between minimizing travel distances, reducing fuel consumption, and lowering CO_2 emissions. The system utilizes a heuristic optimization approach that allows it to process large datasets and find near-optimal solutions quickly, even in complex urban environments. This makes it particularly effective for waste management, where variables such as traffic conditions, road restrictions, and collection schedules must be considered.

The route optimization module includes the following key inputs.

- Collection Point Data: Geospatial coordinates of waste bins or collection sites, automatically sourced from the Mobile Field Application.
- Road Network Data: Detailed maps with information on road types, traffic patterns, turn restrictions, and one-way streets.
- Operational Constraints: Factors such as vehicle capacity, service time windows, driver shift limits, and priority levels for specific routes.
- Real-Time Data (Optional): Traffic updates, construction zones, and other dynamic factors that could impact route efficiency.

The algorithm processes these inputs to determine the optimal sequence of stops for each collection vehicle. It considers both of static constraints (like road networks) and dynamic factors (like real-time traffic). RouteSmart applies route balancing techniques to ensure an even or optimal distribution of workload among vehicles, thus reducing operational costs and improving the overall fleet efficiency.

The output includes optimized routes for each collection vehicle as well as a detailed street-by-street report. This report includes directions for every turn and instruction required for drivers to navigate their routes effectively and reach their collection points, dumping site, and back to the main facility with ease.

3.3 Decision-Maker Dashboard

The Decision-Maker Dashboard show in in Figure 2 is the front component of the SWMS. It is designed using ArcGIS Dashboards to provide real-time, data-driven insights to support informed decision-making. This dashboard serves as the central interface for monitoring and managing the waste collection operations to provide a comprehensive overview of system performance through dynamic visualizations and interactive features.

Figure 2: Interactive dashboard interface.

At the center of the dashboard is an interactive map that displays the optimized collection routes generated by the Route Optimization Module. This map is complemented by a range of critical data visualizations, including a bar chart that shows the distribution of waste bins by size, which helps in understanding waste generation patterns across different regions. The dashboard also provides metrics on the total distance travelled by each vehicle, both pre-and post-optimization to allow for direct comparison of efficiency gains from the system's optimization. One of the most impactful metrics displayed is the percentage of CO_2 savings, which is calculated both per route and for the entire system. This provides a quantifiable value that highlights the environmental benefits of the optimized operations.

The dashboard is entirely interactive. For instance, zooming into specific areas or regions automatically updates all displayed statistics to reflect data relevant only to the visible map area. This allows decision-makers to focus on localized performance metrics to facilitate targeted analysis and resource allocation. Moreover, clicking on specific routes or collection points reveals detailed information about those elements, such as bin status, collection frequency, and route efficiency. This data can be viewed, analyzed, or even edited in real-time, allowing decision-makers to make agile, data-informed adjustments as needed.

To enhance usability, the dashboard includes a legend positioned on the right side of the screen, providing clear context for all map icons, symbols, and colour codes. This feature ensures that users can easily interpret the data, improving situational awareness and operational oversight. Overall, this dashboard transforms raw data into actionable insights for the decision-makers, allowing for a more effective management of waste collection processes.

3.4 Navigator App

The Navigator App is an on-site tool developed using ArcGIS Navigator. While the Route Optimization Module's output is efficiently visualized for decision-makers through the Dashboard, operational staff in the field require a more streamlined solution that eliminates the need to read extensive, complex street-by-street reports from Routesmart. The Navigator App bridges this gap by providing truck drivers with a user-friendly, interactive navigation system that is seamlessly integrated with the SWMS.

This app is designed to display optimized routes directly on the truck’s onboard screen to ensure drivers have easy access to real-time, clear, and concise directions. It eliminates the inconvenience of manual route interpretation by offering an intuitive map interface that highlights the driver’s current route and provides turn-by-turn navigation. The app is automatically synchronized with the Route Optimization Module, meaning any updates or changes made by decision-makers in the dashboard are reflected instantly within the Navigator App. This ensures that drivers always have access to the most current route information, even if adjustments are made mid-operation due to factors like traffic disruptions or emergency collection requests.

In addition to navigation, the app features a progress bar that tracks the driver’s journey, from the moment they leave the waste collection facility, through each collection point, to the landfill or waste processing site, and finally back to the facility. This feature offers drivers a clear overview of their progress, helping them manage time effectively and stay on schedule. The app also enhances operational efficiency by reducing the cognitive load on drivers, allowing them to focus on safe driving while following optimized routes.

3.5 Adaptive Waste Demand Management Module

The Adaptive Waste Demand Management Module is a transformative component of the SWMS. It is designed to address the inefficiencies from traditional waste collection practices. Waste bins are normally assumed to have a demand equivalent to their full capacity when assigning collection routes. Although this is a conservative approach, it inaccurately presumes that bins are at 100% capacity every time they are scheduled for collection. This assumption overlooks the fact that waste generation rates are highly variable and are influenced by factors such as population density, seasonal activities, commercial versus residential usage, and even special events that can cause temporary spikes in waste production.

To overcome these limitations, the Adaptive Waste Demand Management Module introduces a dynamic, data-driven approach that measures the actual demand of each bin in real-time. This is achieved through the installation of load cells on collection vehicles that record the change in weight before and after each bin is emptied. The difference in weight directly reflects the true demand for that specific bin at the time of collection. They are matched to the collection point through the sequential order of collection along with the expected timestamp.

What sets this system apart is its adaptive learning capability. Each new demand measurement is averaged with previous data for the same bin to create a continuously updated and increasingly accurate demand profile over time. This ongoing refinement ensures that the system's understanding of waste generation patterns becomes more precise with every collection cycle.

The updated demand data is automatically integrated into the SWMS and real-time reoptimization of collection routes is conducted after each collection event. This creates a continuous feedback loop that ensures routes are always designed for maximum efficiency, reflecting the latest demand information.

The impact of this adaptive approach is substantial. For example, an area that traditionally required five trucks to service based on the conservative demand=capacity model might only need four trucks when actual demand data is applied. This reduction translates to significant savings in fuel consumption, vehicle usage, and labor costs, while also minimizing the environmental footprint associated with waste collection operations.

4. Methodology for System Evaluation

To evaluate the effectiveness of the Smart Waste Management System (SWMS), a comprehensive methodology was developed. The defined methodology allowed for the assessment of the system's performance under real-world conditions as well as controlled scenarios to analyze specific functionalities such as adaptive waste demand management.

4.1 Study Area and Data Collection

The evaluation was conducted across three distinct areas in the UAE: Al Quoz, Umm Suqeim, and Al Barsha. A total of 110 waste bins of varying capacities were identified within these areas. The bins included four different sizes: 240L, 1100L, 2400L, 4500L. Each bin was geolocated and assigned using the ArcGIS Field Maps application. The data was collected on-site and information such as the bin size, area code, specific remarks, as well as a photo was recorded for ease of identification.

4.2 Network Setup and Route Optimization

The collected data was integrated into ArcGIS, where the street network of Dubai was defined along with all necessary constraints for route optimization. These constraints included road restrictions, traffic flow directions, service time windows, and vehicle capacity limits. A fleet of three waste collection trucks, each with an 8m³ capacity, was assumed to cover the designated areas. Route optimization was performed using RouteSmart for ArcGIS to generate the most efficient collection routes considering the given constraints. These optimized routes were automatically synchronized with the Navigator App to provide seamless integration for on-site implementation.

4.3 CO_2 Emissions Calculation

To quantify the environmental impact of the optimized routes, CO_2 emissions were calculated based on diesel consumption. The following assumptions and formulae were used:

- Diesel Consumption Rate: 12.5 km/L for an $8m^3$ truck
- CO_2 Emission Factor: 2.6 kg of CO_2 per liter of diesel

The calculation process involved:

- Total Distance Travelled (per truck) ÷ 12.5 km/L = Liters of Diesel Consumed
- Liters of Diesel Consumed × 2.6 kg/L = CO_2 Emissions per Trip

To evaluate the efficiency of the SWMS, CO_2 emissions were calculated for both optimized routes and unoptimized routes. The unoptimized routes were generated using a traditional Vehicle Routing Problem (VRP) model within ArcGIS Pro, applying the same constraints for a fair comparison. This comparison provided a clear quantification of the CO_2 savings achieved through the implementation of the SWMS.

4.4 Evaluation of the Adaptive Waste Demand Management Module

Since large-scale field evaluation of the adaptive waste demand management module is not practical, its functionality was instead tested on a controlled laboratory-scale environment that simulated real-world conditions.

To do so, a scaled model of a waste collection truck was developed, equipped with a load cell and a load cell amplifier to measure weight variations. The model truck represented actual waste collection vehicles, while small bins filled with marbles (each bin containing seven marbles to represent weight) were used as proxies for real collection points. This setup allowed for a precise measurement of weight changes before and after the simulated waste collection events. The load cell data was processed using a Raspberry Pi microcontroller, which captured the weight differences and calculated the corresponding demand for each bin. Figure 3 shows a snapshot of the experimental setup.

Figure 3: Experimental setup of the scaled waste collection model.

5. Results and Discussion

The implementation of the SWMS demonstrated significant improvements in route optimization and adaptive waste demand management. The optimized routes, as shown in Figure 4, revealed notable reductions in total route distances compared to the unoptimized routes. Specifically, the total distances covered by routes 1, 2, and 3 after optimization were 91.7 km, 84.5 km, and 84.9 km, respectively. In contrast, the corresponding unoptimized route distances were 98.8 km, 105.9 km, and 106.3 km.

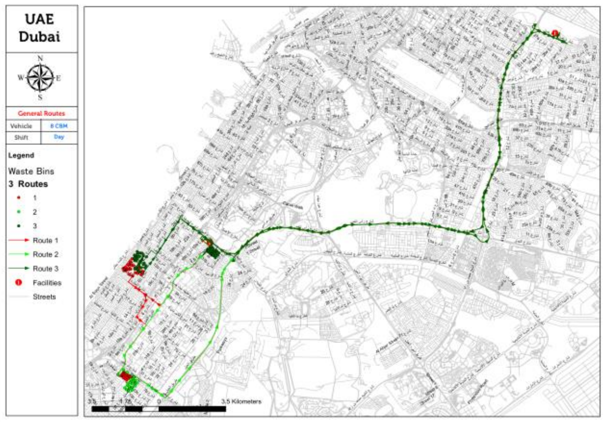
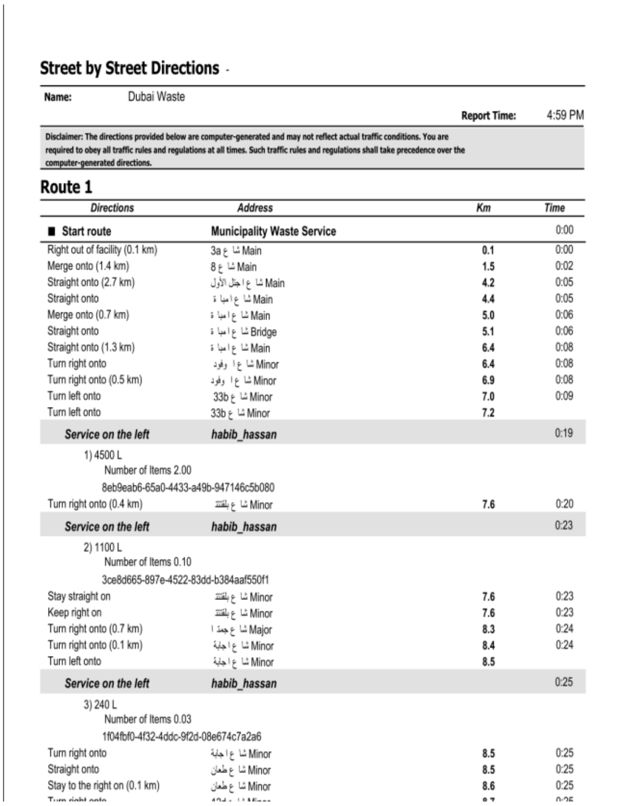


Figure 4: Optimized waste collection routes.

This reduction in travel distances translated directly into substantial CO_2 emissions savings. Using the diesel consumption and emissions calculations previously described, the CO_2 savings achieved for each route were 8.7% for route 1, 25.3% for route 2, and 23.2% for route 3. When averaged across all three routes, the overall CO_2 emissions reduction for the system was 19.1%. These results highlight the effectiveness of the SWMS in not only optimizing operational efficiency but also contributing to environmental sustainability by significantly reducing greenhouse gas emissions. A sample of the street-by-street report is displayed in Figure 5, which describes the directions to be followed by truck 1, also reflected on the navigator app.



Street by Street Directions -

Name: Dubai Waste

Report Time: 4:59 PM

Disclaimer: The directions provided below are computer-generated and may not reflect actual traffic conditions. You are required to obey all traffic rules and regulations at all times. Such traffic rules and regulations shall take precedence over the computer-generated directions.

Route 1

Directions	Address	Km	Time
■ Start route	Municipality Waste Service		0:00
Right out of facility (0.1 km)	3a ع شا Main	0.1	0:00
Merge onto (1.4 km)	8 ع شا Main	1.5	0:02
Straight onto (2.7 km)	الأول ع اجل شا Main	4.2	0:05
Straight onto	ة ع امبا شا Main	4.4	0:05
Merge onto (0.7 km)	ة ع امبا شا Main	5.0	0:06
Straight onto	ة ع امبا شا Bridge	5.1	0:06
Straight onto (1.3 km)	ة ع امبا شا Main	6.4	0:08
Turn right onto	وفود ع ا شا Minor	6.4	0:08
Turn right onto (0.5 km)	وفود ع ا شا Minor	6.9	0:08
Turn left onto	33b ع شا Minor	7.0	0:09
Turn left onto	33b ع شا Minor	7.2	
Service on the left	*habib_hassan*		0:19
1) 4500 L Number of Items 2.00 8eb9eab6-65a0-4433-a49b-947146c5b080			
Turn right onto (0.4 km)	بلقتة ع شا Minor	7.6	0:20
Service on the left	*habib_hassan*		0:23
2) 1100 L Number of Items 0.10 3ce8d665-897e-4522-83dd-b384aaf550f1			
Stay straight on	بلقتة ع شا Minor	7.6	0:23
Keep right on	بلقتة ع شا Minor	7.6	0:23
Turn right onto (0.7 km)	ا جمة ع شا Major	8.3	0:24
Turn right onto (0.1 km)	اجابة ع ا شا Minor	8.4	0:24
Turn left onto	اجابة ع ا شا Minor	8.5	
Service on the left	*habib_hassan*		0:25
3) 240 L Number of Items 0.03 1f04fbf0-4f32-4ddc-9f2d-08e674c7a2a6			
Turn right onto	اجابة ع ا شا Minor	8.5	0:25
Straight onto	طعان ع شا Minor	8.5	0:25
Stay to the right on (0.1 km)	طعان ع شا Minor	8.6	0:25

Figure 5: Sample street-by-street directions for Truck 1.

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The adaptive waste demand management module also produced promising results in the laboratory-scale evaluation. The system successfully recorded the net added weight at each simulated collection stop, along with accurate timestamps, as shown in Table 1. This data will be crucial for dynamically updating the demand associated with each bin in the field. Notably, at stop 2, an intentional variation was introduced by adding 9 marbles to simulate fluctuating waste generation, contrasting with the fixed weight of 7 marbles at the other three stops. The system correctly identified this variation, demonstrating its capacity to adapt to changes in waste demand and providing a solid foundation for scalable real-world applications.

Table 1: Output of adaptive waste demand management test.

Stop	Weight (kg)	Timestamp (s)
Stop 1	0.07	10.35
Stop 2	0.09	20.81
Stop 3	0.07	29.86
Stop 4	0.07	41.24

Overall, the results confirm the SWMS's capability to enhance operational efficiency, reduce environmental impact, and support data-driven decision-making in urban waste management.

6. Conclusion

The development and implementation of the Smart Waste Management System (SWMS) showcased its potential to revolutionize urban waste collection processes through the integration of advanced technologies such as GIS, route optimization algorithms, and adaptive waste demand management strategies. This SWMS demonstrated measurable improvements in operational performance and environmental sustainability while addressing inherent inefficiencies faced through traditional waste management practices.

The system's route optimization module, powered by RouteSmart for ArcGIS, effectively minimized travel distances and reduced CO_2 emissions. The comparative analysis between optimized and unoptimized routes revealed a 19.1% overall average reduction in CO_2 emissions, quantifying the significant environmental benefits that can be achieved through intelligent route planning. The reduction in travel distances also implies cost savings in terms of fuel consumption, vehicle maintenance, and labor, thus enhancing the overall efficiency of municipal waste management operations.

In parallel, the adaptive waste demand management module proved to be a valuable addition to the SWMS. Its ability to dynamically update waste collection demands based on real-time data from load cells on collection vehicles ensures that routes are continuously optimized to reflect actual waste generation patterns. The laboratory-scale evaluation confirmed the system's accuracy in measuring and updating demand data, showcasing its potential for large-scale deployment. This adaptive approach not only reduces unnecessary trips but also optimizes resource allocation, potentially decreasing the number of vehicles required for waste collection.

The dashboard for decision-makers and navigator app for truck drivers further streamlined waste management operations. The dashboard provided real-time analytics and performance monitoring for decision-makers, while the navigator app delivered intuitive, up-to-date navigation support for truck drivers to esure field operations were smooth.

In conclusion, the SWMS represents a significant advancement in sustainable urban waste management. Its successful small-scale deployment in Dubai demonstrates its scalability and adaptability to other urban environments fascing similar challenges. The system not only supports the city's sustainability goals but also sets a benchmark for smart waste management practices globally. Future work should focus on expanding the adaptive demand management module to real-world applications, incorporating additional data sources for enhanced predictive capabilities, and exploring the integration of renewable energy solutions to further reduce the environmental footprint of waste management systems.

References

[1] G.M. Hoang, H.T.T. Ha, N.T.L. Le, and N.D. Toan, "Evaluation of municipal waste collection performance using operational data," *Global Journal of Environmental Science and Management*, vol. 10, no. 1, pp. 69-82, Jan. 2024. [Online]. Available: https://doi.org/10.22034/gjesm.2024.01.06.

[2] A. B. B. Bin Bishr, O. Geary, Z. El Kassis, and M. Al Shaibbi, "Smart Dubai — towards becoming the happiest city on Earth," *A Better World*, vol. 5, pp. 36–37, 2017

[3] M.A. Hannan, Md. A. Al Mamun, A. Hussain, H. Basri, and R.A. Begum**,** "A review on technologies and their usage in solid waste monitoring and management systems: Issues and challenges," *Waste Management*, vol. 43, pp. 509–523, Sep. 2015. Available: https://doi.org/10.1016/j.wasman.2015.05.033.

[4] Silpa Kaza, et al., What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050, World Bank Publications, 2018.

[5] G. Tavares, Z. Zsigraiova, V. Semiao, and M.G. Carvalho, "Optimisation of MSW collection routes for minimum fuel consumption using 3D GIS modelling," *Waste Management*, vol. 29, no. 3, pp. 1176–1185, Oct. 2008. Available: https://doi.org/10.1016/j.wasman.2008.07.013.

[6] Z. Zsigraiova, V. Semiao, and F. Beijoco, "Operation costs and pollutant emissions reduction by definition of new collection scheduling and optimization of MSW collection routes using GIS: The case study of Barreiro, Portugal," Waste Management, vol. 33, no. 4, pp. 793–806, Apr. 2013. [Online]. Available: https://doi.org/10.1016/j.wasman.2012.11.015.

[7] M. Rossi, A. Papetti, and M. Germani, "A comparison of different waste collection methods: Environmental impacts and occupational risks," Journal of Cleaner Production, vol. 368, Article 133145, Sep. 2022. [Online]. Available: https://doi.org/10.1016/j.jclepro.2022.133145.

[8] G. B. Dantzig and J. H. Ramser, "The Truck Dispatching Problem," *Management Science*, vol. 6, no. 1, pp. 80–91, Oct. 1959. [Online]. Available: https://doi.org/10.1287/mnsc.6.1.80.

[9] L. H. Son, "Optimizing Municipal Solid Waste collection using Chaotic Particle Swarm Optimization in GIS based environments: A case study at Danang city, Vietnam," Expert Systems with Applications, vol. 41, no. 18, pp. 8062–8074, Dec. 2014.Available: https://doi.org/10.1016/j.eswa.2014.07.020.

[10] M. Faccio, A. Persona, and G. Zanin, "Waste collection multi objective model with real time traceability data," *Waste Management*, vol. 31, no. 12, pp. 2391–2405, Dec. 2011. Available: https://doi.org/10.1016/j.wasman.2011.07.005.

[11] N. Aloui, W. Almukadi, and A. Belghith, "Towards an IOT Approach for Smart Waste Management based on Context Ontology: A Case Study," *Engineering, Technology & Applied Science Research*, vol. 13, no. 1, pp. 10186–10191, Feb. 2023. [Online]. Available: https://doi.org/10.48084/etasr.5530.

[12] Y. L. Chiew and B. Brunklaus, *Life Cycle Assessment of Internet of Things (IoT) Solution in Södertälje Municipality – A Smart Waste Collection System*, RISE Rapport 2021:91, RISE Research Institutes of Sweden, 2021. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-56756.

[13] M. A. Al Mamun, M. A. Hannan, A. Hussain, and H. Basri, "Integrated Sensing Systems and Algorithms for Solid Waste Bin State Management Automation," IEEE Sensors Journal, vol. 15, no. 1, pp. 561–567, Jan. 2015, https://doi.org/10.1109/JSEN.2014.2351452.

[14] M. Rossi, A. Papetti, and M. Germani, "A comparison of different waste collection methods: Environmental impacts and occupational risks," *Journal of Cleaner Production*, vol. 368, Article 133145, Sep. 2022. [Online]. Available: https://doi.org/10.1016/j.jclepro.2022.133145.

[15] A. Malakahmad, P. Md Bakri, M. R. Md Mokhtar, and N. Khalil, "Solid Waste Collection Routes Optimization via GIS Techniques in Ipoh City, Malaysia," Procedia Engineering, vol. 77, pp. 20–27, 2014. [Online]. Available: https://doi.org/10.1016/j.proeng.2014.07.023.