

OPTIMISING URBAN WASTE MANAGEMENT THROUGH SMART MONITORING SYSTEMS: A CASE STUDY IN ENHANCING EFFICIENCY AND SUSTAINABILITY

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Abstract *This paper illustrates the significant potential of advanced waste management strategies, particularly the implementation of a trash level monitoring system, to enhance urban sustainability and operational efficiency. This research rigorously evaluates the superiority of real-time data-driven systems over conventional waste management practices by leveraging a dynamic model to simulate trash fill levels and employing algorithms to identify optimal collection routes.*

Keywords: trash bin, fill ratio, optimal route, efficiency coefficient

1. INTRODUCTION

In the quest to enhance urban sustainability and operational efficiency within the framework of Smart City development, the implementation of advanced waste management systems emerges as a critical area of focus. Given the escalating urban populations and consumption patterns highlighted by [1], the challenge of managing increasing waste levels is more pressing than ever. The current statistics reveal a staggering 477 kg of municipal waste per capita generated in Europe [2], underscoring the urgent need for efficient waste collection and treatment strategies.

The inefficiencies in current waste management practices, characterised by high transportation costs and the frequent collection of underfilled bins, underscore the necessity for a more effective system. In [3], the variability in municipal solid waste amounts and the complexity in predicting bin fill levels further complicate the optimisation of collection routes. A case study presented in [2] within a Portuguese waste collection company illustrates this challenge, with only 40% of recyclable waste bins being collected at over 75% fill-level over six months. This scenario is not isolated but rather indicative of a widespread issue in waste management operations.

Adopting a trash level monitoring system to address this challenge represents a transformative solution. By harnessing real-time data on bin fill levels, operations managers can significantly enhance productivity, benefiting the company's bottom line and contributing to environmental sustainability by reducing greenhouse gas emissions associated with waste collection. Deploying such systems, complemented by expert in-place systems, could mark a cornerstone in establishing optimal

operational management procedures, thereby revolutionising waste collection processes [4].

The integration of real-time monitoring systems for assessing bin fill levels presents a significant opportunity to enhance the efficiency of waste collection operations by mitigating demand uncertainty. The mere collection of data on waste levels is insufficient; it's the strategic utilisation of this data to optimise collection routes that marks a significant leap forward in operational efficiency. The study from [5] advocates for using modern traceability devices, such as volumetric sensors, to facilitate real-time data acquisition, thereby enabling the optimisation of route plans. This strategy reduces the distance covered and decreases the required vehicles, marking a transition from traditional "blind collection" methods to a more dynamic operation. In the traditional approach, bins are serviced without knowledge of their fill levels along pre-defined routes. In contrast, the dynamic approach leverages real-time fill-level data to define more efficient, flexible routes.

This shift towards "smart collection", as depicted in [2], significantly enhances cost-effectiveness, moving away from static routes to adaptively managed ones based on actual need. This evolution underscores the shift from a one-size-fits-all collection strategy to a more nuanced, demand-driven approach that optimises resource allocation and operational efficiency. While the literature explores various integrated methods, such as analysing the impact of bin location and density on disposal behaviours [6] and employing IoT for intelligent route selection and waste segregation [7], there remains a lack of evidence regarding the efficiency of these management techniques within real-world settings.

This study aims to rigorously evaluate the effectiveness of a trash level monitoring systems compared to conventional waste management approaches. It focuses on their influence on optimising waste management practices in public parks. This investigation is set against the backdrop of promoting sustainable urban environments, where efficient waste management is crucial in enhancing the quality of urban life and environmental health. To achieve this, the paper will explore a variety of scenarios, including the reference case (waste management without any monitoring system) and two cases in which a generic bin's level monitoring system is in place (the fill ratio of all the bins known).

2. MATERIALS AND METHODS

This research was conducted over one month within the central region of "Tudor Vladimirescu" Park, located in District 6 of Bucharest. A total of 18 trash bins were monitored, with their fill ratios systematically recorded daily. The bins, characteristic of those found in Romanian park environments, measure 67 cm in height and 30 cm in diameter. Each is equipped with an easily accessible unloading system, facilitating regular waste collection at the end of each week, regardless of the bin's fill level. Upon each collection cycle's completion, the bins are promptly refitted with new bags, marking the commencement of a new monitoring period. In total, 4 cycles were observed and recorded from the 15th of October, 2023, to the 15th of November, 2023. The spatial distribution of the bins within the study area is depicted in Figure 1.

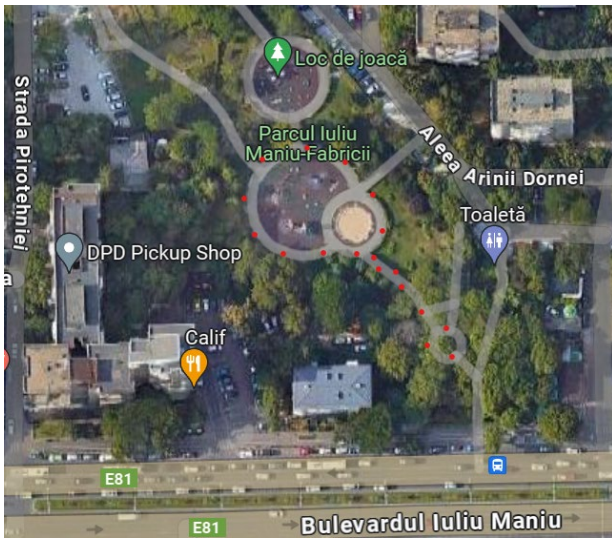


Figure 1. Spatial distribution of the analysed bins (red dots) within "Tudor Vladimirescu" Park

Daily measurements of the trash levels were obtained using a measuring tape, applied externally to the bins, from which the fill ratios were calculated based on the bins' specified volumes (50 litres). These measurements were systematically documented and subsequently illustrated in a weekly plot, as shown in Figure 2.

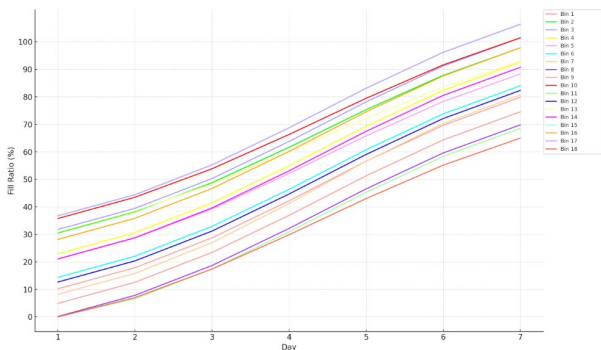


Figure 2. The first week of the trash bins fill ratios

These measurements will serve as the foundational data for developing a mathematical model that represents the bin fill ratio, which is significant for this particular lot. This model will be used to conduct efficiency evaluation scenarios.

The collection process will also be considered for a comprehensive evaluation. Currently, this process is executed by a very narrow garbage collector who navigates through park alleys, with individuals placing garbage bags into the truck. In this study, it will be assumed that the truck visits each bin exactly once and all bins are visited most efficiently (a Hamiltonian path will be employed).

At this stage, the trash level monitoring system is considered generic; any system capable of monitoring the trash level and transmitting this data to a central unit at least once a day is deemed sufficient. Several examples are presented in [3], [4], [7], [8]

3. RESULTS AND DISCUSSIONS

The initial phase of the evaluation process involves developing a dynamic model for the fill ratio of the bins under analysis. Subsequently, the collection process will be modelled and optimised in the latter stage.

3.1. Fill ratio dynamic model

An upper band S growth model [9] will be used based on the collected data. This model assumes that the growth rate decreases as the limit (in this case, the bin's capacity) is reached.

The equation for the model is:

$$P(t) = \frac{K}{1 + e^{-r \cdot (t - t_m)}} \quad (1)$$

where:

$P(t)$ – the amount of trash at time t

K – the maximum capacity of the trash bin (47.33 l)

r – the growth rate

t_m – the curve's inflexion point (the time at which the bin is half full).

Based on the data collected during the initial week, the growth rate and the curve's inflexion point for the generalised model were estimated to serve as an average for the entire lot.

The coefficients were established as $r = 0.62$ and $t_m = 4.4$. The proposed model is represented in Fig. 3.

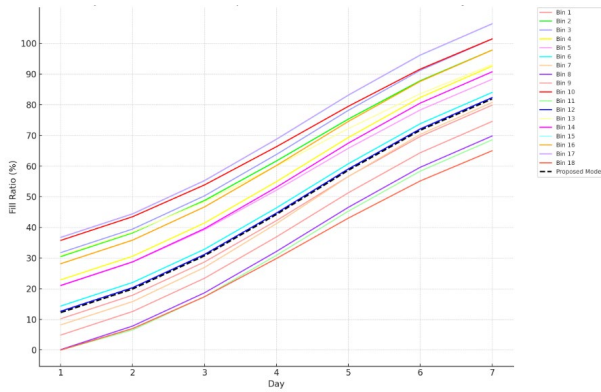


Figure 3. The proposed S growth fill ratio dynamic model

Utilising this model, the period under analysis can be extended, and the actual collection times can yield valuable insights for refining the entire waste management system.

3.2. Collection process evaluation

Considering the current scenario where the collection process is conducted by individual personnel who gather all the garbage bags and place them in a mini truck for an equitable evaluation, it is assumed that this team employs the optimal strategy wherein they visit each bin once and adhere to the shortest path. This assumption is made under the premise that the process will imminently be automated, and a garbage collector robot will undertake the task. This robot is expected to follow this optimal strategy; therefore, it is assumed that the human crew performs identically to establish a correct reference.

A Python script was developed to compute a Hamiltonian path [10] to facilitate this evaluation. A distance unit of 1 was employed for the initial ten bins, whereas for the remaining bins, which are spread over a wider area, a distance unit of 2 was deemed appropriate.

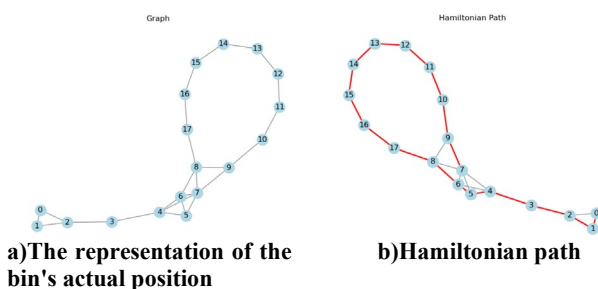


Figure 4. The first week of the trash bins fill ratios

3.3. Reference case

The reference case was established based on the real-world scenario where bins are emptied every seven days, regardless of their fill ratio. Throughout the analysed period, encompassing four cycles, the total volume of garbage was calculated. Subsequently, the volume of

garbage per unit of distance and week was determined using the developed model for the collection process – Fig. 4 a) and b). The reference results were synthesised in Table 1.

Table 1 Reference case

	Week 1	Week 2	Week 3	Week 4	Total
Collected garbage (l)	750.40	773.24	741.11	729.67	2994.42
Path length (units)	26	26	26	26	104
Efficiency coefficient	28.86	29.74	28.50	28.06	28.79

These values serve as benchmarks for assessing the proposed model's efficacy. Upon examining the fill ratio's progression over 7 days for the proposed model—as depicted in Table 2—the cumulative volume across 18 identical bins was calculated to be 710.70 litres. The relative error generated by this model across all observed weeks fluctuates between 2.66% and 8.14%, with a mean error of 5.07%. Such a performance metric positions the proposed model as a viable option for in-depth analysis.

Table 2 Proposed model fill ratio evaluation over 7 days

Day1	Day2	Day3	Day4	Day5	Day6	Day7
10.83%	18.42%	29.57%	43.83%	59.19%	72.95%	83.37%

3.4. Analysed scenarios

New scenarios can now be systematically explored by leveraging the proposed model's insights into fill ratio evolution.

The first scenario envisages extending the collection interval to 14 days, targeting a point where most bins exceed a 95% fill ratio. This adjustment is motivated by observations from a 7-day collection cycle, during which only 11% of the bins reached full capacity, suggesting potential for optimising the collection schedule.

Another scenario analysed involves using a monitoring system to enable a more dynamic and informed collection strategy. In this scenario, the first collection occurs when 50% of the bins surpass the 90% fill threshold, followed by a rest period of at least 4 days. This scenario was performed for one month (4 weeks), and all the bins were considered empty at the end of this period.

Considering the development of the model, the initial collection period was established on day 9. Given the minor variations between bins, only 50% of the bins (located within 1 unit distance) were collected during this initial pickup. Subsequently, after a rest interval of 4 days, another assessment occurs, and the bins not collected during the initial pickup are now scheduled for collection. This cycle repeats two and a half times within a month, reflecting a strategic approach to waste management that adapts to the varying fill rates of the bins.

The obtained results for these scenarios are presented in Tables 3 and 4.

Table 3 Scenario 1 (collection at 14 days) results

	Week 1+2	Week 3+4	Total
Collected garbage (l)	849.72	849.72	1699.44
Path length (units)	26	26	52
Efficiency coefficient	32.68	32.68	32.68

Table 4 Scenario 2 (monitoring system present) results

	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Total
Collected garbage (l)	402.71	424.86	402.71	424.86	402.71	2057.85
Path length (units)	10	16	10	16	10	62
Efficiency coefficient	40.27	26.53	40.27	26.53	40.27	33.19

These two scenarios are compared with the reference case to offer a broader perspective. Scenario 1, which accumulates the smallest amount of trash, indicates that for extended durations, most bins are nearly full, posing a potential health risk. The high-efficiency coefficient observed in this scenario is attributed solely to the reduced collection steps. In contrast, Scenario 2, despite necessitating a higher frequency of collections (totalling five), achieves a superior efficiency coefficient, outperforming the reference case by 13%. This scenario represents an optimal blend of the volume of trash collected and the number of steps per collection, presenting a compelling case for implementing a monitoring system.

4. CONCLUSIONS

This study evaluates the effectiveness of advanced waste management strategies within an urban park over a month, focusing on optimising collection processes to enhance operational efficiency and sustainability. Utilising a dynamic model to track bin fill ratios, two innovative scenarios were compared against a conventional weekly collection schedule. The first scenario extended collection intervals to 14 days, aiming for a high fill threshold to reduce collection frequency. The second scenario implemented a monitoring system to inform collection decisions, targeting bins nearing capacity for efficient routing. Results indicated that while extended intervals minimised collections, the monitoring-based approach significantly improved operational efficiency, demonstrating the potential of smart technologies in waste management.

5. ACKNOWLEDGEMENT

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