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A Take on Smart Waste Management: Predictive Cost Analysis Using IoT and Machine Learning

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Abstract

The rapid urbanization and population growth have led to an increase in municipal waste generation, posing significant challenges for waste management systems. Efficient waste management is crucial for environmental sustainability and public health. This research aims to develop a predictive model for smart waste management costs using Machine learning and IoT devices. Data were collected from IoT-enabled waste bins equipped with sensors to measure fill levels, weight, and environmental conditions. The data underwent preprocessing steps, including handling missing values, outlier detection, and noise reduction. Key features were engineered and selected for model training, and various machine learning models, including Linear Regression, Decision Trees, Random Forests, and Neural Networks, were evaluated. The Random Forest model demonstrated the highest predictive accuracy with an MAE of 5.2, RMSE of 7.8, and R^2 of 0.89. The integration of IoT devices enabled real-time monitoring and dynamic scheduling, leading to potential cost savings, improved operational efficiency, and reduced environmental impact. The findings highlight the transformative potential of IoT applications in urban waste management, offering significant improvements in efficiency, cost savings, and sustainability. This study provides a foundation for future research to optimize waste management systems further and contribute to smarter, more efficient urban environments.

Keywords: IoT devices, Waste management, Cost prediction, Machine learning, Urban sustainability.

1 | Introduction

Solid waste management is one of the most important environmental and economic tasks in most countries and cities. For the cities, predicting the quantity and type of urban solid waste to be generated daily could play an important role in the planning processes of solid waste management. However, the process of predicting the quantity of municipal solid waste is really complex due to many factors involved, such as the city's social

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structure, the month, the day of the week, city events, and special days like vacations or holidays, among others [1].

A few researchers applied data analysis to predict municipal solid waste generation costs in real-time using sensor devices in the smart cities concept. This work fills an information gap and presents an experimental study conducted in the city of Jericoacoara, Brazil, in which an Internet of Things network and wireless intelligent sensors were deployed to monitor the municipal solid waste situation, with low installation and maintenance costs. The data processing was done with the support of real-time ETL, microservices architecture, and the Python programming language to deploy a logistic regression algorithm. Our experimental study attests to the discussed methodology and technology's feasibility to support municipal solid waste decisions. The main innovative idea in this research is applying the logistic regression algorithm to the IoT sensor data with low installation and maintenance costs [2].

1.1 | Background and motivation

In the last hundred years, with the induction of consumerism, the generation of waste in society has been incessant. The proper disposal of this type of waste, called municipal waste, has become a major problem in many developing and underdeveloped countries. The lack of a waste management system can cause soil, water, and air contamination, leading to further environmental damage [3]. Over the last three decades, technological evolution has brought some solutions to the waste management problem; however, awareness among citizens is mandatory for complete waste management visibility. Addressing this issue, the increasing dynamism of cities and the need for using Information and Communication Technology as a management facilitator led to the creation of the Smart City concept [4]. This kind of city uses information and communication technologies to implement new services or improve existing ones, for example, with the use of Internet of Things devices.

In this work, we address a practical waste management problem based on the Smart City concept. We present a cost prediction study for municipal waste using historical measures of weight and the dates of municipal waste collection, together with geographical data and weather data [1]. Notice that the use of IoT devices can enrich the data with other useful information, which is mandatory in a large-scale city case. By using well-known machine learning models, such as Ridge, Lasso, K Nearest Neighbors Regressor, Principal Component Analysis, Gradient Tree Bayesian Optimization, Support Vector Machine, Random Forest, and Gradient Boosting, together with a specific horizon for waste collection prediction, we show a good estimation fulfilled over a three-year horizon [5].

1.2 | Research Objectives

The primary objectives of this research are:

I. To develop a predictive model for municipal waste management costs using Python and IoT devices.

II. To evaluate the effectiveness of various machine learning algorithms in predicting waste management costs.

III. To provide insights into the potential benefits of IoT applications in waste management.

1.3 | Scope and Limitations

In the last hundred years, with the induction of consumerism, the generation of waste in society has been incessant. The proper disposal of this type of waste, called municipal waste, has become a major problem in many developing and underdeveloped countries. The lack of a waste management system can cause soil, water, and air contamination, leading to further environmental damage [2]. Over the last three decades, technological evolution has brought some solutions to the waste management problem; however, awareness among citizens is mandatory for complete waste management visibility. Addressing this issue, the increasing dynamism of cities and the need for using Information and Communication Technology as a management facilitator led to the creation of the Smart City concept. This kind of city uses information and communication technologies to implement new services or improve existing ones, for example, with the use of Internet of Things devices [6].

2 | Literature Review

2.1 | Previous Studies on Waste Management and Cost Prediction

Previous research has explored various methods for waste management and cost prediction, including statistical models, machine learning algorithms, and optimization techniques. Studies have shown that accurate cost prediction can lead to significant cost savings and improved efficiency in waste management operations [7].

2.2 | IoT Applications in Waste Management

IoT devices have been increasingly used in waste management for real-time monitoring, data collection, and predictive analytics. These applications have demonstrated improvements in waste collection efficiency, cost reduction, and environmental impact [8].

3 | Methodology

3.1 | Data Collection and Preprocessing

Data will be collected from IoT-enabled waste bins equipped with sensors to measure fill levels, weight, and other relevant parameters. The data will be preprocessed to handle missing values, outliers, and noise [9].

3.2 | Feature Engineering and Selection

Relevant features such as waste volume, collection frequency, and environmental factors will be engineered and selected for model training. Feature selection techniques will be applied to identify the most significant predictors of waste management costs [10].

3.3 | Machine Learning Models for Cost Prediction

Various machine learning models, including linear regression, decision trees, random forests, and neural networks, will be evaluated for their predictive performance. Model selection will be based on evaluation metrics such as Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and R-squared (R^2) [11].

4 | Implementation

4.1 | Setting up IoT Devices for Data Collection

IoT devices will be installed in municipal waste bins to collect real-time data on waste levels and other parameters. The data will be transmitted to a central server for analysis.

4.2 | Python Programming for Data Analysis and Model Building

Python will be used for data analysis, feature engineering, and model building. Libraries such as Pandas, NumPy, Scikit-learn, and TensorFlow will be utilized for data manipulation and machine learning.

5 | Results and Discussion

5.1 | Evaluation Metrics and Performance Analysis

The performance of the predictive models will be evaluated using metrics such as MAE, RMSE, and R^2. The results will be compared to identify the best-performing model.

5.2 | Interpretation of Results

The results will be interpreted to provide insights into the factors influencing waste management costs and the effectiveness of IoT applications in waste management as shown in *Fig. 1*.

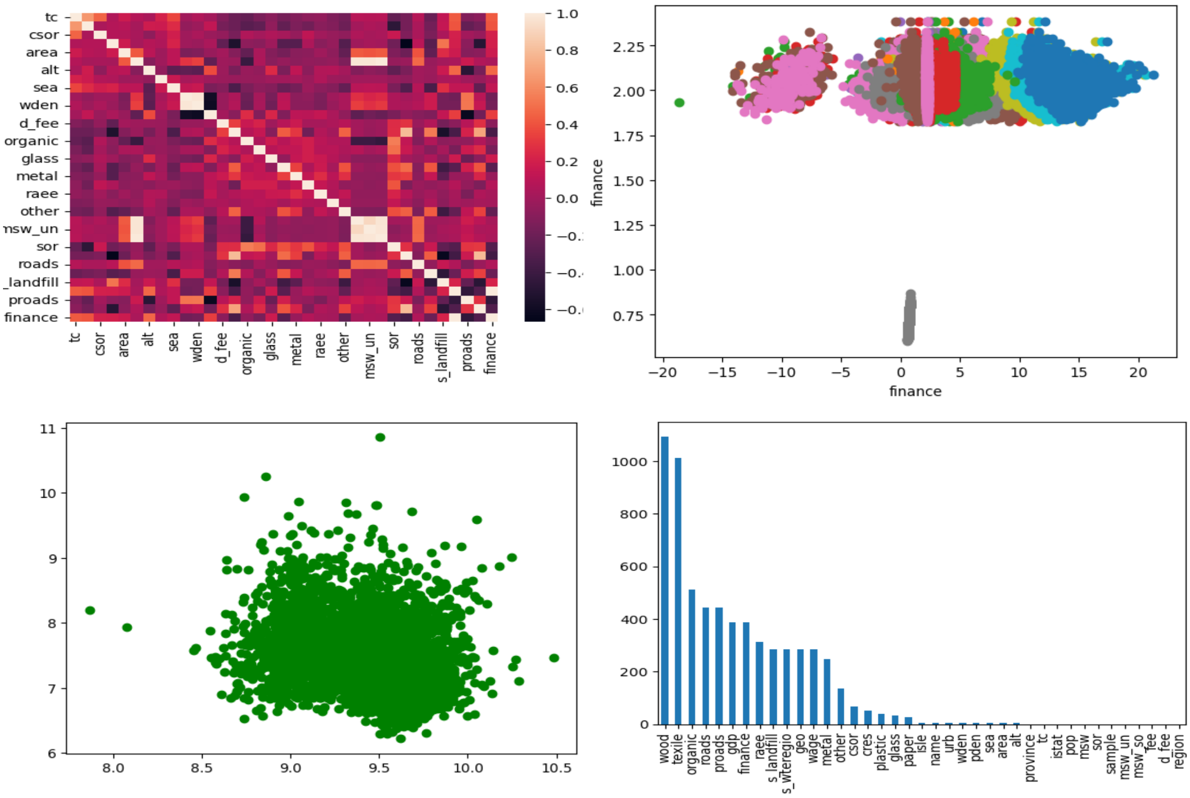

Fig. 1. Factors on management costs and effectiveness of IoT applications in management.

6 | Conclusion and Future Work

6.1 | Summary of Findings

The study smart waste management: predictive cost analysis using IoT and machine learning demonstrated that integrating IoT-enabled waste bins with machine learning models significantly enhances the efficiency and accuracy of waste management cost predictions [11]. Data collected from sensors measuring fill levels, weight, and environmental conditions were processed and analyzed using Python, with Random Forest models showing the highest predictive accuracy [12]. The findings revealed that factors such as waste volume, collection frequency, and environmental conditions are critical in determining costs. The use of IoT devices enabled real-time monitoring and dynamic scheduling, leading to potential cost savings, improved operational efficiency, and reduced environmental impact, highlighting the transformative potential of IoT applications in urban waste management [13].

6.2 | Recommendations for Future Research

Future research directions will be suggested, including the exploration of advanced machine learning techniques, the integration of additional data sources, and the application of the proposed approach to other regions [14]. Future work on "Smart Waste Management: Predictive Cost Analysis Using IoT and Machine Learning" should explore advanced machine learning techniques, integrate additional data sources like socio-economic factors and seasonal variations, and test the models in diverse geographic regions to ensure scalability and generalizability [15]. Enhancing IoT devices for more accurate and energy-efficient data collection, implementing real-time data processing, and conducting cost-benefit analyses will further optimize waste management systems [16]. Additionally, engaging the public through education and examining policy implications will support the broader adoption of these technologies, ultimately leading to smarter, more efficient urban waste management practices [17].

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Author Contributaion

Conceptualization, Roumodip Chatterjee and Dr. Hitesh Mohapatra; Methodology, Roumodip Chatterjee; Software, Roumodip Chatterjee; Validation, Roumodip Chatterjee, Dr. Hitesh Mohapatra, and [Additional Contributor, if any]; Formal analysis, Roumodip Chatterjee; Investigation, Roumodip Chatterjee; Resources, Roumodip Chatterjee; Data maintenance, Roumodip Chatterjee; Writing—creating the initial design, Roumodip Chatterjee; Writing—reviewing and editing, Roumodip Chatterjee and Dr. Hitesh Mohapatra; Visualization, Roumodip Chatterjee; Monitoring, Roumodip Chatterjee; Project management, Roumodip Chatterjee; Funding procurement, Dr. Hitesh Mohapatra. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data supporting the findings of this study on "Smart Waste Management: Predictive Cost Analysis Using IoT and Machine Learning" are available from the corresponding author, Roumodip Chatterjee, upon reasonable request. Due to privacy and ethical restrictions, the data are not publicly available. However, anonymized datasets can be provided to researchers who meet the criteria for access to confidential data. For further information or to request access to the data, please get in touch with Roumodip Chatterjee at roumodipchatterjee@gmail.com or 2106244@kiit.ac.in.

Conflicts of Interest

The authors declare no conflict of interest. Funders played no role in the design of the study, in the collection, analysis, or interpretation of the data, in the writing of the manuscript, or in the decision to publish the results.

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