

Optimization of waste management system and smart garbage collection in large commercial and entertainment complexes with the Internet of Things (Case study: Iran Mall Shopping Center, Tehran)

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ABSTRACT

One of the biggest problems we face in the world today is waste management. Looking at the available statistics, it is predicted that the volume of waste generated in the world by 2050 will reach 3.40 billion tons. Many countries are currently looking at how to recycle this amount of waste. One of the most challenging aspects of managing any city or community is managing the waste generated by consumers, businesses and the public sector. This volume of waste includes 230 million tons of waste and disposable materials each year. While specific efforts to reduce the use of some of the materials used in packaging products may ultimately reduce the amount of waste generated over time, all societies continue to produce waste and will continue to do so. Waste is defined as a combination of recyclable materials, materials destined for landfills and materials that must be carefully disposed of according to their contents.

Managing this waste has traditionally been a manual process, but artificial intelligence (AI) is being used in some communities to reduce the human labor required for this task and, consequently, reduce the costs associated with waste management and processing. By combining a variety of technologies, including machine learning (ML), deep learning (DL), and computer vision, a number of solutions have been proposed that are likely to improve efficiency and productivity in waste management.

Introduction

Waste Classification

One of the ways to utilize artificial intelligence is by training waste sorting robots that can be used at landfills. Instead of requiring workers to sort the waste, these robots are trained using machine learning algorithms to identify and process waste based on its type. These algorithms are trained on images of various types of waste. Using computer vision, the robots can sort the waste in a manner similar to how humans compare waste based on specific characteristics. Most importantly, machines continue to learn over time and become more efficient than humans.

For example, SamurAI, a robotic innovation developed by Machinex, showcased at the Waste Expo 2018, can use artificial intelligence to identify recyclable materials such as cardboard, plastic bottles, and containers. The robot then uses a suction chamber to pick up that waste and place it into the appropriate bin according to the type of waste. According to the company, SamurAI can pick up a maximum of 70 pieces of waste per minute and place them in the suitable waste bin, which is twice as much as what humans can collect.

According to the company, SamurAI can pick up a maximum of 70 pieces of waste per minute and place them in the suitable waste bin, which is twice as much as what humans can collect. This technology can perform the work of two human workers and allows the company to save about \$130,000 a year.

Smart Trash Bins

Smart trash bins are equipped with computer vision sensors to identify the types of waste being thrown into them. For instance, a system developed by Bine.e uses machine learning algorithms to train its designed system to identify and classify the types of waste discarded in the bins, and then sorts the waste into appropriate bins based on its type. In this way, all sorting is done at the point of disposal, eliminating the need for sorting large amounts of waste at a waste processing center.

Additionally, the system can detect when the trash bin is full, thereby optimizing the collection scheduling. Instead of sending garbage collection trucks according to a predetermined schedule, when the bins reach a specified level of fullness, collection routes can be optimized to send trucks only to locations where the bins are full. Such optimization increases the speed of waste collection, reduces labor costs, and lowers fuel expenses.

Waste Classification

Ideally, waste is sorted at the collection point as shown in the example above. However, some waste cannot be separated by the consumer, and for this purpose, the development of artificial intelligence technology is used to perform sorting of low-grade waste. In 2019, TOMRA introduced its GAIN technology, which is a deep learning-based sorting technology designed to perform tasks related to precise and high-capacity sorting. The GAIN technology uses deep learning to eliminate PE silicone cartridges from the polyethylene (PE) stream using computer vision information.

Separating silicone from the cartridges is necessary to ensure the purity of the waste stream. The GAIN technology is fed thousands of images of various types of waste and employs a deep learning system to learn how to connect artificial neurons for object classification. Therefore, this technology can identify various types of silicone cartridges, dual cartridges, and even deformed or partially destroyed cartridges at a faster rate without being explicitly trained on the images of these objects. According to TOMRA, the GAIN system has managed to extract 99% of the cartridges using two systems employed in a sequence.

Improving Efficiency and Reducing Labor Costs

The overall goal of using artificial intelligence in waste management is to address waste at all stages, including disposal at the initial point, during waste collection, and in waste processing plants. By utilizing deep learning, machine learning, and computer vision technology, the processes of waste collection and management can be made more efficient and effective, reducing the labor costs required to carry out these tasks. The mentioned aspects of waste management are just a part of the use of artificial intelligence technology that is likely to enhance the capability of developing smart cities. The application of artificial intelligence in waste management and garbage collection is currently one of the leading and innovative areas that helps improve efficiency, reduce costs, and protect the environment. Below are some of the main applications of artificial intelligence in this field .1:Waste identification and classification Artificial intelligence, using machine vision technologies, is capable of recognizing the type of waste and automatically classifying it. This technology is useful in waste collection centers for separating recyclable and non-recyclable materials .2.Improving the waste collection process By analyzing collected data, intelligent systems can suggest the best collection routes and scheduling, saving time and resources while reducing traffic and costs .3.Predicting waste amounts

AI-based predictive models can estimate the amount of waste generated in each area based on historical data and various indicators, allowing for better planning of collection.

4.Monitoring and managing public waste

Using cameras and intelligent systems to monitor the status of collected waste and identify high-waste areas that require more attention.

5. Smart protocols for garbage collection vehicles

Robotic generators and intelligent vehicles that operate with the help of artificial intelligence have the ability to collect and transport waste with minimal human intervention.

Artificial intelligence in waste management and garbage collection is moving towards efficiency, cost reduction, and environmental protection, playing a significant role in smart cities.

One practical and applicable example of artificial intelligence in waste management is smart waste management systems in large cities, which are currently being implemented in several countries around the world.

Practical example: Smart garbage collection systems in smart cities

Project description: In these systems, waste bins are equipped with smart sensors that measure the fill level of the bin in real-time. These sensors send data to a central control center, which, using artificial intelligence algorithms, determines optimal routes for garbage collection vehicles. How does it work?

Sensors in waste bins collect data related to the volume of waste.

AI-based systems analyze this data to identify areas that need collection the most.

Smart route planning for collection is carried out based on this analysis, instead of emptying all bins at a specific time.

This method reduces unnecessary trips, saves fuel and costs, and decreases the time required for collection.

Real examples:

In Barcelona, smart waste collection systems actively manage waste using smart sensors installed in bins.

In Singapore, the smart city utilizes artificial intelligence and Internet of Things technologies to optimize the collection and sorting process of waste.

If you would like, I can provide more details about the technologies used or other specific examples.

In waste management, various technologies are employed to improve efficiency, reduce costs, and protect the environment. Below, I introduce the most important technologies used:

Internet of Things (IoT) - the use of smart sensors in waste bins to measure their fill levels. Real-time data transmission to a central system for better analysis and planning. Helping to determine optimal routes for waste collection and reduce unnecessary trips.

Artificial Intelligence (AI) - analyzing collected data to predict waste generation in different areas.

Automatic sorting and categorization of waste in recycling centers using machine vision technologies.

Smart planning of collection routes and waste management.

Computer Vision - identifying types of waste and automatically sorting recyclable materials.

Monitoring and supervising the status of bins and their surroundings.

Data mining and big data analytics - analyzing vast amounts of waste production data to formulate policies and strategic planning. Improving waste management processes by analyzing historical trends and future predictions.

Robots and smart machines - using waste collection robots in crowded and difficult locations.

Autonomous systems for waste collection and transportation.

Smart Waste Management Systems are centralized management software for monitoring, analyzing, and controlling the processes of waste collection, sorting, and recycling. They control and improve the waste supply chain.

These technologies have led urban and industrial waste management systems to move towards smart solutions and greater efficiency, ultimately resulting in reduced pollution, cost savings, and better environmental protection.

The fundamental problem statement of the research generally includes the description of the problem and its introduction, the statement of unknown and ambiguous aspects, the relevant variables, and the purpose of the research.

The rapid growth of urban populations and changing consumption patterns have led to the production of massive amounts of waste worldwide, making proper management of it one of the fundamental challenges of modern societies. This challenge is particularly evident in large commercial and recreational complexes due to the high concentration of human activities and the diversity of business units. These centers act like small cities, hosting thousands of visitors and employees daily, resulting in a significant volume of various types of waste, including

recyclable dry waste (paper, plastic, metal, glass), wet waste (mainly from restaurant and food court sections), and special waste (such as electronic waste or certain chemicals from specific service units) (Sadeghi et al., 2022). Iran Mall in Tehran, as one of the largest commercial-recreational complexes not only in Iran but also globally, with its vast area and diverse uses, is a prominent example of this issue, facing multiple challenges in waste management.

Traditional waste management systems in such complexes are often based on fixed schedules for collection, without considering the actual fullness of the bins. This approach leads to multiple inefficiencies: on one hand, bins may be emptied before they are completely full, resulting in wasted resources (human labor, fuel for collection vehicles, time), and on the other hand, overflowing bins cause health problems, unpleasant odors, and damage to the visual appearance of the complex (Ahmadi and Ghasemi, 2023). Furthermore, effective source separation does not occur, and a significant portion of recyclable materials ends up in landfills along with other waste, losing economic and environmental recycling opportunities. The high costs of collection, transportation, and disposal of waste impose a significant financial burden on the management of these complexes, and the lack of optimization of these processes affects their profitability and operational sustainability.

The unknown and ambiguous aspects in this area mainly relate to how to implement an integrated smart waste management system on a very large scale in a commercial-recreational complex like Iran Mall. Although Internet of Things (IoT) technology has shown great potential for transformation in this field (Gupta et al., 2023), its practical application and comprehensive performance evaluation in such complex environments come with specific technical, operational, economic, and even cultural challenges. For example, determining the optimal number and location of smart bins, selecting appropriate communication technologies to cover the entire complex, developing intelligent algorithms for optimal routing of collection vehicles, integrating data from sensors with existing management systems, and training and engaging users (tenants and visitors) are among the issues that require careful examination and tailored solutions to the specific conditions of Iran Mall. Additionally, a precise assessment of the cost reductions, improvements in operational efficiency, and environmental impacts resulting from the implementation of such a system in a real case study has not yet been fully clarified.

The main variables in this research include the independent variable "implementation of an intelligent waste collection system based on the Internet of Things" and the dependent variables "operational efficiency of the waste management system" (including indicators such as reduction in collection costs, reduction in collection time, reduction in unnecessary collection frequency, increase in recycling rates), "environmental impacts" (such as reduction in greenhouse gas emissions from transportation, reduction in landfill waste volume), and "stakeholder satisfaction" (including management of the complex, business units, and visitors). Moderating factors may also include the existing technological infrastructure in the complex, the level of awareness and cooperation of users, and management policies. In this research, the Internet of Things refers to a network of waste bins equipped with fill-level sensors, waste type identification systems (if possible), and communication modules that send data to a central platform, enabling real-time monitoring, data analysis, and dynamic planning for collection (Li and Chen, 2023).

The purpose of this research is to conduct a comprehensive study and present an optimal model for waste management and intelligent waste collection systems in large commercial and recreational complexes, focusing on a case study of Iran Mall in Tehran, using Internet of Things technology. This study aims to identify the challenges of the current system and assess the potential of new technologies to provide practical solutions for increasing efficiency, reducing costs, and improving environmental indicators. This research not only seeks to analyze the

current situation and identify its weaknesses but also aims to propose an implementation framework for the intelligent system by leveraging global experiences and adapting them to local conditions. This framework will include selecting appropriate technologies, designing system architecture, developing optimization algorithms, and conducting economic and technical evaluations of the plan.

One important aspect of this research is the focus on the very large scale of Iran Mall. Waste management in such a space, with diverse uses (stores, restaurants, recreational areas, hotels, parking lots, etc.) and high traffic volume, has its own complexities. The proposed intelligent system must be capable of responding to these complexities and have the necessary flexibility to adapt to changing waste production patterns in different locations and at different times (Rogers and Smith, 2022). This requires a thorough analysis of data related to waste production and the identification of its temporal and spatial patterns to optimally locate sensors and smart bins and intelligently manage collection processes.

Another topic is examining how to create motivation and engage all stakeholders, including tenants of commercial units, service staff, and even visitors, in the success of this system. Source separation and proper use of smart bins require education, information dissemination, and possibly the establishment of incentive mechanisms. This research will also explore cultural and managerial strategies to increase user acceptance and cooperation with the new system. This aspect of the research is very important because the success of any technological system depends on the acceptance and proper use by its end users (Parker et al., 2023).

Additionally, this research will investigate the technical challenges associated with implementing the Internet of Things in a large enclosed environment like Iran Mall. Issues such as network coverage, data security, sensor reliability, and integration with other existing smart systems in the complex (such as building management systems or BMS) are among the matters that need to be carefully considered. Choosing the appropriate software platform for data analysis and providing management reports will also be an important part of this investigation. The goal is to provide a comprehensive solution that is not only technically feasible but also economically justifiable and offers a suitable return on investment for the complex management.

Ultimately, this research aims to provide a conceptual and operational model for optimizing the waste management system in Iran Mall, serving as a model for other large commercial and recreational complexes in the country and even the region. The results of this research can significantly assist managers of these centers in decision-making regarding investments in smart technologies and moving towards more sustainable waste management. This study will offer a roadmap for digital transformation in the waste management of such centers by accurately identifying needs, opportunities, and limitations, and will help clarify the role of the Internet of Things in achieving sustainable development goals at the urban level.

The unknown and ambiguous aspects of this research include the precise impact of cultural and social variables on the acceptance of new technologies in waste management within an Iranian commercial complex of this scale, as well as how to adapt successful global models to the specific infrastructures and limitations of Iran Mall. Additionally, a thorough economic evaluation and long-term cost-benefit analysis of implementing such a system requires the collection of real data and complex modeling, which are part of the challenges of this research. This study seeks to address these unknown aspects with a scientific and evidence-based approach, providing practical and executable solutions.

The importance and necessity of conducting this research can be examined from several angles. First, the growing problem of waste production and the inefficiency of traditional management systems in large human gathering centers is a global and national challenge. Large commercial and recreational complexes like Iran Mall play a significant role in this challenge due to their high volume of activity and waste production. Therefore, finding innovative and efficient solutions for waste management in these centers not only helps improve environmental and health conditions but can also serve as a model for other similar centers (Rahimi et al., 2022). This research, focusing on one of the largest shopping centers in the world, can provide valuable insights into the challenges and opportunities of implementing smart systems on a large scale.

Second, there is a clear research gap regarding the comprehensive application of the Internet of Things for optimizing waste management in very large commercial-recreational complexes in Iran. Although numerous studies globally have addressed the topics of smart cities and smart waste management (such as the studies by Kumar and Singh, 2023), domestic research has often been either theoretical or focused on smaller scales (such as a city area or an organization). The case study of Iran Mall, with its unique characteristics in terms of size, diversity of use, and volume of waste produced, provides an exceptional opportunity to fill this research gap and localize technical knowledge in this field. There may also be disagreements regarding the actual effectiveness of IoT technologies compared to the initial implementation and maintenance costs in such complexes, which this research aims to clarify.

The urgent need to reduce operational costs and increase efficiency in managing large complexes like Iran Mall makes this research even more significant. The costs associated with the collection, transportation, and disposal of waste constitute a substantial portion of the ongoing expenses of these centers. Implementing an intelligent system can lead to significant savings in these costs by optimizing collection routes, reducing unnecessary emptying frequencies, and increasing recycling rates (Abdollahi and Mohammadi, 2023). This research, by providing a precise cost-benefit analysis, can clarify the economic justification for investing in this technology for the managers of Iran Mall and other similar complexes.

The benefits of this research are extensive both theoretically and practically. Theoretically, this study will contribute to the development of knowledge in the field of smart waste management, the applications of the Internet of Things in large commercial environments, and the modeling of complex systems. The conceptual framework and optimization model presented in this research can serve as a basis for future studies in this area. Practically, the results of this research will be directly applicable to the management of Iran Mall, assisting them in decision-making to improve their waste management system. Additionally, these results could be beneficial for other commercial and recreational complexes, municipalities, and companies active in urban services and waste management, promoting sustainable and technological solutions in the country.

Furthermore, this research can utilize innovative research processes and methods. For instance, using simulation to evaluate various scenarios for implementing the intelligent system before actual execution, collecting real-time data through a small pilot of smart bins in part of Iran Mall, and analyzing this data using machine learning algorithms to predict waste generation patterns and optimize collection processes could be some of the innovative methodological aspects of this research. Additionally, combining qualitative research methods (such as in-depth interviews with stakeholders and field observations) and quantitative methods (such as analyzing sensor data and questionnaires) will contribute to a more comprehensive understanding of the issue and provide more practical solutions (Zhang and Liu, 2024).

Ultimately, given the increasing emphasis on environmental issues and sustainable development, optimizing waste management is an undeniable necessity. This research, focusing on reducing waste generation at the source, increasing segregation and recycling, and minimizing the harmful effects of waste on the environment (such as reducing greenhouse gas emissions from less transportation and decreasing soil and water pollution from improper landfilling), directly aligns with sustainable development goals. Presenting a successful and replicable model at Iran Mall could be a significant step towards moving the country towards a circular economy and a society with less waste, demonstrating how modern technologies can serve the protection of the environment and enhance urban quality of life.

Review of literature and related backgrounds (a brief statement of the research background conducted inside and outside the country regarding the research topic and their results, as well as a review of the literature and theoretical framework of the research)

Domestic Research:

Hosseini et al. (2023) in their research examined the challenges and solutions for implementing smart urban waste management in the metropolis of Tehran and concluded that the lack of technological infrastructure, the need for high investment, and the low level of citizen participation are the main obstacles. However, the use of sensors and data analysis can significantly improve the efficiency of collection.

Rezaei and Akbari (2023) in their research investigated the technical and economic feasibility of using smart waste bins in a municipality area of Mashhad and concluded that despite the initial costs, the reduction of operational costs in the long term and the improvement of health and environmental conditions make this project justifiable.

Sadeghi-Nia et al. (2022) in their research examined the role of information technology in optimizing reverse logistics and managing electronic waste in large companies and concluded that tracking systems and integrated information platforms can significantly facilitate the collection and recycling processes of this type of waste.

Norouzi and Ghasemi (2022) in their research studied the factors influencing the acceptance of smart city technologies by citizens, focusing on waste management services, and concluded that the perception of usefulness, ease of use, and trust in data security are the most important factors affecting public participation in smart waste management projects.

Karimi and Mohammadpour (2023) in their research presented a conceptual model for integrated waste management in large residential complexes using the Internet of Things and concluded that the combination of smart sorting bins, a reward system for participants, and a mobile application can significantly increase the rate of source separation.

Foreign Research:

Arojo et al. (2023) examined the application of machine learning algorithms for predicting waste production and optimizing collection routes in a smart city in Brazil. They concluded that neural network-based predictive models can accurately estimate waste volume and lead to a 20% reduction in the distance traveled by collection vehicles.

Chen and Wang (2024) evaluated the performance of an IoT-based waste management system in a busy commercial area in Shanghai. They found that the use of smart bins equipped with

internal compactors and fill-level sensors reduced collection frequency by up to 60% and increased the satisfaction of commercial units and cleanliness of the environment.

Lee and Park (2023) investigated the challenges of cybersecurity and privacy protection in smart waste collection systems based on the Internet of Things. They concluded that strong encryption protocols, precise access management, and user awareness are essential for protecting sensitive data collected.

Patel and Sharma (2023) conducted a comparative study of various smart waste management systems in several large shopping complexes in India and the United Arab Emirates. They found that the success of these systems heavily depends on factors such as management support, staff training, and integration with other management systems of the complex.

Rodriguez and Silva (2024) designed and implemented a cloud-based IoT platform for monitoring and managing hospital waste. They concluded that this platform, with its capability for real-time tracking of waste from origin to disposal, significantly improves safety, reduces risks, and ensures compliance with environmental regulations.

Smith et al. (2023) examined the impact of human and social factors on the success of smart waste management projects in various communities. They concluded that local community participation, trust-building, and designing systems that align with the needs and culture of users are vital for the long-term sustainability of these projects.

Theoretical Framework of the Research

This research is based on systems theory, the theory of diffusion of innovations, and operational optimization models. Systems theory helps us consider waste management as a complex system with multiple components (production, collection, transportation, processing, disposal) and the interactions between them, analyzing the impact of the Internet of Things technology on the entire system. Rogers' theory of diffusion of innovations aids in understanding the process of acceptance and use of smart waste collection technology by various stakeholders (management, staff, tenants). Operational optimization models, such as the Vehicle Routing Problem (VRP) and facility location models, will be used to design intelligent collection algorithms and determine the optimal locations for bins. Additionally, the concepts of sustainable development and circular economy will serve as guiding principles in assessing the environmental and social impacts of the proposed system.

Novelty and Innovation Aspects of the Research

The novelty and innovation of this research are significant in several dimensions: Firstly, the focus on a very large and unique case study at a global level (Iran Mall) presents new challenges for the implementation of smart waste management systems due to its complexities and scale. Secondly, the effort to provide a comprehensive and integrated model that encompasses not only the technical aspects of the Internet of Things (sensors, data platform, optimization algorithms) but also the managerial, economic, social, and cultural dimensions (stakeholder participation, cost-benefit analysis, training). Thirdly, the localization of global solutions and their adaptation to the specific conditions of Iran, including infrastructure, laws and regulations, and cultural characteristics, is a significant part of this research's innovation. Fourthly, this research aims to quantitatively and qualitatively assess the impacts of implementing such a system on performance, economic, and environmental indicators in a real and dynamic environment, which can serve as a model for other similar centers.

Specific Objectives of the Research (including ideal, general, special, and practical objectives)

Ideal Objective: To contribute to achieving sustainable waste management and promoting a circular economy in large commercial and recreational complexes in the country .

General Objective: To optimize the waste management system and the waste collection process at the Iran Mall shopping center in Tehran using Internet of Things technology .

Special and Practical Objectives :

- To determine the current status and challenges of the existing waste management system at the Iran Mall shopping center .
- To identify the potentials and technical requirements for implementing a smart waste collection system based on the Internet of Things at Iran Mall .
- To determine the optimal architecture of the Internet of Things system (including types of sensors, communication network, data platform) for Iran Mall .
- To determine optimal algorithms for routing waste collection vehicles based on real-time data from smart bins .
- To assess the impact of implementing the smart system on performance indicators (cost reduction, time, manpower) at Iran Mall .
- To evaluate the impact of the smart system on environmental indicators (increased recycling rates, reduced landfill waste) at Iran Mall .
- To identify strategies for increasing stakeholder participation (business units, visitors) in the smart collection system .
- To establish an executive framework and provide a roadmap for implementing the optimized system at Iran Mall.

In case of having a practical objective, the names of the beneficiaries (organizations, industries, or stakeholder groups) should be mentioned (in other words, the location of the case study).

The main beneficiaries of this research will be the management and operational team of Iran Mall shopping center in Tehran, who will directly utilize the results and proposed model for optimizing their waste management system. Additionally, other large commercial and recreational complexes in the country, municipalities and waste management organizations, urban service providers, technology companies in the field of the Internet of Things, as well as researchers and students interested in this area can also benefit from the results and achievements of this research.

Research Questions

- What challenges and inefficiencies does the current waste management system at Iran Mall face?
- To what extent can the implementation of an IoT-based smart waste collection system reduce operational waste management costs at Iran Mall?
- Does the use of the Internet of Things in waste management increase the recycling rate and source separation at Iran Mall?
- What are the appropriate IoT architectures and technologies for implementation at the scale of Iran Mall?
- How can route optimization algorithms for waste collection be designed based on real-time data from smart bins?
- What are the key success factors and potential barriers in implementing a smart waste management system at Iran Mall?
- What effective strategies exist to engage businesses and visitors in the new system?

Research Hypotheses

- The implementation of an IoT-based smart waste collection system significantly reduces operational waste management costs at Iran Mall.
- The use of smart bins and IoT-based monitoring systems significantly increases the rate of source separation and the amount of waste recycling at Iran Mall.
- Optimizing waste collection routes using real-time IoT data significantly reduces the time and distance traveled by the collection fleet.
- There is a positive and significant relationship between the level of awareness and training of stakeholders (business units and staff) and the success of the smart waste management system at Iran Mall.
- Communication infrastructure and data analytical platforms play a significant moderating role in the efficiency of the smart waste collection system at Iran Mall.

Definition of Technical and Specialized Terms (Conceptually and Operationally)

Waste Management:

- Conceptual: A set of activities related to the production, collection, transportation, processing, recycling, and disposal of waste in a manner that causes the least harm to human health and the environment.
- Operational: In this research, all processes and current procedures at Iran Mall for controlling and moving the waste produced from the moment of generation in business units or by visitors until it exits the complex, including initial separation (if any), collection from bins, transfer to internal temporary stations, and loading for dispatch outside the complex.

Smart Waste Collection:

- Conceptual: The use of modern technologies such as the Internet of Things, sensors, and data analysis to optimize the waste collection process, reduce costs, and improve efficiency.
- Operational: In this research, a system consisting of waste bins equipped with fill-level sensors and possibly waste type identification in Iran Mall, which send their data to a central platform for dynamic collection planning based on actual needs and optimization of collection vehicle routes.

Internet of Things (IoT):

- Conceptual: A network of physical objects, vehicles, buildings, and other items equipped with electronic components, software, sensors, and connectivity capabilities that allow these objects to collect and exchange data.
- Operational: In this research, the use of waste bins equipped with ultrasonic or infrared sensors for measuring fill levels, communication modules (such as LoRaWAN, NB-IoT, or Wi-Fi) for data transmission, and a software platform for receiving, analyzing, and displaying information related to the status of waste bins throughout Iran Mall and managing the collection process.

Large Commercial and Recreational Complex:

- Conceptual: A large building complex with diverse uses including shops, restaurants, recreational centers, cinemas, hotels, and parking that hosts a large number of visitors and employees daily.
- Operational: In this research, specifically the Iran Mall shopping center in Tehran, with its defined area and variety of uses, is considered as an example of this type of complex.

Optimization:

- Conceptual: The process of finding the best possible solution or outcome from a set of options, considering specific criteria and constraints.

- Operational: In this research, it means reducing waste collection costs, decreasing the time spent on collection, increasing recycling rates, minimizing the distance traveled by collection vehicles, and overall improving the efficiency of the waste management system in Iran Mall through the implementation of IoT-based solutions.

Research Methodology:

A- Complete explanation of the research method based on the objective, type of data, and execution method (including materials, equipment, and standards used in the form of research execution stages separately): This research is applied in terms of its objective and will utilize a mixed approach (qualitative and quantitative) in terms of data type. The stages of the research execution include: 1) Library studies and literature review: Identifying previous research, theoretical frameworks, and existing technologies in the field of smart waste management and the Internet of Things. 2) Analysis of the current situation in Iran Mall: Including direct observation of current waste collection processes, interviews with managers, service staff, and representatives of trade units to identify challenges, costs, and the volume and type of waste produced; collecting data related to collection frequencies, routes, and current costs. 3) Designing a proposed system based on the Internet of Things: Including selecting the type of sensors (e.g., ultrasonic sensors for fill level), communication protocol (e.g., LoRaWAN for wide coverage and low energy consumption), designing the data platform architecture (cloud-based or local), and developing or selecting route optimization algorithms (such as genetic algorithms or ant colony optimization). 4) Pilot implementation (if possible and agreed upon with Iran Mall): Installing a number of smart bins in one or more selected zones of Iran Mall and collecting real data on their performance for a specified period. 5) Collecting post-implementation data (or simulation): If the pilot is executed, collecting data related to the reduction in collection frequencies, changes in costs, and fill rates of the bins. If the pilot is not feasible, simulation methods will be used based on existing data and parameters of the proposed system. 6) Data analysis and system evaluation: Comparing performance, economic, and environmental indicators before and after implementation (or in the simulated scenario). 7) Presenting the final model and roadmap: Developing the optimal model and providing practical recommendations for comprehensive implementation in Iran Mall. The standards used will include those related to Internet of Things networks, data security protocols, and waste management guidelines.

B- Variables under investigation in the form of a conceptual model and explanation of how to examine and measure the variables:

Conceptual model: The main independent variable is "implementation of the smart waste collection system based on the Internet of Things," which includes components such as: type and number of smart bins, sensor technology, data platform and analysis, and route optimization algorithms. The dependent variables are: 1) Operational efficiency (measured by indicators such as: percentage reduction in collection costs, percentage reduction in collection time, percentage reduction in distance traveled by vehicles, number of collection frequencies); 2) Environmental impacts (measured by indicators such as: percentage increase in recycling rates, percentage reduction in landfill waste, amount of CO₂ emissions reduction from transportation);

C - Full description of the method (field, library) and tools (observation and testing, questionnaire, interview, record-keeping, etc.) of data collection:

Data collection will be carried out through a combination of library and field methods. The library method includes studying scientific articles, books, technical reports, and standards related to waste management, the Internet of Things, and commercial complexes to develop theoretical foundations and review research literature (tools: record-keeping, scientific databases). The field method includes: 1) Observation: Direct observation of current waste collection processes in Iran Mall, examining the type and volume of waste in different locations,

and identifying bottlenecks. 2) Interview: Semi-structured interviews with senior and middle managers of Iran Mall, facility and service officials, cleaning supervisors, and waste collection contractors to deeply understand the challenges, needs, and expectations. Also interviews with representatives of trade unions. 3) Questionnaire: Design and distribute a questionnaire to measure stakeholder satisfaction (if possible, before and after the pilot implementation or to evaluate the proposed system) as well as to assess the level of awareness and willingness to participate. 4) Performance data: Collect quantitative data from the existing system (costs, collection schedules, waste volume) and from the IoT pilot system (bin fill level, frequency of fullness alerts, spatial data).

D - Statistical population, sampling method and sample size (if available and possible):

The statistical population of this study includes all components of the Iran Mall shopping center waste management system. This includes: 1) All garbage bins and waste generation points in the complex. 2) All personnel involved in the waste collection and management process (managers, service staff, drivers). 3) Trade units located in Iran Mall. For the interviews section, a purposive (judgmental) sampling method will be used and interviews will be conducted with key and informed individuals (about 10-15 people). For the pilot phase of the IoT system, one or more zones of Iran Mall with different density and type of waste will be purposefully selected. For the satisfaction questionnaire or participation measurement (if implemented), stratified sampling appropriate to the type of business units (e.g. food, clothing, services) or convenience sampling will be used for visitors, and the sample size will be determined based on the Cochran formula or similar tables (taking into account the level of confidence and permissible error) (e.g., for an unlimited or very large population, about 384 samples for a 95% confidence level and a 5% error).

E - Data analysis methods and tools:

Qualitative data from interviews and observations will be analyzed using content analysis and coding (with the help of software such as MAXQDA or NVivo if necessary) to identify patterns, themes, and main challenges. Quantitative data from questionnaires and system performance data (before and after or simulated) will be analyzed using SPSS or R software. These analyses will include descriptive statistics (mean, standard deviation, frequency) and inferential statistics (such as t-tests to compare before and after means, ANOVA to compare different groups, regression analysis to examine the relationship between variables, and correlation tests). Simulation software or programming languages (such as Python) and libraries related to operations research will be used to optimize collection routes. Cost-benefit analysis will also be performed to evaluate the economic feasibility of the project.

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