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IoT-based Waste Management:

A New Approach for Smart Cities

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IoT-based Waste Management: A New Approach for Smart Cities

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Dissertação apresentada ao Instituto Nacional de Telecomunicações, como parte dos requisitos para obtenção do Título de Mestre em Telecomunicações.

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"Standing on a hill in my mountain of dreams,

telling myself it's not as hard, as it seems"

Led Zeppelin – *Going to California.*

Dedication

To my wife Fatima Cristina Pereira and my son Leonardo Pereira Pardini, who waited patiently through the entire time of my absence due to the dedication in this dissertation, and to the memory of my mother, Orasilia Dias de Oliveira, the person who generated the bases to make this dream come true.

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Abstract

With the increase of population density and the rural exodus to cities, urbanization is assuming extreme proportions and presents a tremendous urban problem related to waste generation. The increase of waste generation has been considered a significant challenge to urban centers worldwide and represents a critical issue for countries with accelerated population growth. Internet of Things (IoT) and cloud computing paradigms offer an automation possibility through cyber-physical systems that will change the way solid waste management is performed. Considering the IoT requirements, this dissertation explores a revision analysis of waste management models available in the literature, carries out a deep review of the related literature on IoT infrastructure for efficient handling of waste generated in urban scenarios, focusing on the interaction among concessionaires and waste generators (citizens) from the perspective of a shorter collection time with reduced costs as well as citizenship promotion. An IoT-based reference model is described, and a comparison analysis of the available solutions is presented with the goal to highlight the most relevant approaches and identify open research issues on the topic. Next, an integrated system is proposed. It combines identification through ultrasonic sensors and load cell sensors, location by Global Positioning System (GPS), and communication through Global System of Mobile Communications (GSM)/General Packet Radio Service (GPRS). In other words, a solution offered to provide citizens with a better disposal methodology for waste generated in their homes, besides being easily integrated with the municipal collection service to assist in efficient collection scheduling by promoting optimized routes. Finally, the integration of the system with a software layer, called Middleware, that receives the data transmitted by intelligent devices, performs the necessary treatments, and stores data. Through a mobile application developed and also via Web, data can be accessed and turn information available to users. The solution is demonstrated, validated, and it is ready for use.

Keywords

Internet of Things; Smart Cities; Smart Recycle Bin; Solid waste management; Waste Disposal System; Prototype; Performance Evaluation.

Resumo

Com o aumento da densidade populacional e o êxodo rural para as cidades, a urbanização está assumindo proporções extremas e apresenta um tremendo problema urbano relacionado à geração de resíduos. O aumento da geração de resíduos tem sido considerado um desafio significativo para os centros urbanos em todo o mundo e representa uma questão crítica para os países com crescimento populacional acelerado nas cidades. A Internet das Coisas (do Inglês, *Internet of Things* – IoT) e a computação em nuvem (do Inglês, *Cloud computing*) oferecem uma possibilidade de automação por meio de sistemas ciber-físicos que mudarão a maneira como o gerenciamento de resíduos sólidos é realizado. Considerando os requisitos de IoT, esta dissertação explora uma análise de revisão dos modelos de gestão de resíduos disponíveis na literatura, efetua uma profunda revisão literária relacionada à infraestrutura de IoT para o manuseio eficiente de resíduos gerados em cenários urbanos, focando na interação entre concessionárias e geradores de resíduos (cidadãos) na perspectiva de um menor tempo de coleta com redução de custos, bem como promoção da cidadania. Um modelo de referência baseado em IoT é descrito e uma análise comparativa das soluções disponíveis é apresentada, com o objetivo de destacar as abordagens mais relevantes e identificar questões abertas de pesquisa sobre o tema. Em seguida, é proposto um sistema integrado que combina identificação por meio de sensores ultrassônicos e sensores de célula de carga, localização por Sistema de Posicionamento Global (em inglês, *Global Positioning System* - GPS) e comunicação através do Sistema Global de Comunicações Móveis (do inglês, *Global System for Mobile Communications* - GSM) / Serviços Gerais de Pacote por Rádio (do inglês, *General Packet Radio Service* - GPRS). Em outras palavras, tudo para fornecer aos cidadãos uma melhor metodologia de disposição dos resíduos gerados em suas residências, além de ser facilmente integrado ao serviço de coleta municipal para auxiliar no agendamento eficiente da coleta, promovendo rotas otimizadas. E por fim é apresentado a integração do sistema com uma camada de software, denominada *Middleware* que recebe os dados transmitidos pelo dispositivo inteligente, executa os tratamentos necessários e faz o armazenamento desses dados para que a aplicação através do App desenvolvido para smartphones possa, via *Internet*, acessar os dados presentes no *middleware* e disponibilizar informação aos usuários. A solução é demonstrada, validada e está pronta para uso.

Palavras chave

Cidades Inteligentes; Gestão de Resíduos Sólidos; Internet das Coisas; Lixeira Inteligente; Sistema de Eliminação de Resíduos; Protótipo; Avaliação do desempenho.

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List of Abbreviations and Acronyms

6LoWPAN	– IPv6 over Low-Power Wireless Personal Area Networks
Cloud SWAN	– Cloud-based Smart Waste Management
CN	– Control Network
DNS	– Domain Name System
DNS-SD	– DNS Service Discovery
EPC	– Electronic Product Code
ETSI	– European Telecommunications Standards Institute
EXI	– Efficient XML Interchange
FIRS	– International Forum on Solid Waste
GPS	– Global Positioning System
GPRS	– General Packet Radio Service
GSM	– Global System of Mobile Communications
HTTP	– Hypertext Transfer Protocol
IBM	– International Business Machines Corporation
IBSG	– Internet Business Solutions Group
IDE	– Integrated Development Environment
IEEE	– Institute of Electrical and Electronic Engineers
IETF	– Internet Engineering Task Force
IIRA	– Industrial Internet Reference Architecture
IoT	– Internet of Things
IoT-A	– Internet of Things Architecture
IP	– Internet Protocol
IPv4	– Internet Protocol version 4
IPv6	– Internet Protocol version 6
LR-WPAN	– Low Rate Wireless Private Area Networks

LTE – Long Term Evolution

LTE-A – Long Term Evolution Advanced

M2M – Machine to Machine

MAC – Medium Access Control

MATLAB – Matrix Laboratory

mDNS – multicast Domain Name System

MTU – Maximum Transmission Unit

MTC – Machine Type Communication

MWS – Municipal Solid Waste

NFC – Near Field Communication

NIR – Near Infrared

ONS – Object Name Service

OSI – Open Systems Interconnection

OWL – Ontology Web Language

PHY – Physical Layer

QoS – Quality of Service

QR codes – Quick Response codes

RAN – Radio Access Network

RDF – Resource Description Framework

REST – Representational State Transfer

RFID – Radio-frequency Identification

SBC – Single Board Computer

SC – Smart Cities

SOA – Service Oriented Architecture

TCP – Transmission Control Protocol

TCP/IP – Transmission Control Protocol/Internet Protocol

uCode – Ubiquitous Codes

UDP – User Datagram Protocol

UMTS – Universal Mobile Telecommunications System

UWB – Ultra-Wideband

W3C – World Wide Web Consortium

WCDMA – Wide Band Code Division Multiple Access

WPAN – Wireless Personal Area Network

XML – eXtensible Markup Language

1 Introduction

Waste management is a name given to a waste collection system, including its transportation, disposal or recycling. This term is attributed to waste material that is produced through a human activity which must be handled to avoid its adverse effect for health and for the environment. Most often, waste is managed to reuse available resources. Waste management methods may differ between developed countries, between an urban and a rural environment, or between an industrial and a residential area. The management of waste in metropolitan and rural areas is the general responsibility of a municipality, while waste produced by industries is their responsibility and managed by themselves.

According to data released by the United Nations Department of Economic and Social Affairs, the share of the urban population worldwide is expected to reach 66% by 2050, compared to 52% in 2014, resulting in increased waste production in cities. Data released by the World Bank Group confirm that waste generation rates are growing. In 2012, cities worldwide generated about 1.3 billion tons of solid waste, representing 1.2 kilograms of waste generated per person–day. With rapid population growth occurring along with urbanization, urban waste generation is projected to rise to 2.2 billion tons by 2025, confirming that municipal solid waste (MSW), the main by-product of an urban lifestyle, is growing even faster than the rate of urbanization. This increase in municipal and industrial waste generation, together with stricter regulations aimed at ending illegal waste disposal, stimulate the growth of applications for better waste management. Other factors that have driven the growth of applications designed for the effective management of waste worldwide are directly linked to the constant use of recycling techniques, the cycle of technological innovation, the application of advanced techniques for waste collection, and the use of technologies based on IoT and big data. There is also a vision of strengthening waste management based on public initiatives aimed at building more correct and safer environments, as well as reducing greenhouse gas emissions.

According to Allied Market Research, Portland, Oregon [1], waste management worldwide is expected to grow at an annual rate of 6.2% by 2023, with greater growth in the emerging Asia Pacific region. In Europe, this sector grew by more than 30% in 2016 and growth is expected to continue to accelerate due to the presence of advanced infrastructure and the high demand of several interested sectors.

Currently, there are increasing initiatives by governmental and public authorities in relation to waste management to efficiently improve the collection and intelligent disposal of waste generated by a city. These are already considering the accelerated pace of urbanization worldwide and the expansion of the industrial sector, and the manufacturing and healthcare industries that are likely to produce a significant amount of waste and can already be efficiently treated by smart management. Moreover, growth of infrastructure facilities and a rising adoption of advanced waste management systems in developing economies with the goal of using cost-effective and waste–time disposal methods should positively impact the growth of smart management of waste. The great precursor of technological development that has led to innovations in the waste management sector is undoubtedly the advance of the Internet [2]. The Internet has revolutionized the world and offers global connectivity. Similarly, the Internet of Things (IoT) [3] is also set to underpin significant change and represents an Internet evolution known as the next generation of the Internet (i.e., the Fourth Industrial Revolution).

1.1 Motivation

The search for solutions to proper management of waste generated by large urban centers has become a significant challenge for the public and private sector. According to International Forum on Solid Waste (FIRS), there are high concerns especially regarding of water resources pollution as well as understanding the biodegradation mechanisms of tailings mass and its influence on landfills behavior and, by extension, in the population's lives [4]. There is also a very worrisome urban factor as the inadequate collection of these wastes or inappropriate waste disposal by the society, that provides the accumulation in public areas, sidewalks, roadsides, leisure areas, or even being carried to underground gutters during rainy times causing obstruction and consequently lead to flood problems that are chronic problems of large urban centers. For the private sector, there is a massive waste of raw material, simply, because there is no adequate separation of reusable waste. Based on these aspects that nowadays stain the large urban centers, associated with the need for sustainable handling of these wastes, the Internet of Things (IoT) paradigm brings a methodology that incorporates a network where all things can be connect to the Internet, aiming to improve the different communication modes and play a leading role in various domains, e.g., Smart Cities. This concept allows physical objects to see, hear, think, and perform tasks, causing them to "talk" to each other, share information and coordinate decisions [5].

Within this ocean of IoT possibilities that arise every day, Waste Management for Smart Cities concept is considered, and use this technologic innovation to identify areas with higher waste generation and thus provide the necessary amount of resources to assist the useful wastes collection with the correct positioning of the trucks fleet that implies directly at a lower cost with fuel.

This technology can help awakening the ecological sense of the people, through mobile applications that point to places with green bins, encouraging interest in recycling materials pointing out the enormous available potential. It is also needed to promote a re-education of people to only disposing of their waste when there is availability on the bins.

The interaction, between the user and waste bins, can also be done through a mobile application that accesses the database and based on global location point the locations and levels of the nearest bins. This is the motivation for the study presented in this dissertation.

1.2 Problem definition

In many places, the Municipal garbage bins are overflowing and are not cleaned at the proper time. This results in pollution of the environment, the spread of disease, unhygienic conditions for people, obstruction of the underground gutters, and still brings ugliness for the place. There are also issues related to the inefficient use of the trucks fleet that travel large areas without wanting to collect adequate levels of waste, which leads to substantial unnecessary expenses with fuel and non-optimized human resources. Waste collection services have been carried out for years, but no statistics of the waste generation have been done until today. The collection is done in some places without even knowing if there is something to be collected.

It is necessary to create systems that provide information about compartment filling, alerting the municipality so that they can clean the container in time and generate statistical data for a future optimized collection. Also, the system can contribute to information that can lead citizens to the best points of disposal and thus contribute to the maintenance of cleanliness in cities and build healthier environments.

1.3 Research objectives

The main objective of this dissertation is to present an efficient waste management solution with a primary focus on the citizen (waste generator). The solution can provide a new model of interaction with citizens and bring innovations that can guide them during the process of their waste disposal always aiming at cleaner cities and free of waste accumulation in the open air due to overflow of dumps (when existing) and/or collection outside of time. The system also serves as a basis for municipal waste collection services, seeking the efficiency of the service with reduced time and operating costs.

Based on studies of waste management models currently presented in the literature, this work presents a prototype developed to address the problems identified in the research, which is ready for use. In addition, the study will also serve as a guideline for future waste management research using Internet-based solutions (like IoT). To achieve this main objective, the following partial objectives were defined:

- Review of the related literature on IoT-based waste management solutions;
- Proposal to solve the problem of garbage accumulation in public roads, the basis of the desired solution;
- Smart bin prototype construction and integration with an IoT middleware platform and application development that will make the front end of the solution to users;
- Performance evaluation, demonstration, and validation of the complete solution.

1.4 Main contributions

The first contribution of this dissertation is a deep review of the state of the art on waste management using an Internet of Things based approach. This review analyzed, in detail, the models presented in the literature, evaluating their individual characteristics, architectures, protocols, and used platforms, as well as the challenges and associated problems. This study is presented in Chapter 2. This review was published in the Journal of Sensor and Actuator Networks, eISSN: 2224-2708, Special Issue Sensor and Actuator Networks: Feature Papers 2018, Vol. 8, No. 1, January 2019 [6].

The second contribution is focused on the proposal that solves the problem of garbage accumulation on public roads. A device capable for monitoring the level of residues presents inside the compartment, in real time, and providing information to users (citizens) that can consult the coordinates of the compartments closer to them and know the level of residues present in each one. At the same time, it makes possible for utilities responsible for garbage collection to use this information generated from the compartments to perform more efficient routes, passing through areas with greater need of collection. A prototype of this solution was built and had its operation validated. This contribution is described in Chapter 3 and was published in a paper presented at the 3rd International Workshop on Communication for Intelligent Networking Cities (CorNer 2018), IEEE Technology Vehicle Conference (VTC 2018-Fall), Chicago, USA, August 27-30, 2018 [7]

The third contribution of this dissertation proposes the integration of the smart bin with a platform of middleware that besides being responsible for receiving, processing and storing the information related to intelligent compartments can also be used as interface to present the information.

In addition, a mobile application was developed so that the citizen can interact with the solution and thus enable the complete closure of a city's waste management cycle, which includes responsible disposal, intelligent monitoring and efficient collection.

Finally, a demonstration, validation and evaluation of the full-scale solution's performance is presented as a final contribution, and together with the previous contribution are detailed in chapter 4 with a paper submitted for ACM transactions over the Internet.

1.5 Publications

During this research, two scientific papers have been published and a third was submitted for publication.
Publication in International Journals:

1. **Kellow Pardini**, Joel J. P. C. Rodrigues, Sergei A. Kozlov, Neeraj Kumar, Vasco Furtado, "IoT-Based Solid Waste Management Solutions: A Survey", *Journal of Sensor and Actuator Networks*, eISSN: 2224-2708, Special Issue Sensor and Actuator Networks: Feature Papers 2018, Vol. 8, No. 1, January 2019, Paper Id 5, pp. 1-25, DOI: 10.3390/jsan8010005.

2. **Kellow Pardini**, Joel J. P. C. Rodrigues, Ricardo A. L. Rabêlo, Jalal Al-Muhtadi, Valery Korotaev, "A Smart Waste Management Solution Geared Towards Citizens", submitted for publication in an International journal.

Figure 1: Cover of the journal edition which the article was selected to compose.

Publication in International Conference:

1. **Kellow Pardini**, Joel J. P. C. Rodrigues, Syed Ali Hassan, Neeraj Kumar, Vasco Furtado, “Smart Waste Bin: A New Approach for Waste Management in Large Urban Centers”, *3rd International Workshop of Communication for Networked Smart Cities (CorNer 2018), 2018 IEEE 88th Vehicular Technology Conference* (VTC 2018-Fall), Chicago, USA, August 27-30, 2018.

1.6 Thesis statement

An IoT-based waste management system is a highly complicated issue when we think of real solutions to be deployed at a significant city level, given the complexity and diversity involved in urban environments.

A good example would be to define the best wireless technology to be used based on the area of coverage or volume of data to be transmitted, to format the best power system to be used, the best algorithm to define efficient periods of measurement and data transmission and thus avoid the awkwardness of energy with redundant data and other aspects often not considered as the positioning of the lane compartments of shadow areas caused by parked vehicles.

Creating a prototype and evaluating its performance in a real situation can contribute substantially to selecting the best path and achieving the goal of the scenario being studied.

These aspects have shown that the best way to evaluate the performance of a waste management system in a real situation is through the creation of a prototype, since only in this way it is possible to consider substantial aspects that contribute to selecting the best path and thus achieving the objective of the scenario under study. The study aims to improve urban, social, and public health in cities, as well as to improve the quality of life of people living in these large urban centers. It also contributes to sustainability and reduces public expenditure on the collection and management of this waste. Without efficient waste management solutions produced in urban centers, one can get to the point of social collapse.

1.7 Document organization

The remainder of this dissertation is organized as follows. Chapter 2 provides a review of the literature presenting an overview of types and methods of solid waste disposal, offers information on solid waste management together with the IoT architecture reference models available for waste management systems, provides the value chain of waste management systems based on IoT and the most relevant standard protocols used in waste management systems. In addition, the most recent models proposed in the literature are considered, and a comparison between them is presented.

A relevant model related to waste management research with the description of a work proposal based on hardware, software and communication solution integrated with a middleware platform and the construction of a mobile application, a solution that aims to optimize the management of waste produced in cities is presented in Chapter 3.

Chapter 4 presents the demonstration and validation of the integrated solution contemplating experiments in which the location of the smart bin and the amount of waste deposited within it is validated within the mobile application, as well as the validation of the smart bin energy source.

Chapter 5 concludes the dissertation, showing lessons learned of inestimable value, key conclusions, and suggestions for further studies.

2 Related work

Internet of Thigs (IoT) began with the increasing number of interconnected physical objects providing interactions. The IoT paradigm [8] has a main role as a key facilitator of the integration of various application solutions and communication technologies, such as identification and tracking [9,10], sensor networks, wired and wireless actuators [11], improved communication protocols, and distributed intelligence for objects. According to the Internet Business Solutions Group (IBSG), a milestone of IoT emergence occurred when the Earth's population was exceeded by the number of objects connected to the Internet, which happened in 2008–2009. IBSG predicts that by 2020, about 50 billion devices will be connected to the Internet [12–15]. IoT can include a large number of applications designed to assist in many sectors, such as industry, transportation, markets, education, agriculture, healthcare, environment, and smart cities (Figure 2) [16–19].

Figure 2: Illustration of an Internet of Things (IoT) general framework with several vertical applications.

The European Union has defined smart cities (SC) as a system where people interact and use energy, materials, services, and waste to stimulate economic development and improve the quality of life. These interaction flows are considered intelligent because they make strategic use of infrastructures, services, information, and communication in planning urban management, a way to meet the social and economic needs of society. Despite being a relatively recent concept, the smart city topic has already become synonymous with sustainable development within global discussions on sustainability [20]. Currently, cities in emerging countries are investing heavily in smart products and services to sustain economic growth and, at the same time, developed countries need to upgrade existing urban infrastructures to remain competitive. Among the evolutions that have been taking place to classify a Journal of Sensors and Actuators Networking 2019, 8, 5 3 of 25 intelligent city, a vast range of applications can be listed, such as waste management based on an IoT approach [21–25].

The IoT concept predicts a world in which physical, digital, and virtual objects are interconnected in a network supporting higher order applications. The intelligence of objects comes from the automated data processing of an existing state or the environmental state in which it is immersed. These data are then transmitted to a processing node where they are analyzed, and an appropriate performance profile is determined, considering data acquired from various objects. This actuation profile is then transmitted back to the smart object [26]. The waste management system is included in this context because it has a large number of containers with an inconsistent level of filling that can last from days to weeks, with the possibility of seasonal changes, as well as different emptying requirements, such as distances and type of waste. However, biomedical, chemical, and electronic residues have specific collection points, usually with uniform production and long filling periods. This amount of data analysis is called data mining, which refers to the semi-automatic analysis process of large databases to determine a pattern that includes problem formulation, data collection, and cleaning, i.e. preprocessing by focusing on the automation of the handling large heterogeneous data.

There is considerable difficulty in identifying the filling level of the dumps because of the differences in the waste packaging process, such as the variety and the irregularity of the discarded materials, which in a certain way generate unnecessary costs to the municipal collection system [27,28].

2.1 Types and methods of waste disposal

The garbage generated by various segments of society can be classified according to its composition (physical characteristics) and destination. This classification is fundamental because it facilitates the selective collection, the recycling, and the definition of the most appropriate goal. These solid wastes discarded by urban municipalities represent a highly heterogeneous volume of matter, as well as a more homogeneous load of industrial and hospital waste [29]. Currently, a selective collection is the basis for proper waste management and the primary method adopted around the world when the goal is recycling. For a waste management system based on IoT, it is vital that classification is done previously, so specific containers for each waste type should be considered.

As an example, the collection of solid waste, in London, is done according to the requirements of selective collection. It uses garbage bags or different colored containers, such as toxic waste in red; hospital waste in yellow; hospital waste after disinfection in blue; black household waste; glass bottles are divided into green, black, brown groups, according to their types and colors, and placed in different containers [30]. Then, the different types of considered waste are described as follows:

Organic Waste. It is the garbage derived from organic waste [31]. They are generated mainly in residences, restaurants, and commercial establishments that work with food. They must be separated from other types of waste since they are mostly destined to municipal landfills.

Recyclable Waste. It is all the waste that can be used in the process of transformation to other elements or in the manufacture of raw materials [32]. It is generated in residences, companies, and industries, and must be separated so that the selective collection teams gather and then deliver to final processing in cooperatives and recycling companies.

Industrial Waste. They are the residues, mainly solid, originating in the process of production at industries. It is usually composed by leftovers of raw materials destined for recycling or reuse in the industrial process [33].

Hospital Waste. It is the waste originated in hospitals and medical clinics and can present contamination and transmit diseases to people that come into contact with it [34]. It should be treated according to established standards, with all possible care. This type of waste is intended for companies specializing in the treatment of such waste, where it is usually incinerated.

Commercial Waste. It is the one produced by commercial establishments, such as clothing stores, toys, and appliances. This waste is almost entirely for recycling [35].

Green Waste. It is the material that results, mainly, from the pruning of trees, branches, trunks, barks, and leaves that fall in the streets. Because it is organic matter, it could be used for composting and production of organic fertilizer [36].

Electronic Waste. This is the waste generated by the disposal of consumer electronics products that no longer work or have become obsolete [37]. For disposal, there are appropriate places, such as companies and cooperatives that operate in the area of recycling. They send this waste in a way that does not cause damage to the environment.

Nuclear Waste. It is the one that is generated, mainly, by nuclear plants. It is a highly dangerous waste because it is a radioactive element and should be treated according to strict safety standards [38].

2.2 Solid waste management

Several published papers cover different aspects of IoT technology for waste management solutions. For example, in Reference [39], the authors present a solution that, through intelligent monitoring, allows the planning of garbage collection. Through a Smart-M3 platform (extension of cross-domain search for triple-based information), it is possible to interoperate applications from different domains of information and communication, and to bring a great ease of implementation. The solution is developed in two phases: the first is a monitoring phase where the levels of waste inside the compartments are constantly measured, transmitted and stored; the second is a phase in which the calculation of the collected information is applied to optimize the waste collection routes. In Reference [40], the authors address a dynamic waste management model through a set of infrastructure services for Smart Cities based on IoT. With the use of sensors, radiofrequency (RFID) and actuators in the process of monitoring identification, this set is divided into three phases: (*i*) Planning and execution of waste collection using solutions of routing in trucks with dynamic adaptation of routes according to restrictions introduced; (*ii*) transport to a specific place according to the type of waste; and (*iii*) recycling of waste that can be reused. However, it was basically used in the first one that deals with the planning and collection of waste. The dynamic term presents the capacity of the system to adapt in real time to the parameters and the plans that interest the collection of residues during the activity. These works provide a macro view of a waste management infrastructure with emphasis on the processes applied on excellence management of waste without entering the merit of the sensors applied for monitoring and the used communication methods, unlike this research that aims waste management with an emphasis on its origin and, thus, extracts relevant information that can provide knowledge for the applicability of the necessary solutions.

The authors of [41] provide a solution identified as cloud-based smart waste management (Cloud SWAM). It addresses a solution with specific containers for each type of waste (organic, plastic, bottles, and metal) equipped with sensors that constantly monitor and update their status to the cloud, where stakeholders are connected to receive information relevant to their interest. The system acts not only in waste management but also in the decision of the best collection route, tracing a more economical path within the metropole. Moreover, in Reference [42], a new management model that specifically focuses on the discovery of better areas for the construction of landfills is introduced. As landfills are used as the final destination of commercial and industrial residential waste, identifying an appropriate location within large urban areas requires special attention, because there should be concern about the economy, the environment, and public health. The solution uses the information collected by the waste management system associated to a language that uses a genetic algorithm that assists in the selection of suitable land for the construction of landfills. In Reference [43], the authors describe the various methods of waste disposal in which waste management can be applied. They feature an integrated solution of fill level sensors with solar-powered waste compaction called a smart box, which optimizes waste collection. The information is transferred to a server in the cloud via wireless communication and is applicable to any type and size of container, and stakeholders can log in to the server and access the data in real time through monitoring of the smart boxes. In these addressed solutions, the authors present a more targeted approach to the concessionaires, considering the reduction of collection costs, providing information about the waste of interest, and lower transportation costs for disposal in landfills to the real problem faced by large companies. Cities refer to poor management of too much waste generated. Additionally, the proposed architectures are not well portrayed.

Intelligent waste management as a model for the improvement of waste collection is presented in Reference [44]. In some countries, such as Australia, municipalities usually charge fees for waste produced in the city and generally measure the weight of garbage for each neighborhood or street and then rate the average of each user per household. This collection model is not the most accurate, and as the cost of waste disposal increases every year, waste producers (users of the system) demand a solution that reduces the cost and changes the form of charging, applied through a fixed rate. Intelligent waste management can solve this issue by ensuring that the user is taxed only based on the waste that produce. In addition, the system can reduce costs with many containers that are missing or stolen. The work presented here addresses a good proposal when the lack of waste collection affects only the budget of citizens, but the architecture used was not well portrayed.

A review of the literature on the optimization of waste collection and vehicle routing is presented in Reference [45]. To conclude the idea, a multirestricted and multicompartmental routing problem is proposed that, through modeling using container scheduling strategies in a decision-making process, produces results that indicate that the differentiated collection has the potential to search the best routing strategies with lower collection costs, which ensures that advances in optimization strategies can present intelligent and ecological solutions. In addition, the study presented in Reference [46] proposes an intelligent system of trash recycling. Pre-separation of waste before disposal is required where the glass will be destined in brown containers, paper and aluminum cans in blue containers, and plastic products in orange containers. The system automatically evaluates the type and amount of waste disposed of and a benefit is provided in the form of points credited to a card. The accumulated points can be exchanged for an item or even withdrawn through the banking network, simulating a virtual currency. The above authors follow a baseline of specific containers for a pre-separation of waste, where a first model focuses on gains provided by a differentiated collection and the second case focuses on the offer of a prize for citizens who discard their waste correctly, but they do not detail how the sensors are not trapped in the solution.

In Reference [47], a solution is proposed to the problem of dumps that are not cleaned in time and reach overflow. The system offers a monitor that triggers an alarm and informs the authorized persons that the container is ready to fill, associated with a screening system through near infrared spectroscopy (NIR) that identifies five types of plastic resin and the remainder of biodegradable waste is destined to produce biogas. The authors of [48] provide a model for collecting information on the use of garbage and helping dumpers to identify and decide if a particular area needs extra dumps or remove them to other places where they are needed. From the daily trash information, cleaning operators can plan better when they should send their cleaning contingents to empty the boxes and can also set routes for their cleaning trucks. In Reference [49], a "smart bin" solution is provided, where bins are distributed on the streets with a unique ID. Sometimes, when the container is about to be filled, there will be a query in a database to determine who is responsible for that compartment and a global system for mobile communications (GSM) notification will be sent containing the container ID and location. The presented models cover the perspective of intelligent dumps, but in all these models, the sensor component is not very clear, as just a communication model is described.

The authors of [50] present the disadvantages of existing systems in comparison to the method proposed by them. The proposal is based on an Arduino IDE and an 8051 microcontroller that reads the data from an infrared sensor used to measure the depth of waste inside the container, processes and transmits via wireless communication to a central system based on a microcontroller Intel Galileo. The proposal presented by these authors approaches the sensors used in the solution very well and the used communication as well. They have another model based on a better collection route.

A literature review for smart waste management and a comparison of the different methodologies is surveyed in Reference [51]. It focuses on IoT, considering its elements (identification, sensing, communication, computation, semantics, and services) and to its characteristics (anything communicates, anything identifies, and anything interacts).

An algorithm for decision making during waste collection is presented in Reference [52]. Some algorithm models are compared, considering several performance metrics, such as receiving data in motion, multiobjective, loss of data during transmission, and increased data reception. It concludes that not all algorithms that are capable of receiving data in motion also serve the multi-objective or are still able to cope with increased data reception, but none of them can address data loss. Based on this information, some case studies are proposed and some objectives, such as reducing pollution through collection on time, reduce the operational cost, using trucks of appropriate size for demand, and using a better collection route, are considered. The algorithm should also consider the speed and volume of data input as well as data generated by similar sensors. Thus, an algorithm model to optimize the collection decisions is proposed in this work. Moreover, in Reference [53], the proposed model uses information received from the compartments to define effective routes for each truck during collection. Within the model, some constraints are considered as maximum bin capacity and a Poisson distribution models the waste arrival rate. When a dump reaches a filling threshold, a garbage collection alarm is triggered and sent to the base station which, in turn, communicates with the cloud to process the data and find the best collection route. In the end, the trucks head to the emptying area where the amount of visited dumps is verified and establish the optimal path of collection with the objective of optimization based on lower cost for the waste collection. The solution presents a waste management approach based on three heuristics, considering the nearest vehicle first, a collection based on the upper limit, and a collection based on the upper and lower threshold. MATLAB was used to solve the optimization models based on cost and delay, and a Java-based simulator for heuristic methods. The proposals presented by the authors specifically deal with search algorithms for an optimal path for waste collection with a focus on reducing the collection time and cost. In Reference [54], a municipal waste management system for domestic use is presented that focuses on the application of biological and physicochemical methodologies that can eliminate or significantly reduce the stage of waste collection and transportation.

The survey, by A. S. Wijaya - Z. Zainuddin - M. Niswar [55], proposes a model to manage whole containers of a city and monitoring the entire process. The proposal includes a sensing unit based on level and load sensors installed in the cover and the bottom of the container, respectively. A microcontroller is programmed to control the load of the bin by activating the sensors after a specific time interval. A transmission unit based on Bluetooth modules (used for maintenance in case of system failure) and Global System for Mobile Communications (GSM) for communication with the server.

A WEB-based monitoring unit (where all data is managed) and a Mobile application that receives the information from the Web unit through GSM, so the collection is done efficiently. It uses GSM for communication.

In [56], the authors address a model of the waste management focused on a model where the base is the energy saving device. It is based on a bin, called the Field Unit, which features a lid opening mechanism and it is made with a durable hard plastic coupled to a detection unit based on ultrasonic sensors that are more advantageous in providing variation measurements independently of the contained objects. The data stream is transmitted through RFID, which was chosen based on the cost of implementation, but with a greater emphasis on the energy considerations where the energy consumption of the node and the sensors must be minimal to prolong the life use of the battery (externally coupled). It presents the advantage of not relying on any communication infrastructure. The other unit in the system, called Mobile Sink, is based on a RFID reader, a Raspberry Pi, and a corresponding RFID middleware. A staff can perform the Mobile Sink or installed in a vehicle of the existing organized transport systems to collect data discreetly as the vehicle travels through the city. To download the data is used a network interface that can be Bluetooth, Ethernet, or Wi-Fi. The approach used for the communication on the described model is RFID (Global System for Mobile Communications).

The authors of [57] provide a structure designed in three segments. The first one is a bin with ultrasonic and load sensors that measure the deposited waste rate and send data to the second segment, a gateway. It integrates two different communication technologies, ZigBee that communicates with the bins receiving the measured data and, a second, via GSM/GPRS. The gateway is a bridge between the first and the third segment. This gateway is a built-in Meshlium device based on the Linux operating system of Libelium. Finally, the third segment is a data processing base, composed by servers that store data and some applications to represent the level of bins usage. The communication approach used was ZigBee-PRO that is technology in an open standard based on IEEE 802.15.4.

The work presented in [58] addresses a model of three main parts designated as Smart Bin, gateway, and control station. The Smart Bin includes sensors installed in the bin lid, as an accelerometer sensor that accompanies when the compartment cover is opening. The Hall Effect sensor that monitors whether the compartment cover is open or closed, which also predicts an overload of the bin, and an ultrasonic sensor that measures the waste level into the container. At the bottom container, load sensors are installed to measure the weight of the waste, as well as temperature and humidity sensors. The data measured by the sensors is sent to a gateway via ZigBee-PRO communication. The gateway stores the data in a local database and relays it to the control station via GPRS through a Meshlium from Libelium system. The control station has a database that receives the data sent by the gateway and stores it to be made available via WEB to collection users' interactions. The approach used for the communication was ZigBee-PRO.

In [59], it is proposed an integrated solution system of waste collection and monitoring of collection trucks. The system uses communication technologies, such as RFID, where the dumps are equipped with an RFID tag that contains the ID information. The bin address, as well as an RFID reader, is placed in the garbage trucks that read the tag information and stores them along with the exact date and place of waste collection, every time the bin is empty. There is also a Camera that photographs the containers before and after being flushed and the information is also stored and then transmitted via GPRS to the data processing point. A GPS system is coupled to the truck control box that verifies the coordinates of the bin at the collection time so, after, via GIS system can be displayed on a map to best route for collection. The communication used on the described model is RFID.

The work proposed in [60] shows a model where the bin is equipped with ultrasonic and infrared sensors for monitoring the level of waste of each item, a Raspberry Pi device and an Arduino system. After the waste level exceeds a threshold, the data is sent to the Raspberry that triggers an alert via SMS, and via e-mail, in parallel, the information is also sent to an Arduino system that, via Wi-Fi communication, transmits the data to a Microsoft Azure platform and a Power Bi platform for data processing. This communication is performed via Wi-Fi.

In [61], the authors describe a solution of smart bin equipped with a Passive Infrared sensor (PIR) to detect movement. An ultrasonic sensor to measure the usage level of the container, temperature sensor for checking the temperature inside the tray, and a proximity sensor for bin cleaning and attendance monitoring, LCD, real-time clock, and servo engine. An Arduino Uno board is used to automation the entire system and an Ethernet shield/Wi-Fi shield are used along with the Arduino to provide internet connectivity and support transmission of real-time data. The operation is activated when the PIR sensor detects a person approaching the bin. It sends a signal to the Arduino that, in turn, instructs the servo engine to rotate and open the bin lid. The container remains open for approximately 20 - 30 seconds then automatically closes to prevent the entry of animals and depending on natural conditions, fill the compartment. Once the lid is closed, the ultrasonic sensor that measures the fill compartment is activated. The LCD connected to the chamber continuously displays the percentage of fill, date, and time. This approach uses Wi-Fi communication.

The authors of [62] present a smart Bin design using ultrasonic sensors positioned at 120° from each other on the compartment cover and covered by a protection. On the bottom bin (in the corners), a load cell that is used as a secondary form of measurement, is placed to be used such as backup when the ultrasonic sensors fail. There is an amplifier coupled to the cell output. The measured data is sent to a base of waste collection via a GSM module with GPS combined to provide the bin coordinates. A microcontroller is programmed to monitor the level of waste, thus allowing the voltage to flow through the sensors after a certain period that will lead to minimizing waste energy through sensors. When the trash is full, a GSM modem will send an SMS to the base that will collect the waste. After collected, the residues are taken to a separate station where the plastic will be separated from the remaining residues by infrared reflectance spectroscopy.

In [63], a specific proposal with a focus on the intelligent container was already presented. The authors propose an approach where monitoring not only occurs inside the compartment but also in the environment around it, to avoid waste disposal outside the container. The compartment is equipped with infrared sensors that play the role of detecting discarded garbage out of a bin, as well as measuring the compartment fill state. Infrared sensor signals that detect the garbage in the environment are delivered to an alarm system that is triggered to inform the person who disposed the garbage improperly, this alarm will cause people to use the garbage properly. For cases of waste accumulation around the container, the system has a mechanical lift consisting of a rack, electric engine, pinion, gear shaft, and chain pulley that are driven by a master controller and collect accumulated waste around the compartment. The grouping of the rotating mechanical axis together with the elevation ensures the common area around the waste-free compartment providing a clean, hygienic, and healthy environment for society. When the internal sensor detects the garbage limit level, the system automatically sends a message to the corresponding authorities, notifying the need for collection.

An intelligent collection system based on the level of residues present in the compartments and updated information of landfills is proposed in [64]. The system includes sensors installed in a compartment that determine the level of residues present internally through the distance measured from the cover and the beginning of the deposited garbage. For it, the authors use a sonar like the HC-SR04. A battery-optimization process has been considered, which can be achieved through an association of optimized waste detection rates (that can be done one or more times a day) in conjunction with a wireless transmission system (Wi-Fi is considered). It is a factor with strong influence in the energy consumption that can raise the life of the device. The data obtained through the sensors installed in the trash can be transmitted to a MySQL database via Internet and, then, passed through optimization algorithms to calculate the best collection path. Associated with artificial intelligence (AI) based approaches, future waste levels can be predicted and properly associated with information from landfills and a lower route of disposal can be determined. Every day, workers of the collection system update the paths on their navigation devices based on an essential feature of this system, which is to improve previous experience and to decide not only the status of the daily level of the compartments but also the foreseeable future state and other related factors, such as congestion, blockages, and parking area to receive the fleet at the end of a journey. Based on the historical data of dumps and future projections it is possible to anticipate the occurrence of exhaustion of the landfills and, thus, planning new localities assuming less distance from the waste generation center.

Another proposal based on a garbage container solution is presented in [65]. The architecture of the solution is primarily based on an intelligent compartment that is responsible for updating the system with volume information, the type of content present in its interior, and the environment surrounding the place where the compartment is inserted. The enclosure is equipped with a range of sensors that enable detection and communication with the cloud and are managed through a microcontroller, such as Arduino Yun or a Latte Panda card, which receive the collected data, aggregate the data and transmits them to the cloud. This range of sensors is basically comprised by proximity sensors that provide neighborhood status data around the enclosure, such as information on a restricted physical access for collection due to parked vehicles. There is a load cell that calculates the weight of the garbage available inside the compartment and updates the microcontroller. A humidity sensor is used to detect the level of dryness of the contents inside the compartment when it is not under usage for a long time, and either the collection can be triggered when wet fragments are detected to avoid leakage. In addition, the compartment is also equipped with a GPS that identifies your exact location. Also present is a lever-like drive key which is used to detect open-lid physical events, generally due to over-filling of the tray. Complementing the solution, a mobile application is used by drivers of collection vehicles to determine the route and location of the bin within a collection schedule, and the application can be used by public to control the disposal of a residence, QR code technology allows only registered users. The driver module inserted into the application ensures the implementation of dynamic routing by continuously monitoring the speed of the vehicle and its location. The cloud is the central processing unit of this system that receives data pertaining to the management carried out by dumpsters. These data are aggregated and interspersed with weather conditions, rush time traffic, sporting events, and commemorative events with potential effect on the garbage truck route. The proposed system actively reacts to optimize waste collection routes.

The work presented in [66] also focuses in the context of waste management through smart bins. The presented model defends specific dumps applied to each type of waste and considers the following elements: wet / biodegradable paper; paper / clothing / wood; glass / metal; chemical / medical and hazardous waste. In each compartment there is a coupled GPS module that determines the exact location of the compartment, an infrared sensor to determine the compartment fill level, a gas sensor to detect harmful gases, a temperature and humidity sensor, and a sound sensor for noise pollution monitoring. All the sensors are managed by a microcontroller with a LoRa coupled communications module that is used to transmit the information obtained from the smart bin. A Linux-based gateway device (Raspberry pi) with LoRa module receives data from smart bins and, in the sequence, sends it to the cloud through a LAN/Wi-Fi connection using an MQTT message broker as the application layer protocol. The cloud layer includes data storage with a NoSQL database, event processing, and data analysis with alerts sent to the garbage trucks for collection when the boxes are full. These messages are received in an application that determines the best route for the truck to collect the waste.

Much of the research work presented in this literary review deals with the management of solid waste with focus only on the collection system, i.e., smart bins were developed for monitoring the waste discarded and generated information that can benefit the collection system through the positioning and the used volume of the compartments. It always aims to optimize routes for collection reducing time and cost regarding fuel, trucks material, and human resources. There are also works that focus on a smaller transport route from the waste generation to the landfill. Thus, data serve as information to predict the exhaustion of landfill capacity and to search for new ones in areas around the waste generating region, keeping always short routes from collection to disposal in the landfill, which keeps focusing on the collection system. Of course, it is assumed that best approach for waste treatment should be recycling and reuse. Among the discussed studies, few of them presents mobile-based solutions, which is a key factor today. Moreover, the available solutions have also shifted their focus to other aspects of IoT-based waste management which can be huge contribution, furthermore, none of the studies discussed has presented a performance evaluation or even a demonstration that can validate the operation of the proposals.

The summary of the comparative assessment of the most promising solutions performed in this survey is presented in Session 2.6. A total of twenty-eight research efforts were reviewed and their strengths and weaknesses are analyzed, and each model is classified to represent essential parts of the proposed systems.

2.3 Available IoT architecture reference models for waste management systems

To standardize this IoT segment or vertical, being supported by a reference architecture model is very important, so in the future, these waste management devices, which are called objects in IoT, can be connected (and the interoperability challenge is solved).

The Internet is supported by the Transmission Control Protocol/Internet Protocol (TCP/IP) architecture so that communication between network hosts is possible as it is known today. Similarly, an architecture for IoT-based applications is also necessary, always addressing factors such as scalability, interoperability, reliability, Quality of Service (QoS), etc. According to the author of [67], there are several models and reference architectures available for IoT. Each group or company describes its own, which often causes conflicts of ideas and makes the task of standardization more complex.

Among the predominant reference models, it is possible to mention some initiatives, such as RAMI 4.0, a reference architecture for intelligent factories applied to IoT standards, which began in Germany and later became relevant through the direction of companies from large industrial sectors. Another initiative was launched by a consortium formed by AT&T, Cisco, General Electric, International Business Machines Corporation (IBM) and Intel, called Industrial Internet Reference Architecture (IIRA), and provided a reference architecture that involves broad discussions and considerations, while Internet of Things Architecture (IoT-A) is an initiative that stimulates an architecture model which covers detailed system requirements [68].

Many project models focus on a typical architecture based on needs analysis or on some layers that form a basic model of a reference architecture. Figure 3 illustrates the basic layered architecture. The most basic approach only considers a three-layer architecture composed by application, network, and perception layers [14]. There are also, in recent literature, some other models that add more abstraction to an IoT architecture, such as the Service Oriented Architecture (SOA) model, the middleware model [69-71], and the five-tier model [15, 72, 73].

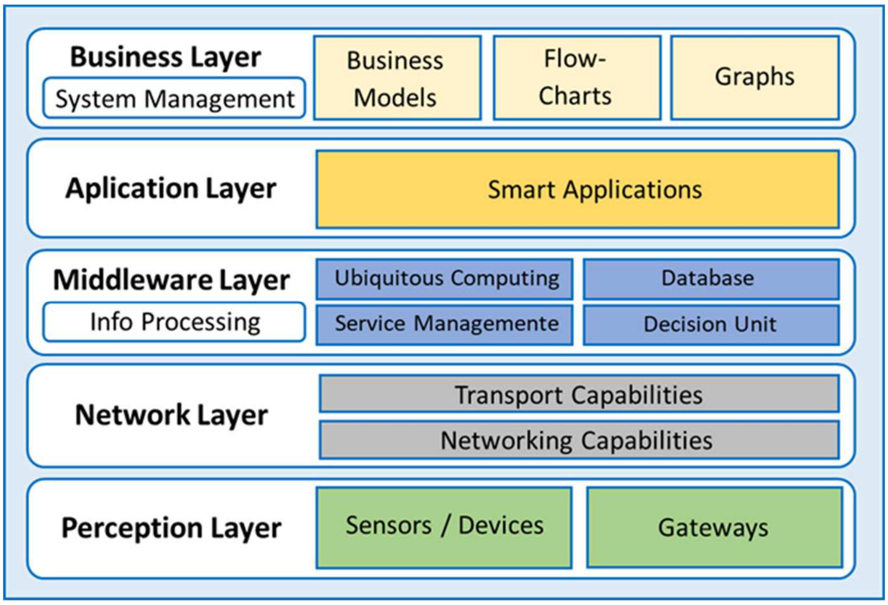

Figure 3: Illustration of layered architecture for waste management systems.

Even with a flexible architecture, there are still relevant challenges, especially related to security and privacy. Therefore, to overmatch these challenges, new standard architectures need to be proposed with a focus on critical factors, such as QoS, sustainability, data integrity, confidentiality, and reliability. Next, there is a brief discussion about these layers that, in turn, alternate between the presented models.

Perception Layer. The IoT architecture perception layer is similar to the physical layer of the Open Systems Interconnection (OSI) model, because it is based on the hardware level and has the responsibility of collecting physical information, processing it, and transferring it to the upper layers through secure channels. It applies technologies for the detection of parameters of physical characteristics through specific sensors, such as weight, temperature, humidity, etc., in addition to the collection of object identification data, such as Quick Response codes (QR codes) and RFID.

Network Layer. The network layer is responsible for transferring the measured information in the perception layer to the upper layers, where the processing systems are located and uses ZigBee, Z-wire, GSM, UMTS, Wi-Fi, Infrared, 6LoWPAN. In addition to the basic assignments, the network layer also performs the cloud computing process and the data management process.

Middleware Layer. The middleware layer is a layer of software or even a set of sublayers that work to interconnect components of the IoT that would not be possible to communicate otherwise, that is, an interpreter. In addition to providing concurrency so that the application layer can interact with the layer of perception and ensure effective communication, it plays an important role in the development of new technologies.

Application Layer. The application layer does not directly contribute to the construction of an IoT architecture, but it is in this layer where the various services are built that interface with users, that is, where the interpretation and availability of the information occurs.

Business layer. This layer is responsible for managing the entire IoT System, including service-related applications such as providing high-level analysis report of the underlying layers, as well as addressing user privacy. The responsibility of creating graphs and business models can be attributed to this layer.

Since IoT connects everything to exchange information among themselves, the traffic and the stores within network tend to increase exponentially. Thus, IoT application development depends on technology progress and design following a reference model of an IoT architecture.

2.4 Value chain of IoT-based waste management systems

Understanding the integration of several empowering technologies in a system (such as data acquisition and network transmission) offers an improved insight into the meaning of each functionality within the context of IoT [74]. An overview of how these technologies play a key role in an IoT-based solid waste management system is presented in this section. A set of activities is appropriately related from the beginning of its cycle through the identification of each compartment. It is associated with a useful sensing and capable of accurately presenting service level conditions with adequate communication and capable of providing the minimum requirements necessary for the proper functioning of this system. Moreover, an applied computation is added to break the information that meets the users' need within a large amount of collected data accessed by simple services, and it is easy to use until semantic representation of information through an object. Figure 4 illustrates this value chain for IoT-based waste management systems.

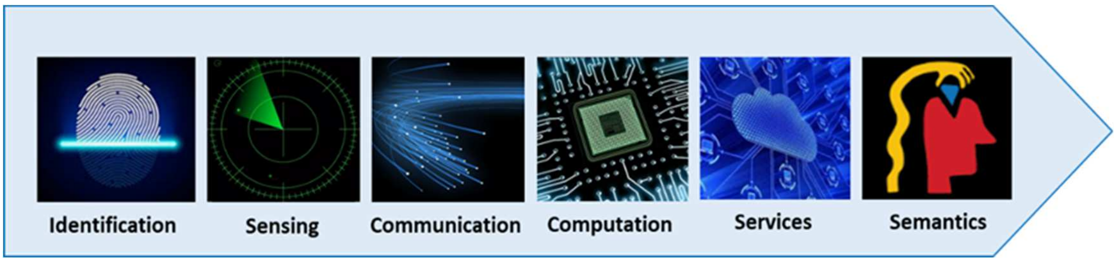

Figure 4: Illustration of a value chain for IoT-based waste management systems.

As may be seen in Figure 4, the proposed value-chain for IoT-based waste management systems considers the following aspects that are described as follows:

Identification. For IoT, classifying services and linking them to demand is extremely important, so various identification methods are supported by IoT, such as the electronic product code (EPC) and ubiquitous codes (uCode) [75], and GPS trackers [76], which will determine the exact location. The key to identifying a particular object within a telecommunication network is to provide you with an ID and address. The ID refers to the name of the object, e.g., "P1" for a specific pressure sensor and its address refers to a number that identifies that device within the network. The methods of object nesting within an IoT network may include Internet Protocol version 4 and version 6 (IPv4 and IPv6). The IPv6 on low power personal networks (6LoWPAN) [77] provides a compression mechanism over headers. As a method of identifying objects within a network, public IP addressing is used.

Sensing. Sensing means to capture specific and relevant data from objects on a network and send them to a database or cloud so that they can be analyzed and serve as the basis for decision making in a particular service. Sensors can be classified as intelligent [78], such as actuators [79], or sensitive portable devices. Many IoT solutions associate sensors with single board computers (SBCs) that are devices (for example, Arduino Yun, Raspberry PI, Beagle Bone Black) which connect to application software in a central management to provide information that clients need.

Communication. In order to integrate different objects and provide specific services within an IoT environment, it is necessary to apply communication technologies such as Wi-Fi [80], Bluetooth [81], Institute of Electrical and Electronic Engineers (IEEE) 802.15.4 [67], LoRa [82], wave Z, GSM/GPRS, Wide Band Code Division Multiple Access (WCDMA), long term evolution (LTE) and Advanced LTE [83,84], near field communication (NFC) [85], Ultra-wideband (UWB) [86] and 6LoWPAN [77,87], and the IoT nodes must operate with low power consumption. RFID [88] is a specific communication technology that can also be considered where a query signal is emitted from the RFID reader against a label called TAG that reflects and returns to the reader. There are different types of TAGs; active TAGs that are battery powered; passive TAGs that operate without the presence of a battery for power supply; and semi passive TAGs that, when necessary, use the board supply [89]. NFC technology operates in a high-frequency band of 13.56 MHz with rates of 424 kbps in a band of up to 10 cm [77]. UWB, also known as 802.15.3, is a communications technology standardized by the IEEE to operate within areas of low coverage and bandwidth requirements. [86]. Wi-Fi uses radio waves for communication within a range of 100 m and allows devices to communicate through an ad hoc configuration [80], i.e., without the use of a router. Bluetooth is a communication technology widely used for communication between devices at a short distance. It uses basic radio waves with short wavelengths to guarantee a saving in the consumption of batteries [81]. The standard IEEE 802.15.4 provides specifications in low power wireless networks for both the physical layer and the medium access control layer by promoting reliable and scalable communication [90]. Long term evolution (LTE) is a wireless communication standard that enables high speed data transfer between mobile phones based on GSM/UMTS network technologies and encompasses devices in locomotion at high speeds in addition to providing multicast-based services and broadcast [83]. LTE Advanced (LTE-A) is an enhanced version of conventional LTE and includes broadband coverage, spatial multiplexing, greater coverage, and better performance with lower latencies [84]. Better known as the fourth generation of mobile communications is an evolution of WCDMA (3G) and GSM/GPSR (2G).

Computation. It is the unit that represents the computational capacity of IoT, based on software and applications. There is a huge range of hardware development platforms for IoT application operation; some examples are: Arduino [91], UDOO [92], FriendlyARM [93], Intel Galileo [94], Raspberry PI [95], Gadgeteer [96], Beagle Bone [97], Cubieboard [98], Z1 [99], WiSense [100], Mulle [101], and T-Mote Sky [102], but operating systems are seen as vital because they run throughout the entire system execution period. In addition to TinyOS [103], LiteOS [104], and RiotOS [105], which also offer a lightweight operating system, it is possible to cite the Contiki RTOS, widely used in IoT scenarios [106,107] for IoT environments. Cloud platforms are another important computing component within an IoT solution. These platforms provide capabilities for receiving data from intelligent objects to be processed or stored, so that in the future, users can benefit from the knowledge of the extracted data. Data analysis platforms within IoT are crucial due to the specific characteristics of this type of solutions given heterogeneous data and systems integration. Similarly, IoT-based solid waste management works with real time data that require correlation and sharing. To meet these requirements in a system with a large volume of connected devices generating data by different flows, it is increasingly necessary to adopt cloud computing where storage, processing, and connection capacity are needed according to the growing demand for data analysis.

Services. Within IoT, services can be classified through four classes: Services related to identity that represents the most basic and essential to other services—applications that need to take objects from the real world to the virtual must first identify them; information aggregation services responsible for summarizing the raw information that needs to be processed and exposed to the applications; collaborative–aware services acting on aggregation services in decision making; and ubiquitous services, providing support services.

Semantics. Semantics refers to the ability to extract knowledge in an intelligent way, but through other possibilities and in the proportion in which the services require [108]. This extraction of knowledge covers the discovery and use of modeling resources and information and includes the recognition and analysis of the data so that it makes sense for the right decision by providing the exact service. Semantics behaves like the brain of IoT, sending demands to the specific resource. Such requirements are supported by semantic web technologies, such as the resource description framework (RDF), web ontology language (OWL), and efficient XML interchange (EXI).

2.5 Standard protocols used in waste management systems

IoT requires different protocols to address a full range of activities, such as protocols for sensor data collection, communication protocols, etc. Various working groups, such as the Institute of Electrical and Electronic Engineers (IEEE), the Internet Engineering Task Force (IETF), the World Wide Web Consortium (W3C), EPCglobal, and the European Telecommunications Standards Institute (ETSI) began to include efforts to provide standard support protocols for IoT. For an IoT-based waste management solution, the protocols described below represent the most used in this technology context. Their brief description is presented per layer according to their main functionalities: Application, service discovery, and network infrastructure protocols.

2.5.1 Application layer protocols

At the application layer, the protocols are used for end-user communication and are usually integrated in middleware solutions for IoT [109]. End-user applications detect systems, which means they can communicate directly with lower layers of the protocol stack, such as web servers widely used in system integration and communication between different applications.

Constrained application protocol (COAP). The COAP is an application layer protocol developed to support applications within IoT systems [110, 111]. Based on the Representational State Transfer (REST) functionalities over HTTP [112], REST is a transport protocol used in networks with low power nodes, mobile applications, and social networks, being able to transfer data between client and server in a more direct way, in addition to be a cached connection protocol. Unlike REST, COAP is linked to User Datagram Protocol (UDP), which makes it a lighter and more appropriate protocol for IoT applications, containing adaptations of HTTP functionalities for low power consumption when operating on links in the presence of noise and packet loss.

Message queue telemetry transport (MQTT). MQTT [113] is a publishing and signing transport protocol based on a TCP/IP server–client structure developed for the connection between embedded applications and middleware. It uses one-to-one, one-to-many, and many-to-many routing mechanisms, ideal for IoT systems, providing flexibility and simplified deployment. MQTT has a fixed 2-byte header suitable for devices with limited resources, such as connections with low bandwidth, battery leaks or untrusted links, and IoT requirements.

Extensible messaging presence protocol (XMPP). The XMPP is an instant messaging protocol over the Internet independent of operating system, designed for chat, voice and video calls, and telepresence [114]. It supports authentication, access control, privacy metering, encryption, and interoperates with other protocols. XMPP communication, based on text using XML, establishes an overload to the system that is solved with XML streams compression using EXI [115] discussed and based on Reference [116].

Advanced massage queuing protocol (AMQP). AMPQ [117] is an open standard IoT connection layer protocol applied to a message-oriented environment with a publishing and signing structure. It supports reliable communication through primitives that guarantee delivery but requires a reliable transport protocol, such as TCP. It is facially interoperable with other protocols with communication-based on message transfers and queues using a SWAP to route messages to the appropriate queues.

Data distribution service (DDS). DDS [118] is a subscription and publishing protocol developed for real time communications of machine to machine (M2M). In contrast to AMPQ and MQTT, DDS has a decentralized structure and does not require the presence of a broker. It uses multicast as a form of guaranteed traffic delivery and excellent QoS that supports 23 queues with a variety of communication parameters, such as security, urgency, priority, durability, and reliability.

2.5.2 Service discovery protocols

Due to a large number of devices connected and given the need to ensure the proper functioning of the applications developed for IoT based systems, a resource management mechanism is essential for excellent coverage of the technology. Thus, the system must be able to discover resources and register the services automatically. The most notorious protocols to meet these needs are domain name system (DNS), multicast (mDNS) and DNS Service Discovery (DNS-SD). Current research studies aim to adapt lighter versions to the IoT environment.

Multicast DNS (mDNS). mDNS is a very flexible protocol and uses the DNS namespace locally, being a timely option for Internet devices because it does not require manual configuration or an administration that manages the device and is capable of operating without an infrastructure or even in failures. The name query is done through multicast messages, in which the client requests all domain nodes the Internet Protocol (IP) address for a specific name. At that moment, all the ones in the network update the caches with the provided address [119].

DNS Service Discovery (DNS-SD). The DNS-based discovery service (DNS-SD) performs the service delivery function required by clients through mDNS, enabling customers to discover the desired services using standard DNS messages. Like mDNS, DNS-SD does not require a naming configuration [120] and the DNS packets are sent through the UDP transport protocol, having as destination a multicast address. A first step in finding the necessary services is to find the corresponding IP address of the respective host, and then the pairing function is sent, also via multicast, containing the essential details for connection as the IP/Port pair of the connected hosts, so that the names of the instances can be kept constant, increasing reliability.

2.5.3 Infrastructure protocols

Infrastructure protocols provide communication between devices and the network, i.e., they are based on connectivity between different types of systems and devices, which may use different data types and may be spread out over considerable distances. Thus, the Internet is a connecting option between them.

2.5.3.1 Routing protocol

Routing Protocol for Low Power Lossy Networks (RPL). The RPL [121,122] was developed to support the minimum routing requirements, always considering a robust topology, when the network is faced with environments where the links have great influence of noises or losses of packages. It guarantees the delivery of traffic from the simplest point-to-point to more complex traffic such as point-to-multipoint and multipoint-to-point. The core of RPL is represented by a target-driven acyclic graph (DODAG), where there is only one root and the network nodes have known their parents and establish redundant paths by establishing one as the primary (faster route to increase performance), but has no information on inferior relationships, children. In order to keep the topology in place and with its routing information up to date, RPL uses some types of control messages, such as the DODAG information object (DIO), which is used to determine the distance between each node of the network until the root based on specific metrics to choose the preferred parent path. Another type of message is the destination announcement object (DAO) that provides information about the traffic of receiving data. The third type of message is the DODAG information request (DIS), used by a node to acquire DIO messages from an accessible adjacent node. The last type of message is DAO confirmation (DAO-ACK), which is a response to a DAO message sent from a DAO target to a DAO parent or DODAG root [123].

2.5.3.2 Network adaptation layer protocols

6LowPAN. Wireless personal area networks (WPANs) are characterized by differences with older link layer technologies, such as limited packet size (127 bytes for IEEE 802.15.4). This difference in packet length is required to ensure low bandwidth, necessitating the creation of an adaptation layer that corresponds to the length of the IPv6 header within the IEEE 802.15.4 specifications. This IETF 6LoWPAN working group developed the 6LoWPAN (low power personal network IPv6) standard that specifies the mapping required by IPv6 over WPANs [124] and provides IPv6 header compression to reduce transmission overhead and fragmentation to meet the requirement of the IPv6 maximum transmission unit (MTU) and support routing on networks where delivery will be through multiple jumps. The 6LoWPAN significantly reduces the IPv6 overhead in such a way that a small datagram can be sent through a single 802.15.4 frame packet at best and the IPv6 headers can be compressed in two bytes [125].

2.5.3.3 Link layer protocol

IEEE 802.15.4. This protocol specifies the physical layer (PHY) and the medium access control (MAC) sublayer in low rate wireless private area networks (LR-WPAN) [33]. Due to its specifications (low cost, low power, low data rate) it is widely used in IoT, M2M, and WSNs, as well as providing reliable communication with a high level of security, offering encryption and authentication to networks with a large number of IEEE 802.15.4 standard network topologies that may be in a star, peer-to-peer, mesh, and tree format. The star topology specifically contains a total function device (FFD) that acts as the master of the PAN network and is located in the center of the topology and is intended to control all other nodes and other reduced function devices (RFD). The topology point to point contains an FFD, and other nodes communicate with each other or through intermediate nodes. Tree topology is a particular case of point-to-point topology and consists of an FFD and common nodes [67].

2.5.3.4 Physical layer protocols

Bluetooth Low Energy (BLE). Compared to previous versions, Bluetooth Smart uses a short-range radio up to 100 meters, ten times longer than the classic Bluetooth and guarantees a 15-fold slower latency [126]. It operates with low power consumption at a transmission power between 0.01 mW and 10 mW, which prolongs the useful life of the device for up to years and makes the BLE a suitable suitor for IoT applications [127], more efficient than the ZigBee not only with regard to the consumption of energy as the rate of power transmitted per bit [128]. The BLE allows a star topology with master devices or writes with a discovery mechanism based on sending messages from the slaves to the master through a dedicated advertising channel that are checked by the master for the discovery to complete. Except when two devices are exchanging data, they are in standby mode.

Electronic Product Code (EPC). The EPC is a technology where an individual identification number is stored in an RFID tag used in supply chain management to identify items [129]. The RFID system is divided into two main components, the radio signal transponder (tag) and a tag reader. This tag uses an object's identity storage chip and an antenna to allow communication with the reader utilizing radio waves reflected in the tag so that after, the read information is sent to a specific computer application called object name service (ONS). O EPC is considered a promising technique for the future of IoT applications due to its openness, scalability, interoperability, and reliability [130].

Global System for Mobile Communications/General Packet Radio Services (GSM/GPRS). GSM networks were deployed throughout as an evolution of first-generation mobile communication systems. Initially, they were developed for voice transmission, but later they started to support data transmission through some specific timeslots at a low 9.6 Kbit/s rate in the uplink and downlink. After a technical evolution of the GSM, the HSCSD, the data rate had a rise and went to reach 14.4 Kbit/s in the uplink and 43.2 Kbit/s in the downlink. GPRS was made available to GSM users from GSM version 97 and enabled the use of data services, such as Internet browsing, WAP access, and SMS/MMS, but unlike the previous version, GPRS uses a packet-switched mode and shares the same transmission channel only when the data are to be addressed. The achievable data rates in GPRS depend on the supported multislot class that can reach 21.4 Kbit/s with a maximum of 8 downlink or uplink slots [131].

Wideband Code Division Multiple Access (WCDMA). WCDMA was set to provide high speed, packet-switched data services, enabling the more efficient use of the spectrum which provides higher transmission rates of up to 2 Mbit/s. WCDMA supports access to Internet-based services, such as fixed-line services. However, WCDMA has been defined without second generation backward compatibility requirements [132].

Long Term Evolution-Advanced (LTE-A). LTE-A encompasses a set of communication protocols that are well suited to machine type communication (MTC) infrastructures, machine-to-machine communication that does not require human interference, in addition to IoT, especially for smart cities where the long-term durability of the infrastructure is expected [133]. LTE-A outperforms other cellular mobile communication solutions related to the cost and scalability of the service and has an architecture that is divided into two parts where the first, called a control network (CN), contemplates mobile devices and treats the IP packets. The other, a radio access network (RAN), deals with wireless communication via radio and establishes the user plan and control protocols. The RAN uses base stations (evolved node) that are connected by an interface, called X2 since the connection of RAN as CN is made through an interface, called S1. Mobile devices or MTCs can connect to base stations either directly or through the MTCG gateway. They may also have direct communication with other MTC devices.

With the advancement of communication infrastructure to 5G, the current available technologies will be incorporated into this concept, meaning that 5G guarantees the specific needs as required. For example, some applications require low network latency, others require high bandwidth, and there are others that only require connectivity because of their low volume of data being transmitted, such as IoT-based applications. Considering these requirements for IoT applications and the current legacy networks under use, it is assumed to take over this demand until the NB-IoT and eMTC networks are fully available for the applications to use as a communication infrastructure.

2.6 Comparative analysis and discussion.

The summary of the comparative evaluation of this study is presented in Tables 1, 2, and 3, which include research efforts based on waste management using IoT, with attention to waste bins, which will receive the dumps and generate information through an IoT infrastructure.

Table 1 deals with the physical infrastructure of waste bins, such as types of waste supported by the container (organic, glass, plastic, paper, metal, toxic, or general waste without any selection criteria); bins positioning (indoor or outdoor); the pneumatic tube that automatically compacts garbage to decrease volume; and recycling and processing points for the refuse to be returned as a raw material or processed for the correct disposal. Through the provided study, each model is classified considering the important parts presented in each system. Regarding the physical infrastructure, in four models, waste bins for the organic discard are considered; in six models, waste bins for glass discarding; in seven models, waste bins for the disposal of plastics; in six models, waste bins for paper discard; in four models, waste bins for metal disposal; in only two models, waste bins for toxic waste disposal; and in nineteen models, general waste. In just one model, the dumps can be positioned both externally and underground; in the others, only externally. Pneumatic tubes are incorporated into two models, five models consider recycling points, and processing points for organic waste are supported in only one model.

Table 1: Physical infrastructure comparison considering the most relevant solutions available in the literature.

Ref.	Bins Type	Bins Location	Pneumatic Pipes	Recycling Points	Processing Points
[39]	Glass; Plastic; Paper; General Waste	Outdoor	Disregard	Not Supported	Not Supported
[40]	Organic; Glass; Plastic; Paper; Metal; Toxic	Outdoor; Underground	Incorporated	Supported	Supported
[41]	Organic; Glass; Plastic; Paper; Metal	Outdoor	Disregard	Supported	Not Supported
[42]	General Waste	Outdoor	Disregard	Not Supported	Not Supported

[43]	General Waste	Outdoor	Incorporated	Not Supported	Not Supported
[44]	General Waste	Outdoor	Disregard	Not Supported	Not Supported
[45]	Glass; Plastic; Paper; Metal	Outdoor	Disregard	Supported	Not Supported
[46]	Glass; Plastic; Paper; Metal	Outdoor	Disregard	Supported	Not Supported
[47]	Plastic	Outdoor	Disregard	Supported	Not Supported
[48]	General Waste	Outdoor	Disregard	Not Supported	Not Supported
[49]	General Waste	Outdoor	Disregard	Not Supported	Not Supported
[50]	General Waste	Outdoor	Disregard	Not Supported	Not Supported
[51]	General Waste	Outdoor	Disregard	Not Supported	Not Supported
[52]	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified
[53]	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified
[54]	Organic	Indoor	Not Specified	Not Specified	Not Specified
[55]	General Waste	Outdoor	Not Specified	Not Specified	Not Specified
[56]	General Waste	Not Specified	Not Specified	Not Specified	Not Specified
[57]	General Waste	Outdoor	Not Specified	Not Specified	Not Specified
[58]	General Waste	Outdoor	Not Specified	Not Specified	Not Specified
[59]	General Waste	Outdoor	Not Specified	Not Specified	Not Specified
[60]	General Waste	Outdoor	Not Specified	Not Specified	Not Specified
[61]	General Waste	Outdoor	Not Specified	Not Specified	Not Specified
[62]	General Waste	Outdoor	Not Specified	Not Specified	Not Specified
[63]	General Waste	Outdoor	Not Specified	Not Specified	Not Specified
[64]	General Waste	Outdoor	Not Specified	Not Specified	Not Specified
[65]	General Waste	Outdoor	Not Specified	Not Specified	Not Specified
[66]	Organic; Glass; Plastic; Paper; Metal; Toxic	Outdoor	Not Specified	Not Specified	Not Specified

Table 2 deals with IoT technologies considering the following: RFID support; types of used sensors (capacity, weight, temperature, humidity, chemical, pressure); automatic actuators (prevent excessive deposit); cameras positioned to overlap sensor function; global positioning system (GPS); and IoT architecture (solution not mentioned and declared as implicit or solution developed and declared as defined). RFID is embedded in six models, a capacity sensor is present in twelve models, and weight in eight, while temperature in four models, humidity in tree modes, chemical and pressure sensors are present in only one model.

Table 2: IoT Technology comparison for the most relevant solutions available in the literature.

Ref.	RFID	Sensors	Actuators	Camera	GPS	Architecture
[39]	Disregard	Capacity; Weight	Disregard	Disregard	Disregard	Implied
[40]	Incorporated	Capacity; Weight; Temperature; Humidity; Chemical; Pressure	Incorporated	Disregard	Incorporated	Defined
[41]	Disregard	Capacity	Disregard	Disregard	Disregard	Implied
[42]	Disregard	none	Disregard	Disregard	Disregard	Defined
[43]	Disregard	Capacity	Disregard	Disregard	Disregard	Implied
[44]	Incorporated	Capacity	Disregard	Disregard	Disregard	Defined
[45]	Incorporated	Capacity	Disregard	Disregard	Disregard	Defined
[46]	Incorporated	Capacity	Disregard	Disregard	Disregard	Defined
[47]	Disregard	Capacity; Weight	Disregard	Disregard	Incorporated	Defined
[48]	Disregard	Capacity	Disregard	Disregard	Incorporated	Defined
[49]	Disregard	Capacity	Disregard	Disregard	Disregard	Defined
[50]	Disregard	Capacity	Disregard	Disregard	Disregard	Defined
[51]	Incorporated	Capacity	Disregard	Disregard	Disregard	Defined
[52]	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified
[53]	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified
[54]	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified
[55]	Not Specified	Capacity; Weight	Not Specified	Not Specified	Specified	Not Specified
[56]	Incorporated	Capacity	Not Specified	Not Specified	Not Specified	Not Specified
[57]	Not Specified	Capacity; Weight	Not Specified	Not Specified	Not Specified	Not Specified
[58]	Not Specified	Capacity; Weight; Temperature; Humidity	Not Specified	Not Specified	Not Specified	Not Specified
[59]	Incorporated	Not Specified	Not Specified	Disregard	Disregard	Not Specified
[60]	Not Specified	Capacity; Infrared	Not Specified	Disregard	Not Specified	Not Specified
[61]	Not Specified	Capacity; Infrared; Temperature; Proximity	Not Specified	Disregard	Not Specified	Not Specified
[62]	Not Specified	Capacity; Weight	Not Specified	Not Specified	Incorporated	Not Specified
[63]	Not Specified	Infrared	Incorporated	Not Specified	Not Specified	Not Specified
[64]	Not Specified	Infrared	Not Specified	Not Specified	Not Specified	Not Specified

[65]	Not Specified	Infrared; Weight; Humidity	Not Specified	Not Specified	Disregard	Not Specified
[66]	Not Specified	Infrared; Gas; Temperatute; Humidity	Incorporated	Disregard	Incorporated	Not Specified

To conclude, Table 3 deals with software analysis, i.e., how the information will be used. It can follow a dynamic collection planning; a dynamic routing of the collection; and the experimental evaluation for each research effort (Simulator or Real). In the category of software analysis, eleven models for dynamic programming are considered and the dynamic routing is also present in seventeen models, while real experimental data are adopted just in one model, with all other models using simulators.

Table 3: Experimental analysis comparison for the most relevant solutions available in the literature.

Ref	Dynamic Scheduling	Dynamic Routing	Experimental Data
[39]	Not defined	Not defined	Simulator
[40]	Defined	Defined	Simulator
[41]	Defined	Defined	Simulator
[42]	Not defined	Not defined	Simulator
[43]	Defined	Defined	Simulator
[44]	Not defined	Not defined	Simulator
[45]	Not defined	Not defined	Simulator
[46]	Not defined	Not defined	Simulator
[47]	Not defined	Not defined	Simulator
[48]	Not defined	Not defined	Real
[49]	Defined	Defined	Simulator
[50]	Defined	Defined	Simulator
[51]	Not defined	Not defined	Simulator
[52]	Defined	Defined	Simulator
[53]	Defined	Defined	Simulator
[54]	Not defined	Not defined	Simulator
[55]	Not defined	Not defined	Simulator
[56]	Not defined	Not defined	Simulator
[57]	Not defined	Defined	Simulator
[58]	Not defined	Defined	Simulator
[58]	Not defined	Defined	Simulator
[59]	Not defined	Defined	Simulator
[60]	Not defined	Defined	Simulator
[61]	Not defined	Defined	Simulator
[62]	Not defined	Defined	Simulator
[63]	Defined	Not defined	Simulator
[64]	Defined	Defined	Simulator
[65]	Defined	Defined	Simulator
[66]	Defined	Defined	Simulator

Among all the papers analyzed, from physical infrastructure, many authors propose a waste management model through IoT with collection emphasis, offering scheduling models with dynamic routing for greater effectiveness of collection, using low fuel consumption. Other authors focus on specific bins for each type of waste that promote to users a selective disposal way; there are even models where a bonus based on the amount of recyclable waste is offered to the user and models where the user, based on a mobile app, can query green waste points. There are also authors who propose recycling and processing points not relevant to this research. In a general context, all the models have a focus on the collection system.

Considering aspects of IoT technology, some authors incorporate the identification of a waste bin through RFID and others not, a fact that makes it not necessary when a GPS is considered, but few models adhere to GPS technology. The variety of sensor types is not well explored in most models, which can lead to false positives when waste disposal is low in volume and high in weight. Automatic actuators are not necessary, since not all types of discards are compressible. Cameras installed in bins are a fact that can be discarded when using appropriate sensor models. The waste management system has its architecture explicitly defined when dependent on a standard or implicit model when part of the overall design of the system.

One of the critical points of solid waste management that are being studied today is waste collection. This research effort makes a lot of sense when we stop to reflect that 80% of the costs spent on waste management are used in fleets of trucks that travel daily to cities, collecting waste discarded by the population [134], a situation that expresses a reasonable basis for a collection process to be practiced, with optimized routes where any improvement achieved can represent a considerable saving of time and money.

Many studies aiming to optimize routes for solid waste collection often relate them to the problem of the street vendor [135] (one of the most studied optimization problems), defined as a salesman who needs to visit several cities passing through each of them only once and return to the home city by running the course at the shortest distance. A system to calculate the better collection routes can be modeled as the problem of the hawker, and the solution of this problem can be through exact algorithms that are an algorithm that always finds the ideal solution for an optimization problem or by heuristic algorithms that can sometimes produce worse solutions. This great challenge of solid waste management systems has been an opportunity for study and proposing robust algorithms capable of dealing with adverse issues presented by IoT-based systems. Within these adversities, the main aspects that can be considered include the large volume of data offered, the speed of receiving such data, the data heterogeneity, and the data loss during transmission. Running a data analysis from heterogeneous sources (in the order of Terabytes or even being able to reach Petabytes, which arrive at high speed and often with losses during transmission) becomes hard work that can take a tremendous amount of time and there is not a useful parameter for a solid waste management system or even an unlikely one for some algorithms. Moreover, in Reference [136], the authors propose an algorithm-based tool model with automatic learning "machine learning" that stipulates efficiency metrics to be used to obtain help in making decisions, based on open information.

Among the major algorithms available in the literature, the following are relevant: Backtracking search algorithm [137], ArcGIS [138], heuristic [139], and particle swarm optimization [140]. Recently, a study was published in Reference [52], where a comparison of these algorithms is presented by adding an expectation algorithm model to a waste collection approach. It takes into consideration the receipt of moving data. Receiving data in movement is very different compared to receiving statically. The paper concludes the study by proposing a guideline for the development of intelligent multiobjective approaches based on algorithms with a weighted sum to convert it into a single goal model through known priorities and loss-measuring capabilities.

Human factors are another critical aspect that should be considered during the design of the solid waste management solution, since smart compartments will be positioned in public areas, such as parks, stadiums, and streets where parties, religious events, music events, sporting events, and widespread demonstrations are usually held. Clusters of people are the most part characterized by the diversity of both physical and socioeconomic as well as cultural characteristics that demonstrate a different behavior when organized in large numbers of people. Studies are applied through simulations in large crowds on different aspects to understand their behavior and establish standards and turn them into heuristics that will help in decision making and predict certain situations, mainly, in evacuation when the so-called panic occurs. In Reference [141], a study is applied through dynamic multisimulation based on modeling agents applied to both urban space and individuals within a crowd. This dynamic becomes important within the concept of solid waste management to predict behavior when present in large clusters of people.

Another important aspect that must be considered within a waste management system is the consumption of the battery generated using the devices/sensors available in a solution. The IoT nodes used in solid waste management include ultrasonic sensors and load cell [142], GPS [143], actuators [40], microcontrollers [144], and transmission modules [145]. Some studies describe the use of renewable energy through photovoltaic panels for battery charge and avoid constant manual intervention for replacement. There are also aspects related to the network topology employed in the solution, such as point-to-point model topology, star model, hierarchical model, etc. Depending on the used topology model, nodes can consume more or less energy, just as the distance of node positioning should also be considered. Nodes closer to the base radio tend to spend less energy than nodes located at the periphery of the cell, bearing in mind that transmission modules are responsible for the higher energy consumption. The communication technology employed is also an aspect to be considered, whenever possible, to use low power technologies, such as 6LoWPAN [77], BLE [126], etc., as well as to consider the aspects of sensing, such as whether it will occur periodically, continuously, reactively, or in real time. Based on the aspects mentioned above in Reference [136], a study was directed at the development of a sensor node for the real time monitoring of the level of filling of dumps based on the low energy consumption and the cost containment. They are retained not only to the sensor node more efficiently in terms of energy levels but also to the architecture of the solution, taking in account microcontrollers that can attend the computational capacity with low energy consumption and to use policies that shut down the node or even part of it when idle.

Another very favorable aspect that can help solid waste management systems is using data analysis to provide the capacity to forecast the generation of waste from a municipality in the short term. Based on data already collected within a specified period, an analysis will be applied, through which more efficient collection planning is enabled and even resources are estimated for a probable growth in the generation of waste that leads to higher investments in infrastructure. Some studies are based on the artificial neural network as presented in Reference [146] that uses input variables related to environmental issues, socioeconomic issues, changes in consumption patterns, and even population growth associated with migration. Through these analyses, it is possible to select the best results based on these performance indices applied for each criterion and thus improve municipal solid waste management implementations. Additionally, in Reference [147], a time series of autoregressive artificial neural networks is used to predict the monthly generation of residue since the characteristics of the solid waste generated are different in different places.

The analysis of the related literature identified open issues that can be addressed in further research work. They can be considered as improvements for proposed systems and identified as follows:

A waste management platform focusing on citizens' perspective that can interact with the system through a mobile application that, through its location, finds the bins closest to their residence with the respective level of use. Knowing this information, the user can choose to discard the garbage at that moment in a container that has availability or even to retain it and wait until the collection system empties the deposit. In this way, the user will be contributing to the non-overflow of the containers and avoiding that their waste is exposed in the open. The solution includes a physical cabinet equipped with an ultrasonic sensor (HC-SR04) and a load sensor coupled with an amplifier module that continuously detects the volume and weight of the waste contained therein. There is also a third sensor (DTH11) that measures the temperature and humidity of the environment where the enclosure is inserted, as well as a GPS module that determines its global coordinates. The sensors are managed by an integrated development environment (IDE) microcontroller. In this proposal, an Arduino Mega 2560 was used, which also controls communication through a SIM900 GSM / GPRS module attached to it. Data is then transmitted to a middleware where it is stored and made available to a mobile application developed for smartphones [7], and the enclosure power is supplied through a rechargeable battery powered by a photovoltaic card.

The waste management system may be the future object of study for solutions of a shorter path for collection routes, that is, trucks already leave with a route previously traced searching for the containers that need emptying. In this way, it is possible to achieve better collection effectiveness in a shorter time and with low fuel consumption. There are many studies available in the literature that present different solutions for the shortest path in collection routes. A waste management platform that focuses on citizens' perspective, as above described, coupled with a resolution of the best collection path can bring enormous gains to smart cities.

The waste management system can be integrated with future parking management studies for vehicle parking. Containers can be positioned as a gateway for parking sensors, which already have an integrated transmission system and the information is presented to users through an application that traces the route from the original position of the vehicle to the available parking space. With a built-in waste management infrastructure, it is possible to add new applications to the base system. A good example would be parking management using infrared presence sensors based on the standard IEEE 802.15.4 with intelligent dumps, which transmit data to the same integrated middleware and, later, are made available to the user through a mobile platform.

Another point that may be the focus of future work is the deepened study on the life cycle of rechargeable batteries to be used in waste management systems. As these batteries are fixed in the containers that most of the time will be propitious climatic actions, an analysis of the functions of the cell and its interactions with the environment must be studied, as well as its handling and protection against the increase of temperature due to outbreaks due. In this case, the study is not targeted at applications based on smart cities, but the development of new generation batteries can benefit many applications and contribute significantly to the evolution of projects within science and technology.

3 Proposal for a waste management solution for citizens

The solid waste is an issue that has been increasing considerably in major urban centers around the world and consequently has substantial urban impacts when municipalities do not have an adequate management of these wastes [27]. The absence of a proper solid waste management program, either domestic or industrial, results in a danger to society. The threat can arise through diseases caused by exposure to waste and through environmental impacts, such as soil contamination and water resources. However, another negative aspect is the visual degradation of cities. In many parts of the world, the solid waste management system has been perpetuating over the centuries without any innovation, remaining with very inefficient collection model, with weekly agendas and trucks traveling long distances to collect the waste that is often laid out on sidewalks and public roads [148]. With the unbridled and disorganized growth of the population and all chances of abandonment of the rural area, urbanization has assumed increasingly extreme proportions, and consequently, the generation of waste has become a major urban problem, which leads to reflection on the importance of reducing the waste generation around the world. However, more effective management of the waste generated by these large urban centers is essential, which is a challenge for the competent authorities. The concept of Smart Cities with its "smart" technology projects makes the future of citizens increasingly sustainable and comfortable, taking urban development to integrate multiple solutions of information and communication technologies into an Internet of Things (IoT) sensitive context and thus manage the assets of a city. The European Union defined Smart City as a system where people interact and use energy, materials, and services to stimulate economic development and improve the quality of life [149]. However, these interactions flows are considered intelligent because they make strategic use of infrastructure, services, information, and communication in the planning of urban management, way to meet the social and economic needs of society. The city resources may include, but are not limited to, information systems for local departments, schools, libraries, transportation systems, hospitals, power plants, law enforcement, vehicle traffic, waste management, and other community services [150].

Based on the concept of smart cities described above, this chapter proposes an efficient waste management model for large urban centers focusing on the citizen's perspective, unlike other studies presented previously, which focus only on the collection carried out by the owners. The complete solution is illustrated in Figure 5, represented by an intelligent dumpster that continually measures the level of waste deposited inside it and the relevant data is transmitted via the internet to a middleware that is responsible for storing and making the information available to the user through a mobile application.

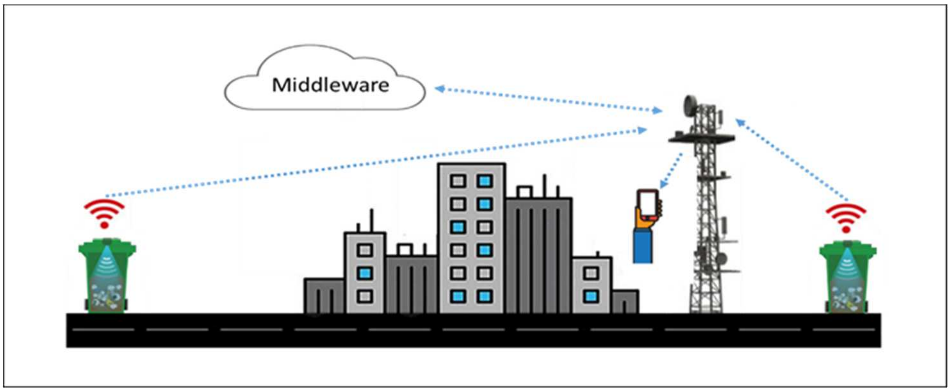

Figure 5: Smart waste management solution.

This dissertation proposes a solution that comprises hardware, software, and communication integrated into a solution that aims to optimize the management of the waste produced in the cities through an approach that generates saving of the public money, contributes with the environment, and encourages citizenship.

3.1 Presentation of IoT-based waste management solution

The waste management system currently used in the cities still follows an old and outdated model that no longer meets the needs of municipalities. It is inefficiently and practiced through large fleets of collection trucks that travel daily long distances, often by unnecessary regions while others are discovered, and with daily or weekly service schedules. These aspects bring unnecessary costs, waste of time and, more significantly, environmental damage, not only by the emission of gases from the burning of fossil fuel which contributes to the greenhouse effect but mainly by the contamination of the soil and water resources due to poor waste management.

The system includes an applied solution where the compartments are monitored continuously by sensors that inform, in real time, the filling level of each one. These data are transferred to a storage and processing unit to serve as information so that competent authorities can stipulate priority collection areas, collection paths with optimized routes, and generate statistical data so the resources are employed adequately in regions with the highest demand for service. However, the focus of the solution is to provide citizenship for residential users. Citizens can identify the compartments close to their home and know their level of usage, in advance, via Web or a mobile App. If the system recognizes unavailability at the nearest collection point, the user will be directed to discard his/her garbage at another available point and will receive the collection forecast from the previous bin, which allows the user to choose between a possible disposal at another location not so close, or even preserve the garbage at home so the disposal takes place at another time, after the municipal collection.

The My Waste Management system considers three large blocks, as shown in Figure 6. The first describes the smart bin, the second block considers the IoT middleware integration, and the last block presents the user’s application.

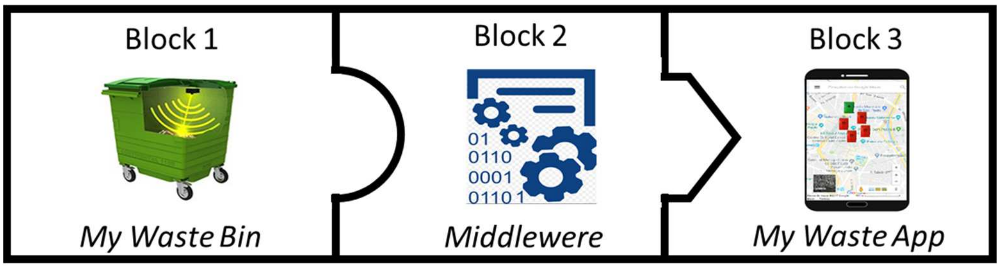

Figure 6: Blocks diagram of My Waste Management System.

3.2 My Waste Bin: A smart waste bin prototype

The waste bin is considered intelligent because the enclosure is equipped with sensors, such as the HC-SR04 module, an ultrasonic sensor responsible for measuring the level of waste filling present inside the compartment. Significant within the solution because through its operation it is possible to avoid the overflow of waste or the excessive garbage deposit. The solution also includes a load cell module (load sensor) that measures the weight of the residues present in the compartment. It is characterized by a great importance within the system since many residues have a small volume and significant mass. The load sensor is coupled to a specific driver, such as HX711, which amplifies the signal emitted by the load cell, in addition to provide interconnection with the microcontroller.

The competence of these two modules is an aid to the HC-SR04 continually informing the weight of the waste deposited in the compartment to contribute with more comprehensively information of the residues present in the smart bin. A temperature and humidity sensor, such as the DHT11 is present in the solution to add relevant information about the environment where the enclosure is inserted. The air temperature and relative humidity are additional information added to assist the system user during the path for disposal of their waste. To enable smart bin tracking, a GPS module (model Neo-6M) was used to print geographic coordinates that represent the exact location of each bin. Through this location, the system will be able to inform users the distances between them and the compartment closest to its location.

The communication between the smart bin and the middleware is performed via a SIM900 GSM / GPRS module. Through this module, the communication using second generation (2G) cellular technology is possible. It was decided to use this type of technology due to the extensive network infrastructure available and the low operating costs. Another important aspect is the access network coverage, as smart bins will be scattered throughout the city and often in the shadow area of mobile services. A technology that uses low frequency of radiation guarantees better penetration, preserving the proper functioning of the system. Finally, the system does not require large bandwidth for data transmission correctly, so these aspects make the 2G technology entirely feasible for the proposed scope [7].

As a central processing system required to control the smart bin, an Arduino board [151] was used. It is based on a programmable physical circuit and an Integrated Development Environment (IDE) used to write and upload code for a physical board. This open prototyping platform features a simple programming feature, ideal for IoT-based applications. The total power of the system is made by an external rechargeable battery coupled to a photovoltaic solar panel capable of recharging the cells during the daylight period. Figure 7 shows the image of the My Waste Bin prototype.

Figure 7: My Waste Bin Prototype.

When initialized, the My Waste Bin system sends its geographical coordinates together the date and time obtained through the satellite through the GPS module to the middleware [152]. The weight and volume of the waste are transmitted initially as zeroes along with the other data obtained through the sensors (temperature and relative humidity of the air). These data are stored in the system and the compartment can already be found by the application as being able to receive waste. In the sketch of the Arduino [153], a timer instruction is inserted and cyclically executes sensing (300 seconds) to evaluate possible changes in the status usage of the compartment. Each time the filling level and volume is changed, a new transmission is executed sending all the data obtained by the sensors. This sensing loop runs until the compartment attain its full fill level. From that moment, the application will notify this compartment as full and the user (citizen) will receive new waste disposal options through other compartments available in the area. For the concessionaires, it is already a compartment eligible for collection. Figure 8 illustrates the working flow diagram of the smart My Waste Bin.

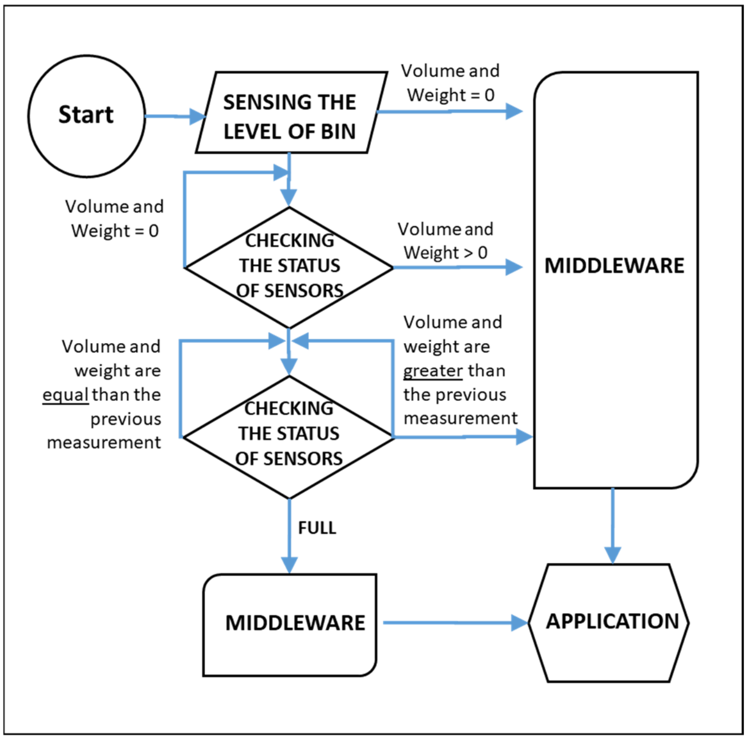

Figure 8: My Waste Bin Flowchart.

It is an excellent way to promote citizenship, i.e., the intelligent trash that does not overflow prevents terrible consequences for citizens life, such as the clogging of Fluvial water gallery, the cause of the flood, diseases proliferation, and the degradation of appearance presented by residues scattered along the sidewalks, as illustrated in Figure 9.

Figure 9: Image of consequences of lack of waste management.

3.2.1 General Architecture

The proposed Smart Waste Bin system can be adapted into general waste-bin and it includes sensing units, a GPS module for location, a GPRS/GSM module for data transmission, the main microcontroller, and power supply. The general architecture of this proposal is shown in Figure 10.

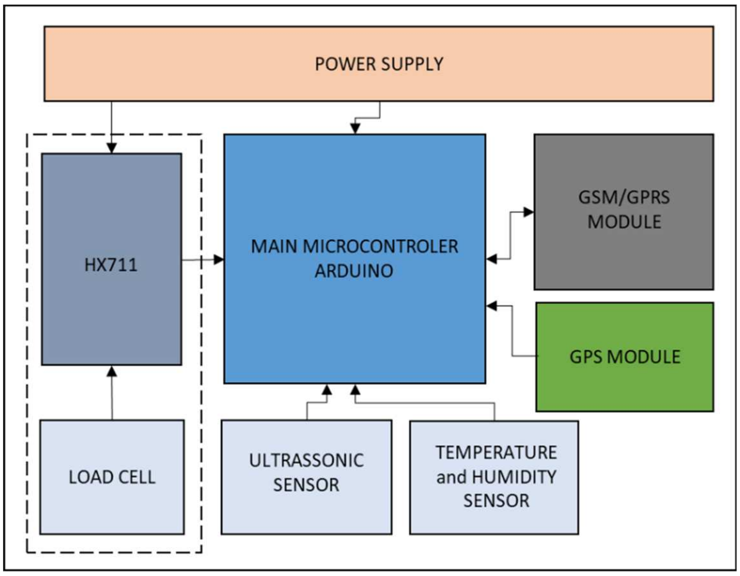

Figure 10: Smart Waste Bin architecture.

The smart bin consists of a container with a lid, equipped with measuring devices that are divided into two paths, where the first path is assembled on the compartment cover and the other is placed at the bottom of the compartment. The other devices (Arduino board, temperature sensor, GSM/GPRS transmission system, GPS system and power devices) are placed in the back of the smart bin. All the used instruments are shown in Figure 11.

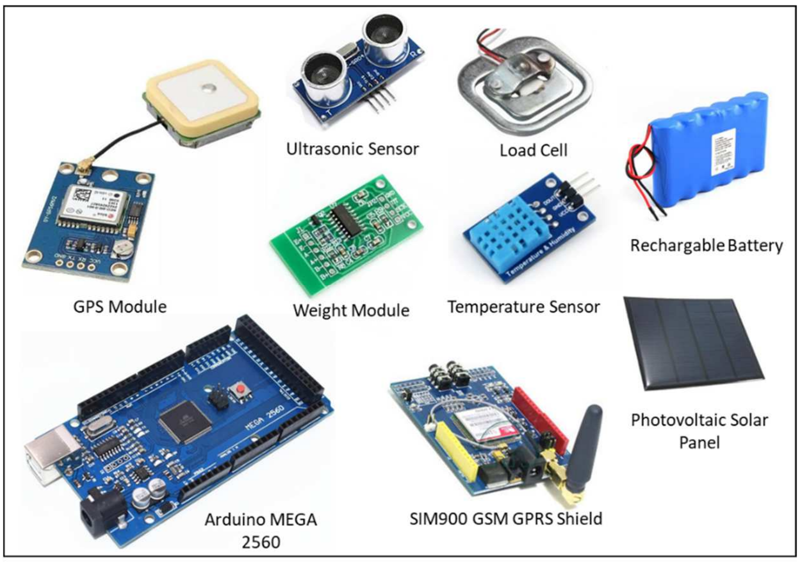

Figure 11: Image of smart bin devices used in the proposed solution.

3.2.2 Measuring device

The measuring device is created with an ultrasonic sensor [154] connected to the upper side of the bin. Ultrasonic sensors are advantageous in providing amplitude measurements because they do not depend on the object's shape which their sound wave will be reflected, making possible the corresponding translation in level measurements. They are more suitable for this type of solution as they can be positioned on the container lid and thus avoid adverse conditions (contact with waste, washing procedure, etc.). Ultrasonic sensors such as HC - SR04 can have a beam with a full field of view operating at a detection distance of 2cm to 450cm so the entire housing can be sensed without cabling and interconnection needs. This type of sensor is typically based on a single transceiver unit that is capable of emitting and detecting sound, so a sonic pulse that is beyond the human ear listening range is created, and most solid objects can reflect these sound waves. The transceiver uses a timer to accurately determine how long an ultrasonic pulse takes to "bump" on an object and return to the unit. From then, the fill level of the smart bin can be measured.

Another measuring device used in this solution is the load cell [155]. This sensor is mounted in the lower part of the compartment below a (plastic) board, simulating a weighing scale, to avoid problems during the washing procedure. Load cells exploit the variation of electrical resistance that occurs when specific materials are subjected to compression or traction. A load cell is composed of a metal bar, characterized by a central cutout, to facilitate flexing when a force is applied. The most important part of the sensor is strain gages that, placed on the bar, can provide information to scale the resistance change. To be interpreted by a specific driver, such as an HX711 (24-bit precision analog-to-digital converter designed for interface directly with a load sensor), allows the Microcontroller to formulate information about the stress (weight) loaded on the bar. The level sensor operating in parallel with the load sensor, aiming to add to the solution an efficient identification model of the deposited residues. Then, it is possible to identify types of low waste volume with high weight and high volume, but low weight.

The last measuring device used in this solution is a temperature and humidity sensor, like DHT11, which allows reading temperatures between 0 to 50 Celsius and humidity between 20 to 90%. The purpose of these sensors is to add information to the solution beyond waste management and to provide citizens with well-being during waste disposal times. Through this sensor, the citizen can monitor, in real time, the temperature of the environment where the box is located.

3.2.3 GPS System

The smart bin global location via GPS is so important to the entire solution as the volume and weight information measured by the sensors. Through these coordinates, it is possible to identify the exact location where the bin is positioned and thus reference the path of the citizens during the process of garbage disposal, and for the optimization of collection routes for the municipal service [156]. The Global Positioning System was created by United States Department of Defense and has as its essential function to identify the receiver located on the surface of the earth. Because GPS is currently the most modern and accurate way to determine a point on the earth's surface, its use is crucial for the exact location of the smart bin. Then, in the future, an application installed on the user's smartphone provides the positioning of the containers and the citizen can choose the nearest available collector container to serve him/her.

3.2.4 Communications

The communication technology used in this waste management solution is GSM/GPRS [157]. This approach is responsible for transmitting all the information related to the waste bin, such as the level and weight of the waste, global location, temperature, and humidity. For a further middleware platform that will be responsible to store and handle data. Then, a user (citizen) can access them through an application and thus visualize the capacity of the bin. A middleware is the software that runs between the operating system and the applications running on it, mainly functioning as a hidden layer of translation, allowing communication and data management for distributed applications. In [107], a plethora of available IoT middleware are studied in detail to find the most suitable one that best performs to support these applications soon.

When the waste bin is reaching the maximum level of filling, a notification is sent to the service of garbage collection. The SIM900 was the chosen option for this solution. It is a quad-band module that works on frequencies GSM 850MHz, EGSM 900MHz, DCS 1800 MHz, and PCS 1900MHz with features GPRS multi-slot class 10 / class 8 and supports the GPRS Coding Schemes, CS-1, CS-2, CS-3, and CS-4, that provide different levels of error detection and correction dependent upon the radio frequency signal conditions and the requirements for the data being sent. It has 68 SMT pads and provide hardware to interface between the module and customers' boards, integrates an IP architecture a non-connection-oriented network service provided. The GSM/GPRS technology was taken into consideration; firstly because of the small amount of information to be transmitted, another relevant point is the IP protocol support that is the basis of the Internet connectivity (facilitating interactivity with other systems). Coverage is a determining factor since this proposal is developed for an outdoor environment. Currently, there is an excellent availability of 2G networks with low license cost and without the need for investments with infrastructure, when compared to technologies like LoRa, SigFox, and LTE, but they are robust technologies that can be an option as well as Wi-Fi (most urban centers already have good coverage).

3.2.5 Microcontroller

The Arduino board is being considered as prototyping to achieve automation. For a high-scale solution, several chipsets can be used turning the solution cheaper, but the Arduino provides simplicity and low assembly time of the prototype. It acts as the central processing unit and controls the interaction and synchronization of the sensors allowing the voltage flowing across sensors after a certain period, which reduces energy waste through sensors. It also controls the GPS modules responsible for the information received from the satellites and the GSM/GPRS module used to transmit the data to a middleware platform. For this, an important aspect is the standard Arduino connection mode that allows CPU being interconnected to other expansive modules, known as shields. Its board consists of an 8-bit Atmel AVR microcontroller with complementary components to facilitate programming and incorporation into other circuits, including a 5-volt linear regulator and a 16-MHz crystal oscillator (which may be variants with a ceramic resonator). In addition, for being a microcontroller, the component is also pre-programmed with a bootloader, which simplifies program loading for the built-in flash memory chip.

3.2.6 Power Supply

The power supply consists in an external rechargeable battery, coupled to a photovoltaic solar panel that enables the recharge of the battery throughout a day, avoiding the need to replace the module after some time of usage.

All these devices working together form the smart waste bin solution. The ultrasonic sensor with the load cell is responsible for measuring the level and weight of the discarded waste to identify when the container needs to be unloaded or stop receiving waste, either by filling its volume or by the maximum weight reached. The GPS module determines the exact geographic coordinates of the container so that its future location is possible. The temperature sensor checks the outside temperature, relevant information to the moment the user leaves home to discard their waste.

All information from the smart bin is transmitted to a Middleware platform through the GSM / GPRS module so that the citizen can, through a mobile application, check the status of these containers online.

3.3 The IoT Middleware Integration

Middleware is a software that connects base systems such as IoT devices to each other and third-party applications [109, 158]. It works as a layer of translation allowing communication and data management for distributed applications. Within the waste management system (and other IoT systems) the middleware plays an essential role because it receives all the data sent by the containers and stores them so that specific queries executed by the application are quickly and consistently accessible to the user. In this case, the middleware used was the In.IoT [https://inatel.br/in-iot/] [159, 160] and it also allows users to visualize the waste bin status in real-time via Web as showed in Figure 12.

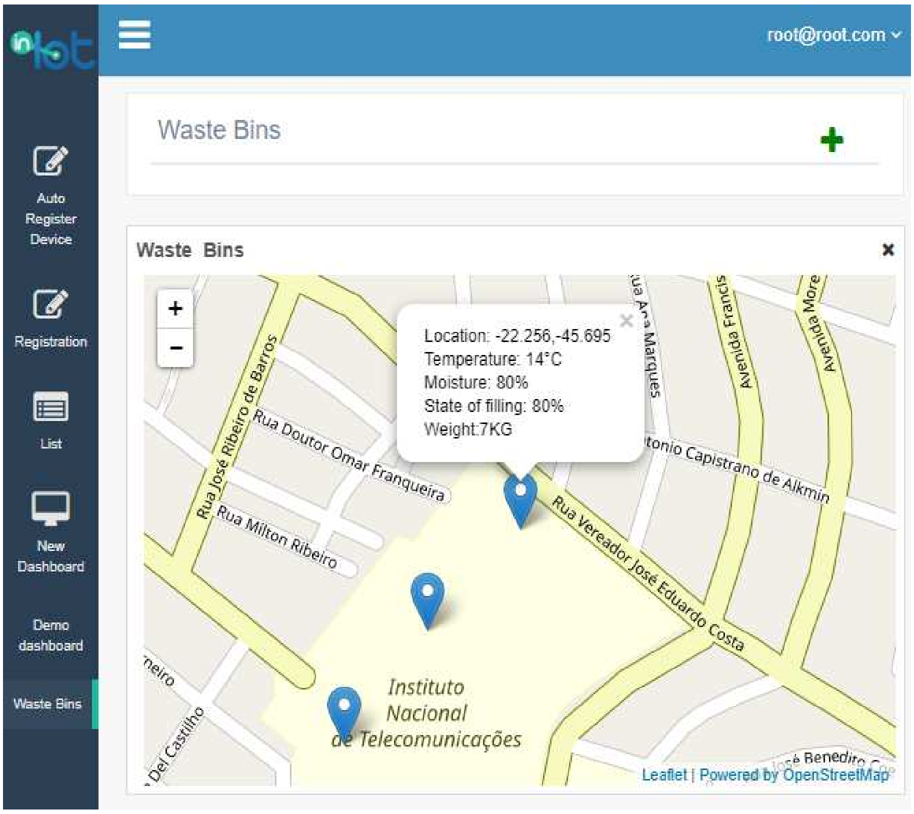

Figure 12: Image from the In.IoT middleware platform showing the location of smart bins.

3.4 My Waste APP

Over the years, mobile phones have evolved from a simple device that just kept communication between people to powerful application processing center where any task happens to be possible. Therefore, modern users would never use a smart waste management solution if not through their smartphone. With this concern, the My Waste App was designed. It is a hybrid mobile application built with Ionic [161] and it is compatible with Android and IOS mobile operating systems. Ionic is an open source framework used for creating mobile applications for the various existing platforms. It has been chosen as a tool for the construction of My Waste App because it is free and present a simple and easy interaction user interface, besides using technologies usually employed in Web solutions which gives the app a very professional aspect.

The App queries data sent to In.IoT and allows users to identify and verify the status of nearby waste disposal sites. In addition, the user can also visualize predictions of disposal sites, allowing users to dispose of their waste after municipal collection.

When starting to build an App it is very important to have a list of well-defined requirements, good requirements provide the development of a clearer system and closer to achieving user satisfaction. A weak application of requirements can lead to the disuse of the App and, thus, ruin the entire productive chain of the system.

Given the importance of this aspect, My Waste App takes into consideration the following requirements: the user need, the requirement for business, and the desire to be obtained with the system. The residential user has a well-defined need that is to dispose of their waste in a practical, fast, and without harming the environment; the requirements of the business is to identify the waste generation sites, capture them correctly using appropriate compartments, encourage user interaction with the system through updates of relevant information, such as location and available capacity of the compartments, collection scheduling, and (of course) receiving feedback from the user. The system aims to provide citizenship (show the user that each one is responsible for the waste generated until the time of disposal), to provide a cleaner environment free of setbacks due to poor waste management, minimize waste collection system, and contribute to reduce the traffic of automotive vehicles.

The My Waste App application can be customized accordingly to the profile of each user with the possibility of a favorite container register as, for example, a container located closer to his / her residence, along with the days of a week and the time that he/she frequently uses to dispose of his/her waste. This way, the application can automatically check the status of the favorite container and pass usage information through a pop-up. If the compartment has a maximum fill level, the collection schedule is already displayed along with a second available bin option. The application can also be used through sporadic queries at times of discard, without the need to register favorites, so the system crosses the location of the user's smartphone with the containers positioning and offers the option that is feasible for the moment. The purpose of the system is to help users practice proper disposal of their waste by presenting waste disposal options available to receive their waste even before the user leaves the house. If no option is feasible at the time, the user can consult a collection schedule and reserve their waste at home for disposal at a more appropriate time.

The system can also be accessed through a Web browser [162], a way for the garbage collection agencies to obtain information on filling the containers and thus to plan their collection routes in an optimized and pre-scheduled manner, as well as facilitating the insertion of data to be made available to users, such as the collection schedule or out-of-service notification for maintenance purposes. The system also allows the estimation of places with higher demand for use which allows the allocation of new collection containers in the areas with application responding quickly to the users' needs. Figure 13 presents a view of My Waste App.

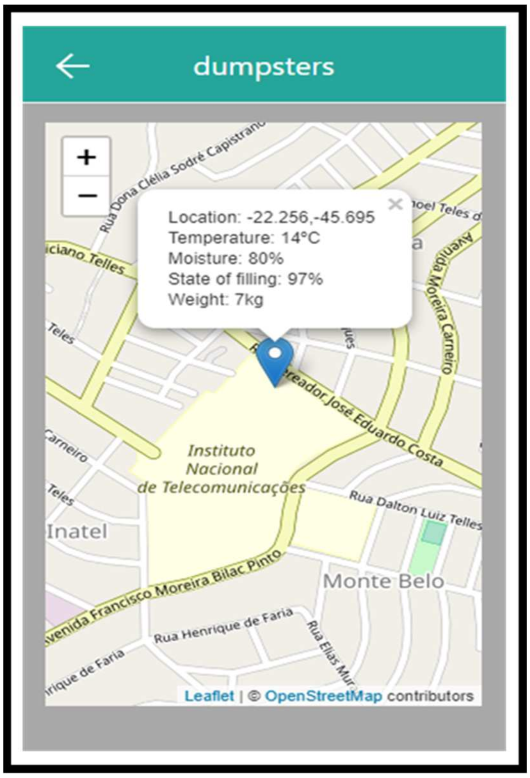

Figure 13: Image of My Waste App.

4 Performance evaluation, demonstration, and solution validation

Solid waste management has been a significant challenge for cities around the world [163]. In the absence of an effective and efficient solid waste management program, waste generated by urban activities, both industrial and domestic, can result in health risks and harm the environment [164]. Understanding the waste generated, the availability of resources and the environmental conditions of a given society are essential for the development of an appropriate waste management system. Solid waste is defined as materials that no longer interest the original owner and are discarded. A good example is an organic waste (including kitchen waste and leftovers from garden pruning), paper, glass, metals, plastics, fabrics, and wood. Solid waste management is associated not only with generation control but also with the disposal of solid waste in a way that follows the best principles of health, economy and other considerations as to the environmental attitudes developed by citizens.

Compared with developed countries, citizens of underdeveloped countries suffer most severely from the impact of unsustainably managed waste, In Brazil, for example, 80 thousand tons of solid waste is disposed of inadequately every day, says United Nations (UN) [165]. In these countries, garbage is often disposed of inappropriately in rivers, streets or even in open incineration, these practices have severe consequences for health, safety, and the environment. Improperly managed waste can serve as a rich source of disease and contribute to global climate change through the generation of greenhouse gases, and even promotes urban violence with the degradation of urban environments. Proper waste management is essential for the construction of sustainable and habitable cities but remains a challenge for many developing countries and cities. Effective waste management often becomes costly, compromising municipal budgets. Operating this essential municipal service requires an integrated system that is efficient and sustainable [166].

The concept of smart cities is aimed at urban development by integrating information and communication technologies (ICT) and the Internet of Things (IoT) [6]. Internet of things is a composition in which all things have an exhibition on the Internet. More specifically, IoT aims to offer new applications and services by bringing together the physical and virtual worlds in which Machine-to-Machine (M2M) communication represents the interface that enables interactions between things and applications in the cloud, such as monitoring waste generated in a city [167].

IoT can deliver significant savings, improve utilization of a city's assets, increase process efficiency, and add productivity by directly linking low-cost technologies such as sensors and actuators to evolving wireless technologies and the power of computing in cloud. In smart cities, the waste management system is a crucial point into the environment that IoT tends to address [168]. Based on this, an efficient waste management model for cities with a focus on citizen perspective is presented. It includes a sensor system where waste information is collected from the smart bin (things), in real time, and then transmitted, through the Internet, to an online middleware platform where citizens can access and check the availability of the compartments scattered around the city. A real prototype of the smart container was created, evaluated, demonstrated, and validated, and is ready mapped in a real solution.

4.1 Prototype demonstration

A Smart Waste Bin prototype was proposed and created, as explained in previous sections. Figure 14.a shows the internal view of the prototype, indicating the load cell at the bottom and the level sensor at the top of the compartment and figure 14.b shows the top image of the prototype, indicating the solar photovoltaic plate and the GPS receptor antenna. Figure 15.a presents the back side of the prototype, where the Arduino board, temperature sensor, GSM/GPRS transmission module, GPS module and the battery were mounted and figure 15.b shows the front view of the Smart Waste Bin. Figure 16 exhibits the Arduino console photo with all the information needed for the proper waste management. It is presented the location Latitude and Longitude, the age of data received from the satellite (milliseconds), date and time (GMT), speed (km/h), and direction (degree) if the container is in motion, volume and weight of the smart bin, and the temperature and relative humidity of the air.

Figure 14.a: Smart bin's internal image. Figure 15.b: Smart bin's internal top image.

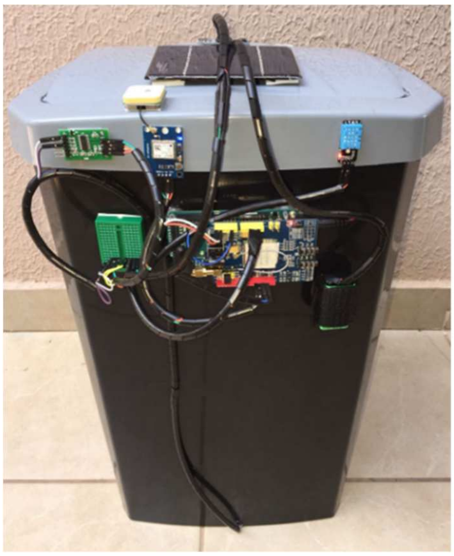

Figure 16.a: Smart bin's back image. Figure 17.b: Smart bin's frontal image.

With the prototype ready, it was possible to validate through the Arduino console all the information collected by the sensors. This information is of extreme importance for active and intelligent waste management, that is transmitted to a Middleware platform for being access to a mobile application or Web page. As above-mentioned, a printout of the Arduino console with the respective measurements is shown in Figure

16. This system was evaluated is a real environment, validated, and it is ready for being integrated into a smart waste management solution.

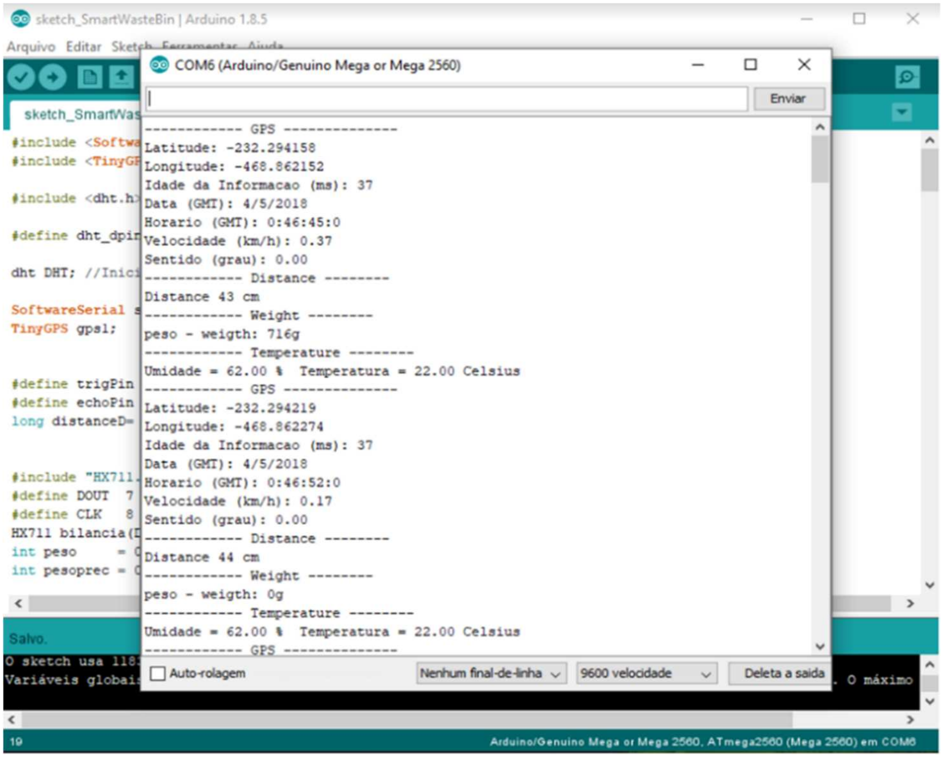

Figure 18: Image of Arduino console view.

4.2 Solution validation

In this section, the performance evaluation of the proposed system, My Waste Management, is presented through a real-scale experiment. With My Waste Bin prototype ready and integrated with the middleware solution for IoT, the In.IoT, it was possible to validate the perfect operation of the solution and guarantee the feasibility of the proposed system. The first step of the experiments was to validate the overall positioning of the My Waste Bin compartment relative to the mobile user using the My Waste App application. The compartment was positioned in an external area and the geolocation information was transmitted to the In.IoT middleware and later accessed through a smartphone using Android platform. Through the My Waste App application it was possible to identify the exact positioning of the compartment and to trace the route to its location, as shown in Figure 17.

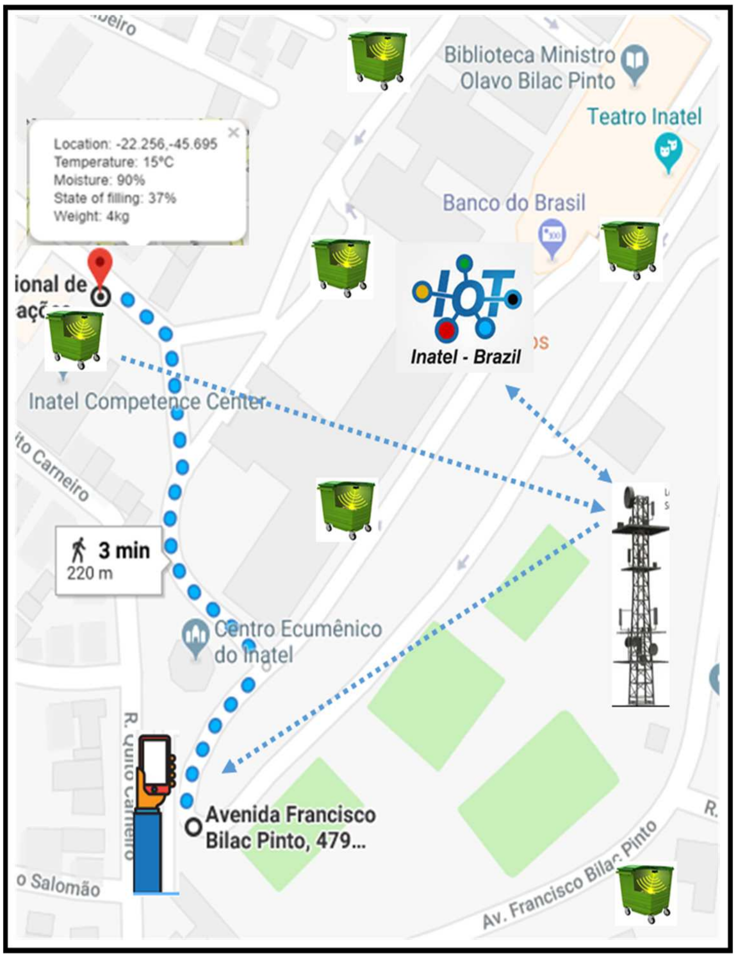

Figure 19: Available route presented by My Waste App.

The second part of the experiments was designed to vary the amount of waste deposited inside the compartment and to validate its representation within the application. Such variation alternated the physical characteristic of the residues since the heavier and less voluminous as the inverse situation. Initially, a quantity of residues representing a weight of 4 kg was added to the My Waste Bin compartment, with a filling of 37% of the total capacity of the compartment. Thus, additional portions of the same residue were inserted until reaching a weight value equivalent to 6.4 kg, which achieved a filling representation of 55% of the capacity supported by the compartment. Subsequently, another type of residue with different geometry was added to the compartment in order to make the residue volume a more representative attribute. In this way, the total weight of the residues deposited inside the compartment reached a weight of 7 kg representing a volume of 97% of the total capacity, for the standard of the container chosen during the assembly of the My Waste Bin prototype. The variation of the values above-mentioned are shown in Figure 18.

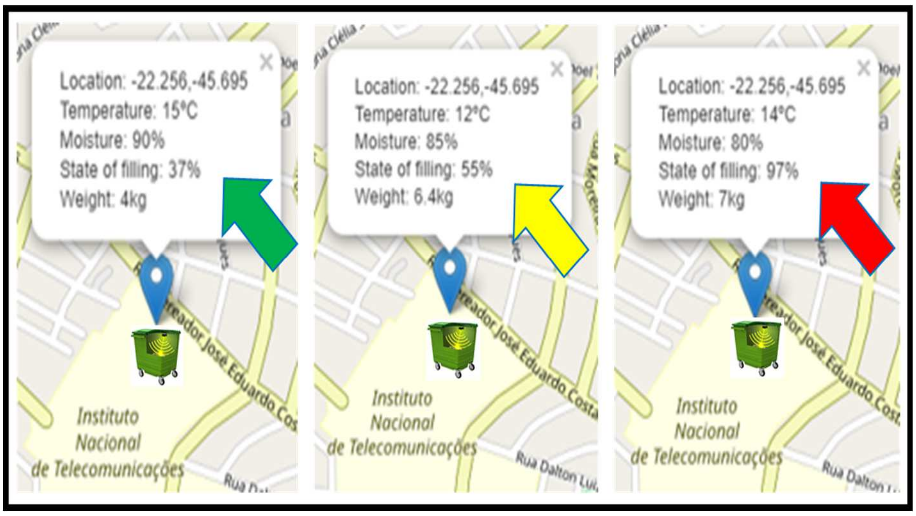

Figure 20: Fill variation presented by My Waste App.

The third and final experiment was the energy source to validation of the My Waste Bin. As the prototype has a rechargeable battery system and is it powered by a photovoltaic board, the compartment was kept on for a period of 8 weeks with alternating situations in the solar luminosity presented during the days and did not lose its energy capacity. Within the Arduino Sketch is being considered a timer with measuring cycles from 5 min and the transmission of information to the In.IoT only happens if the measured values show difference from the previous value stored in buffer, other energy saving models are presented in [169, 170]. Such an implementation helps to ration the energy of the system. However, during this experimentation phase, a lack of visualization of the battery's energy level has been noticed, something that can be improved in upcoming versions of the system.

Through the above demonstration, it was possible to validate the perfect functioning of the My Waste Bin prototype that efficiently was able to collect and transmit information of residues deposited in its interior to In.IoT, and through the application My Waste App collecting information saved in the In.IoT, it was possible to have a perfect interaction with end users.

5 Conclusion and future work

5.1 Learned lessons

Through this research study, valuable lessons have been learned that can help future researchers interested in IoT-based waste management solutions such as developers trying to create/improve solutions, or users who want to evaluate solutions.

Using a waste management system alone does not solve the problem of open garbage accumulation due to excessive discards at inopportune times by citizens, or even the lack of timely collection by competent authorities. People need to raise awareness and exercise citizenship to avoid waste discarding at inappropriate times (for people, the most important thing is to know the location of the nearest ecological point with resources available for that and the closest green points for a possible discard). It is also crucial that concessionaires responsible for public collection always meet the demand in time, changing the current collection systems based on weekly schedules by a methodology based on demand, i.e., mapping the areas with the most significant needs.

Another point observed is related to the final cost of the solution when projected to a municipal scale. To avoid the financial impracticability of the solution, it is necessary to create ways to capitalize on resources to be invested directly in solutions to meet the need of municipalities with fewer investments. A good example may be visual advertising inserted directly into smart containers or even through non-invasive advertisements presented in mobile applications integrated into complete waste management solutions.

5.2 Final remarks

Throughout this dissertation, an updated study on waste management based on IoT, solution dismantling through the construction of a prototype and the performance of the solution based on a real scale was presented.

The dissertation first introduced the motivation and delimited the research topic, describing the objectives and displaying its main contributions. In Chapter 2, an updated study on waste management based on IoT was presented. This chapter begins with a description of the types and methods of waste disposal, and this classification is fundamental because they represent a highly heterogeneous volume of matter because it facilitates the selective collection, recycling, and definition of the most appropriate objective, also, different aspects of IoT technology for waste management solutions. Next, the chapter discusses the IoT architecture reference models available for waste management systems, showing their functional requirements always addressing factors such as scalability, interoperability, reliability, and quality of service. Among the predominant reference models, it is possible to mention some initiatives, such as RAMI 4.0, an effort of a consortium formed by AT & T, Cisco, General Electric, IBM and Intel, Internet of Things Architecture (IoT-A), but many project models focus on a typical architecture based on needs analysis or some layers that form a basic model of a reference architecture. IoT-based waste management, i.e., a set of activities that is appropriately related from the beginning of its cycle to the identification of each compartment, being able to accurately present service level conditions with adequate communication and minimum requirements necessary for the dissertation then focuses on standard protocols. As used in waste management systems, IoT requires different protocols to address a wide variety of activities and the major and most used ones in this context are described. The chapter concludes with a summary of the comparative assessment of the solutions studied that include research efforts based on waste management using IoT.

Chapter 3 introduced a Smart Waste Bin prototype that can be adapted for general waste solutions and includes sensory units, geolocation and communication unit, microcontroller, and the power supply. Next, the chapter described the devices used in the prototype (Arduino board, temperature sensor, GSM / GPRS transmission system, GPS, and power devices) and finally, all the blocks that make up the waste management solution were presented. First, the intelligent bin is described, the second block considers the integration with the IoT middleware and the last block shows the user application developed.

Chapter 4 focused on evaluating, demonstrating, and validating the solution. The first step of the experiments was to validate the positioning of the compartment relative to the mobile user using the application, the compartment was positioned in an outside area, and the geolocation information was transmitted to the In.IoT and then accessed through a smartphone using the platform Android. The second part of the experiments was designed to change the amount of waste deposited inside the compartment and to validate its representation within the application through an alternating variation of the physical characteristics of the waste from the most massive and least bulky in the inverse situation. The third and final experiments was to validate the power source of My Waste Bin. As the prototype has a rechargeable battery system and it is powered by a photovoltaic plate, the enclosure has been maintained for 4 weeks with alternating situations in the solar luminosity presented during the days and has not lost its energy capacity.

The model of society of the 21st century has been increasingly influenced by cities in their context, according to UN data by 2050 approximately 70% of the population will live in urban centers, and this rapid growth of people living in cities has been of great concern since towns do not always grow in a sustainable way. In this regard, smart city design has been increasingly studied and discussed around the world to reverse this problem.

To achieve the transformation of traditional cities into smart cities, waste management becomes a critical element in achieving sustainability, efficiency in public spending, improving urban mobility, and preserving natural resources. Recent literature has been revised to investigate variant characteristics and aspects of intelligent waste management systems using the Internet of Things. Since the deployment of IoT infrastructures can enable many opportunities, first, the leading search motives were identified, and some useful application models on the topic of waste management were described. Through a detailed literature review, solutions to identified problems were related, considering data detection, transmission, analysis, and processing of collected data, and obtaining the result for an efficient handling solution for solid waste. Using IoT, it is possible to track the location of waste containers, monitoring the level of garbage deposited, identify areas with the highest demand, suggest the shortest route for collection optimization of solid waste, or even interface with citizens to encourage disposal at times when the container can receive waste, which promotes citizenship and avoids significant problems resulting from the accumulation of garbage outside garbage collectors.

5.3 Future work

As future work, it would be exciting to verify the performance of the system operating on a large scale, especially concerning the middleware platform worked in conjunction with the application developed to serve as an interface to users. Consider a scenario with data transmission to the middleware platform from multiple smart dumps and at the same time, receive access from various mobile devices looking for the updated information from smart bins.

Another relevant study may be an enhancement of the designed application, adding new facilities that bring to the end user more significant interactions with the waste management system.

The addition of computation algorithms of smaller collection path may also be a very relevant study that is added to the solution in the future.

Finally, a new version of the smart bin can be developed, considering a method of monitoring the battery level of the My Waste Bin prototype, this question was not discussed during the development of the solution, and in the tests, it became evident that it is an interesting aspect to be contemplated.

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