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COLLEGE OF ENGINEERING

COMPARATIVE STUDY OF PERIODIC REVIEW POLICY AND IOT ENABLED POLICY FOR THE DOMESTIC WASTE MANAGEMENT

BY

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ABSTRACT

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"Innovation is the difference between leaders and followers" said the famous Apple's CEO, Steve Jobs. The technological advancement was and will always be exploited into delivering a higher quality of life for communities. The Internet of Things (IoT) technology is not excluded from this fact. Nowadays, many countries are building smart cities that are equipped with smart traffic control, environmental monitoring and public safety. Smart waste management is an emerging initiative in this matter. This thesis addresses the application of the IoT in the waste collection systems. It assesses the Periodic Review Policy and the IoT Enabled Policy of waste collection systems. A model was developed for each system using Anylogic software. Each model performance was tested using six different waste generation scenarios and seven collection policies. The performance analysis of the models was based on the economic, environmental and citizen satisfaction measures. The results of this research showed that each collection model achieved good performance in a specific scenario. The three times per week periodic review policy performed the best for high waste generation scenarios whereas the 70% threshold IoT enabled policy was the best for low waste generation scenarios.

DEDICATION

This Thesis is dedicated to my dear wife Nourhen who showed a lot of encouragement and patience. To my parents Ahlem and Raouf, my two brothers Fares and Kais and all my family for their love, endless support and encouragement

In the memory of my beloved grand-parents may they rest in peace

To all my friends who have supported me in the establishing of this master

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LIST OF ABBREVIATIONS

DSWMC: Domestic Solid Waste Management Center

DVRP: Dynamic Vehicle Routing Problem

GIS: Geographical Information System

GPS: Global Positioning System

IoT: Internet of Things

IT: Information Technology

MENA: Middle East and North Africa

MSW: Municipal Solid Waste

OECD: Organization for Economic Cooperation and Development

RFID: Radio-Frequency Identification

SDSS: Spatial Decision Support System

TSP: Travelling Salesman Problem

VRPTW: Vehicle Routing Problem with Time Window

VRP: Vehicle Routing Problem

CHAPTER 1: INTRODUCTION

1.1. Background

Nowadays, the terms IoT, big data and industry 4.0 are commonly used in many sectors. Many companies are interested in these new trends and assessing their potential in offering a competitive advantage.

The famous Apple's CEO, Steve Jobs, said: "Innovation is the difference between leaders and followers". The concept of the IoT was created long time ago. The famous British entrepreneur and founder of start-ups, Kevin Ashton, formulated the idea in 1999 describing a system where the physical world and the material things would be able to communicate with computers through the exchange of data using sensors technology. In the year 2009, the number of devices connected to the network exceeded the world population. At this point, and according to the worldwide leader in the IT industry CISCO, the IoT was truly born and it was more often known as the "Internet of Everything" where everything from people, data, processes and even animals can be connected and communicate with each other (Witkowski, 2016).

The IoT is described in simple words as a network of connected objects able to collect and exchange data and can be remotely monitored and controlled. The collected information is sent to a central server, where it is processed, analyzed and refined to provide pertinent and useful information helping to achieve tasks more easily and efficiently. The advantages of using IoT solutions touch many fields in the business world, governments, organizations, and even the individual consumer. Using IoT, people these days can track anything from their own pet's location to monitoring their house's security systems. Consumers can take advantage of IoT to make restaurant reservations and monitor their exercise progress and overall health and sleep patterns through mobile applications. Businesses are also using IoT to monitor their supply chains, track customers' spending patterns as well as collect their feedback, dynamically monitor and maintain inventory levels and prepare predictive plans of maintenance to the machinery used in manufacturing processes (Terra, 2019). IoT started to play an important role in the waste management field as well. Due to the increased environmental awareness, more countries are investing in sensors technology and replacing the traditional bins with smart ones. The effort is focused on improving the waste collection process and finding new innovative collection methods.

1.2. Research Statement

The rapid development of Qatar brings many challenges including waste management. During the last few years, the country waste generation has increased due to a considerable increase in the population and to the various ongoing projects in the infrastructure development. One of the major challenges in the waste management is the waste collection. Therefore this thesis explores different waste collection policies to enhance waste management decisions in terms of the collection cost and its environmental and citizens' satisfaction impact.

1.3. Research Objectives

The research aims to assess two strategies in the domestic waste collection problem which are the Periodic Review strategy and the IoT Enabled collection strategy. The Periodic Review Policy is, in fact, the traditional way that municipalities are using to collect waste in most countries. It relies on prescheduled routes and timings that collection trucks follow regardless of the actual waste available in the waste bins. On the other hand, the IoT Enabled collection strategy is more contemporary and includes different technologies in the collection process. It relies on the continuously collected data on waste generation, waste type and bins levels using sensing technology. This data is then processed using algorithms that finally provide an optimal routing solution. These routing solutions differ depending on the collected data hence the dynamic side of this strategy. The assessment of the aforementioned strategies will be based on three performance measures. The economic performance represented by the total distance traveled by the collection truck. The environmental performance evaluated based on the vehicle's total CO_2 emissions. The citizen satisfaction performance is quantified by the percentage of overfilled bins. The research will evaluate the two waste collection strategies by developing a simulation model for each strategy. The developed models will study the waste collection systems over a year for different waste generation scenarios. Finally, the thesis will conduct a comparison between the two developed Periodic Review and IoT Enabled models to find the best performing model for the various scenarios.

1.4. Thesis Outline

The thesis comprises five chapters that are introduction, literature review, model development, experiments, and result analysis and a conclusion chapter. Chapter 1 describes IoT along with its importance in smart waste management and presents the research objectives. Chapter 2 demonstrates statistics on waste generation and focuses on reviewing research papers published on waste collection problems. Chapter 3 is divided into 3 sections. The first section addresses the thesis problem definition followed by a detailed description of the built model. The last section presents the model validation and verification using manual calculations. Chapter 4 presents the performance measures that will be the base of comparison between the models. Furthermore, it describes the experiments performed and the results obtained for the different waste generation scenarios.

Lastly, chapter 5 highlights the main observations obtained from model results and proposes the possible enhancements and extensions for future work.

CHAPTER 2: LITERATURE REVIEW

This chapter is divided into six sections. The first section will present the areas of application of IoT technology. The concept of smart city will be defined in the second section. Statistics on the amount of generated waste worldwide and particularly in Qatar will be presented in the third one. The fourth section will cover the literature reviewed for the periodic review policy systems. The fifth will focus on the papers reviewed for the IoT enabled collection systems and the last section will present the identified research gaps in the domestic waste collection problem.

2.1. IoT Application

To have an idea about the range of applications and the importance of IoT in this modern world, examples of the industries where IoT is applied are presented below.

1. Agriculture**:** IoT makes the instant monitoring and management of micro-climate conditions possible for indoor planting, which enhances productivity. With IoT devices, it is possible to sense soil moisture and nutrients, record weather data and control the smart irrigation and fertilizer systems in a better way for outside planting. Optimizing the sprinkler system by dispensing water only when needed is a great example of how IoT technology can prevent wasting resources (Terra, 2019).
2. Consumer use: Life is becoming easier with the smart wearable and homes. Fitbit, smartphones, Apple watches, health monitoring mobile applications are available now to improve the entertainment, health, and fitness of the individuals. Smart homes give great comfort by remotely activating ovens and crockpots to have the food ready without any human intervention. Security is made easier by activating smart locks controlling people’s access and controlling appliances and lights

remotely (Terra, 2019).

3. Healthcare: the smart wearable helps hospitals monitor their patient's health at home which reduces hospital stays while providing the same amount of care and attention with the real-time information provided by the IoT devices. Equipping hospitals with smart beds keep their staff well informed about space availability enhancing the hospital's service. Critical equipment can be monitored using IoT sensors which increases their reliability and reduces breakdowns and that has a significant role in saving patients' life. Being able to determine if a patient has fallen down or if he's having a heart attack remotely at any point in time is an important advantage in saving lives (Terra, 2019).
4. Manufacturing: is another industry that benefits greatly from the IoT technology. The availability of the RFID and GPS technology now helps manufacturers in tracking their products starting from the factory until its placement in the destination store. The whole supply chain process can be monitored and information about the travel time, product conditions and environmental situations that the product was subject to can be easily gathered. The ability to continuously monitor the semi-finished goods and the final products along all the stages of manufacturing and distribution, to track the performance and to predict when the machinery needs maintenance helps to identify bottlenecks in an easier and faster way improving the efficiency of the process and minimizing waste (Terra, 2019).
5. Retail: industry is revolutionized by the IoT technology. Relying on RFIDs, warehouse automation and robotics now can be controlled by online and in-store shopping sales numbers making it more flexible and dynamic to the volatility

nature of the business. IoT plays a role in analyzing malls' traffics to make the needed adjustments for the stores to enhance the customer's shopping experience. Having historical data on consumers' purchases is also a competitive advantage that helps retailers in targeting them and personalizing promotions for loyal ones. Much of these deals can be easily conducted through customer's smartphones and for that reason, most retailers offer a free dedicated mobile application for their store (Terra, 2019).

6. Transportation: The GPS is being used by transportation companies to identify faster and more efficient routes for trucks moving freight which speeds up the delivery times to satisfy the customers' needs. Data collected from IoT devices help in determining traffic patterns, parking space demand, and road construction and maintenance planning. Without forgetting the self-driving cars and how they can provide a safer and easier mode of transportation to everyone (Terra, 2019).
7. Utilities/Energy: IoT sensors are being employed to monitor environmental conditions like humidity, temperature, and lighting to regulate energy usage throughout the day. With this technology, both businesses and private residences can improve the efficiency of energy consumption and reach a considerable energy savings that not only reduces costs but also benefits the environment. On a larger scale, data gathered can be useful in running municipal power grids more efficiently by examining factors such as usage. Besides, the sensors can help to determine outages faster minimizing the response time of repair crews and reducing blackout periods (Terra, 2019).

Figure 1 shows the top ten IoT segment in 2018 based on 1600 real IoT projects.

It demonstrates that most IoT projects are in the Smart City sector with 367 projects (23%) followed by Connected Industry sector with 265 (17%) projects and Connected Building with 193 projects (12%). When observed from the region's perspective, the Americas come first in which 45% of the projects are being executed. Europe comes second with 35% followed by Asia with 16%. Nevertheless, when looking at individual IoT segments and regions, most of the smart city projects are located in Europe (45%), the Americas focuses on Connected Health (55%) and Connected Cars (54%). While the Asia/Pacific region is focusing on the area of smart agriculture projects (31%) (Scully, 2018).

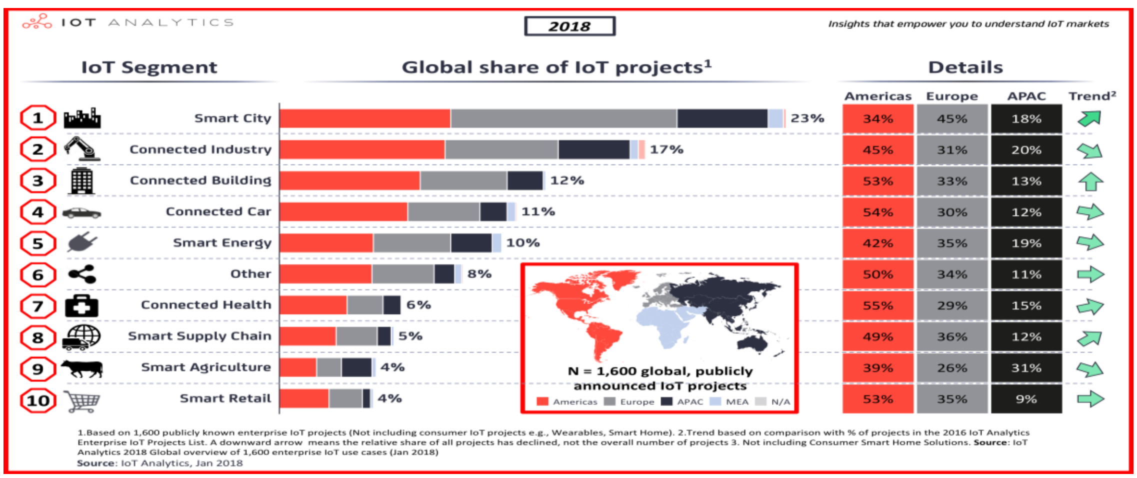

Figure 1. IoT projects top segments (Scully, 2018)

2.2. The Concept of Smart City

Before going further into details, it is imperative to present and define the smart city concept. Bakici et al. (2013) define the Smart City as "The implementation and deployment of information and communication on technology infrastructures to support social and urban growth through improving the economy, citizens' involvement and governmental efficiency”.

Giffinger (2007) described it as “A city well performing in a forward-looking way in the following six characteristics; Smart Economy, Smart People, Smart Governance, Smart Mobility, Smart Environment and Smart Living, built on the ‘smart’ combination of endowments and activities of self-decisive, independent and aware citizens”.

In simpler words, a smart city is a city where resources and assets are managed more efficiently using the IoT. This technology enables governments and officials to collect data on everything from citizens, the environment, and all types of user devices. Process this data and use it to make all aspects of life easier and more pleasant while being environmentally friendly.

It’s evident that IoT has a considerable impact on various sectors and lately, the smart city projects encouraged by government and municipality-led initiatives have surpassed Connected Industry if compared with 2016 ranking (Bartje, 2016).

The best examples of smart cities are Singapore and Barcelona. The most popular Smart City application is Smart Traffic which includes projects such as parking systems, traffic monitoring and control, bike-sharing, smart bus lanes, and more innovative applications like smart ferry systems or smart bus shelters. The other Smart City initiatives encompass utilities, lighting, environmental monitoring, and public safety.

Another new application which is merging now is the smart waste management solutions. The focus of this paper involves the latter and more specifically on domestic waste management and strategies that can be implemented to improve the collection process. Decreasing, therefore, the cost of the whole operation from the number of vehicles used, the personnel employed to the quantity of fuel consumed. The advantages do not reside in the economic side of the operation only but also incorporate the environmental side by reducing the CO_2 emissions and increasing citizens' satisfaction rate by making the neighborhoods cleaner and more pleasant to live in.

2.3. Global Waste Generation Statistics

This section of the chapter will present figures on the amount of waste generated in the world and Qatar specifically along with the waste composition to show the importance of proper waste management strategies.

2.3.1. Waste Generation by Region

Hoornweg and Bhada-Tata (2012) mentioned that municipal waste generation is around 1.3 billion tons per year and is projected to increase to 2.2 billion tons per year by the year 2025. This is approximately an increase of 70%. But a global average is an estimate to provide an overall picture. Waste generation depends on many criteria such as the economic development of the country, its climate conditions, the local population habits and the degree of its industrialization. Thus the waste generation numbers vary greatly between regions and in general, the more developed countries generate more waste (Hoornweg & Bhada-Tata, 2012).

The pie chart presented in Figure 2 illustrates the waste generation in different regions worldwide. Almost half of the worldwide waste generation comes from the Organization for Economic Cooperation and Development 'OECD' countries such as Canada and Australia with an estimate of 572 million tons per year. In the second position comes the region of East Asia and Pacific with an estimate of 270 million tons per year (21% of worldwide waste generation). Latin America and the Caribbean generate 12% of the waste with around 160 million tons per year. Eastern and Central Asia contribute with 93 million tons of waste per year. And both Africa and the Middle

East and North Africa ‘MENA’ regions generate around 63 million tons of waste while South Asia generates slightly more with 70 million tons of waste.

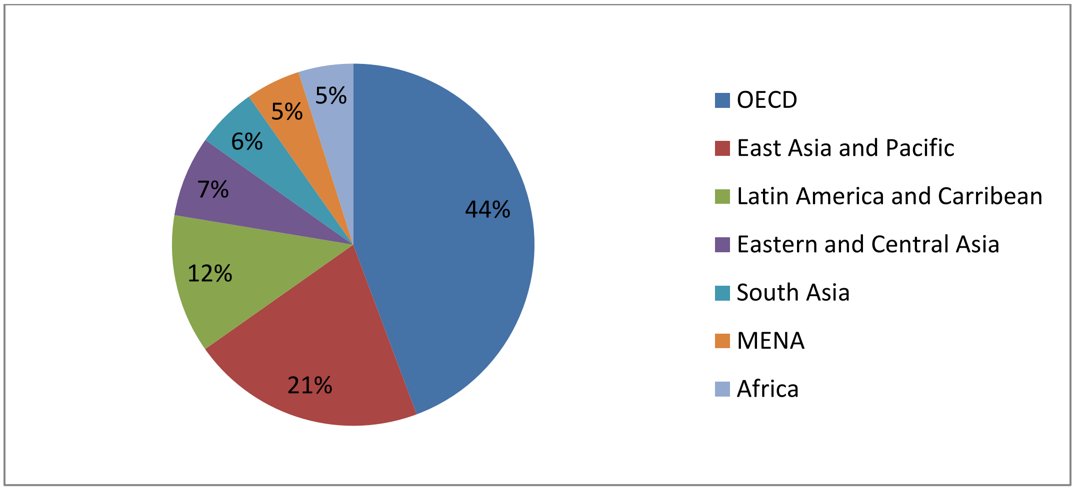

Figure 2. Waste generation by region (Hoornweg & Bhada-Tata, 2012)

Another important criterion that affects the waste generation amounts is the country’s income levels. According to Hoornweg and Bhada-Tata (2012) countries are classified into four income levels High income, Upper Middle income, Lower Middle income, and Lower income countries. The waste generation numbers increase along with the country’s income level. Figure 3 shows the waste generated based on countries’ income group as well as a projected waste generation levels for the year 2025. It is noticed that the lower middle income group generates waste quantities higher than the upper middle income group and is projected to generate even higher waste levels than the high income group in the year 2025. That is because it includes China which is classified as a lower middle income country.

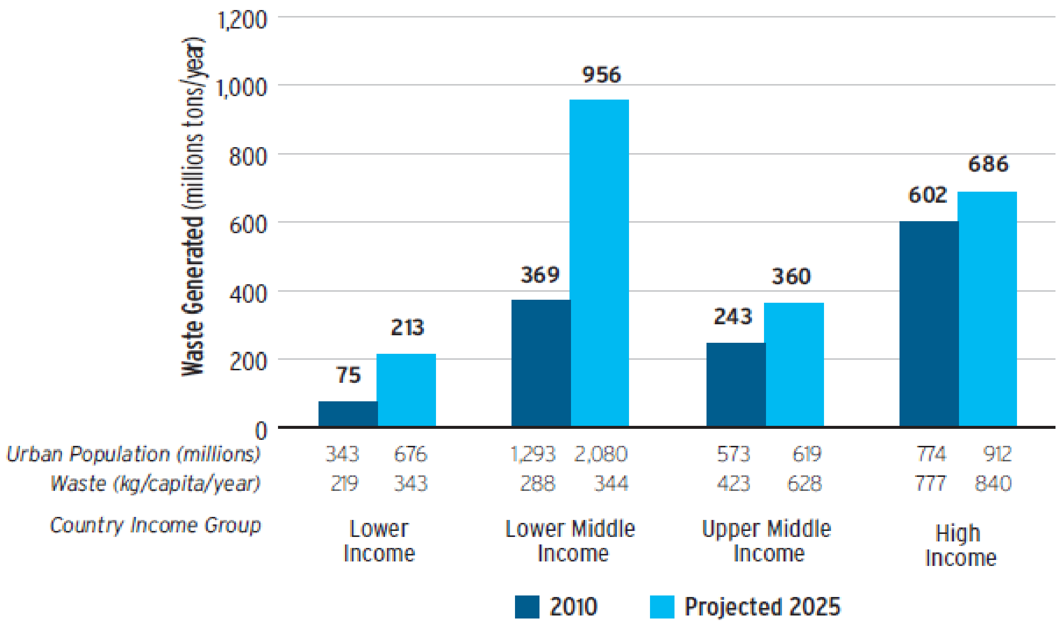

Figure 3. Urban waste generation by income level and year (Hoornweg & Bhada-Tata, 2012)

2.3.2. Waste Composition

According to the global review of solid waste management, solid waste is composed of six types (Hoornweg & Bhada-Tata, 2012).

1. Organic: Food scraps, yard waste (leaves, grass, brush), wood, process residues
2. Paper: paper scraps, cardboard, newspapers, magazines, bags, boxes, wrapping paper
3. Plastic: Bottles, Packaging, containers, bags, lids, cups
4. Glass: Bottles, broken glassware, light bulbs, colored glass
5. Metal: Cans, foil, tins, non-hazardous aerosol cans, railing, bicycles
6. Other: Textiles, leather, rubber, multi-laminates, e-waste, ash, other inert materials

Almost half of the global solid waste is formed by organic waste. Paper and plastic present respectively 17% and 10% of the generated waste worldwide. Whereas

Glass and Metal types of waste are less common with a percentage of 5% and 4% respectively from the total waste generated.

The chart in Figure 4 summarizes the global solid waste composition, but it is important to mention that the waste composition is affected by the situation of the country. As the latter develops and its population becomes wealthier the organic fraction of its waste decreases and the plastic, glass, and metal waste types increase.

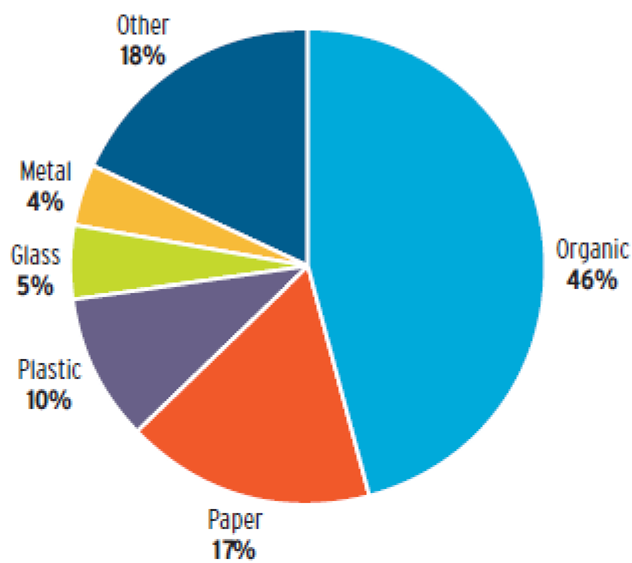

Figure 4. Global solid waste composition (Hoornweg & Bhada-Tata, 2012)

2.3.3. Waste in Qatar

Qatar is considered one of the richest countries in the world. Although this fact is a positive one, many challenges come along with it. Waste management is one of them. Since the population in Qatar has a high income, its consumption of goods is also higher which generates higher domestic waste numbers. Also, the country is developing at a fast pace with many construction projects being executed for several years. All these factors led to high waste generation by both the population and many industries. In this section, statistics will be provided on the generation of solid waste in Qatar divided along with its types and on the facilities available to treat and manage this waste.

In the year 2015, the statistics collected by The Ministry of Municipality and Environment show that there are four waste transfer stations in Qatar each one located in Al-Khor, Dukhan, Doha south and Doha west. Two landfills one in Mesaieed and one in Umm Al-Afai. Two waste dumps in Umm Thintayn and Rawdat Rashed and there is only one solid waste treatment station in Mesaieed (Environment statistics in the state of Qatar, 2017).

The total solid waste generated in the state of Qatar amounted to 7.7 million tons in 2015 including domestic waste, construction waste, bulky waste and other types of waste. Domestic waste amounted to around 1.1 million tons representing 14% of the total solid waste generated. Construction waste represents the highest source of waste generated with more than half of the total solid waste with around 4.2 million tons (Environment statistics in the state of Qatar, 2017).

The focus will be on the domestic waste generation solely since the research is studying the collection of domestic waste. The daily generation of domestic waste has increased from the year 2010 to 2015 by around 30% reaching 3,002 metric tons per day in 2015 with an average of 1.23 Kg per capita per day.

Table 1 shows the detailed increase in domestic waste generated between the years 2010 and 2015.

Table 1. Daily Generation of Domestic Solid Waste (MT/Day)

Year	2010	2011	2012	2013	2014	2015
Domestic waste	2,320	2,234	2,388	2,550	2,871	3,002

A 30% increase in domestic waste generation within five years is a considerable increase that makes the waste management process even more challenging. Table 2 shows the waste management facilities and the treated domestic waste between the years 2010 and 2015.

Table 2. Waste Management Facilities and Treated Waste (Tons)

Facility	2010	2011	2012	2013	2014	2015
Umm Al-Afai	846,630	628,235	44,151	0	0	0
Mesaieed	0	0	258,991	326,960	408,526	482,640
DSWMC	0	187,067	568,466	603,703	639,522	613,226
Total domestic waste	846,630	815,302	871,608	930,663	1,048,048	1,095,866

From Table 2 it is obvious that the total domestic waste generated increased over the year which is aligned with the previously presented table showing the increase of the daily generation of domestic waste. It should be noted that in the year 2013 Umm Al-Afai landfill has been closed which explains the nil value starting from that year and the switch of all the waste to Mesaieed landfill. By the year 2015, almost 60% of the total domestic waste generated is treated in the Domestic Solid Waste Management Center in Mesaieed ‘DSWMC’.

According to the World Bank, the collection cost represents around 80% of the municipal solid waste management budget (Hoornweg & Bhada-Tata, 2012). From the previously represented data, it is obvious that the state of Qatar is taking the waste generation and waste management issues seriously and implementing many solutions to maximize the value recovery and the treatment of this waste. Nevertheless, no much effort was conducted on the collection part of waste management. Evaluating different domestic waste collection strategies can be valuable in terms of cost reduction, environment, and citizen satisfaction rate.

2.4. Periodic Review Collection Policy

The interest in investigating the field of waste management has started long ago with an increase in the number of publications since the year 2000 (Beliën, De Boeck, & Van Ackere, 2014). Ever since the researchers examined solid waste management problems with a particular focus on vehicle routing problems. Nuortioa et al. (2006) worked on optimizing vehicle routes and schedules for municipal solid waste collection in Eastern Finland. They found that a significant reduction in waste collection costs can be obtained with optimized routing and scheduling. Buhrkala et al. (2012) studied the waste collection vehicle routing problem with time window to find a cost-effective and optimal route for the collection trucks taking into consideration the fact that all bins have to be emptied within the pre-specified time window satisfying customers demand.

Other researchers focused on assessing the efficiency of the waste collection process. For instance, Guerrini et al. (2017) examined the effect of many key variables on the efficiency of the municipal waste collection service in the province of Verona, Italy. The team collected data for five years between 2008 and 2012 and used them to compare efficiency scores between the different municipalities. They found that a properly organized collection routes and loads frequency, and suitable allocated trucks for a specific route could improve the efficiency of the operational features examined in the study. On the other hand, Ferreira et al. (2017) focused on assessing and benchmarking the selective municipal waste collection schemes. They highlighted the efficiency differences between these schemes which will help in improving the waste management strategies. The study monitored three performance indicators consisted of effective collection distance, effective collection time and effective fuel consumption. These indicators were considered crucial for the efficiency and costs effectiveness of the waste collection process of each collection scheme.

Many methods were used to find solutions for the waste collection process. Bautistaa et al. (2008) found a solution for the waste collection problem in the municipality of Sant Boi de Llobregat, in Barcelona using an ant colony heuristics that improved previous solutions in terms of operating cost and acoustic contamination. Santos et al. (2008) worked on designing a spatial decision support system (SDSS) that creates vehicle routes as a solution for the multiple-vehicle routing problems. This decision support system includes a geographical information system (GIS) and heuristic solution procedures as well as incorporates realistic details such as time constraints, routing constraints (one-way streets and prohibited turns) and vehicle capacity. After designing the system, the team tested it for the waste collection problem in Coimbra, Portugal and concluded that this system can be of great help in analyzing and solving many complicated vehicle routing problems as well as finding the benefits and cost reductions if certain parameters were to change. Such parameters can be the vehicle capacity and shift durations which can help in planning a more efficient waste collection scheme. They were not the only ones who included the GIS in finding solutions to the MSW collection problem, Arribas et al. (2010) also did along with mathematical modeling to minimize collection time, and operation and transport costs for urban solid waste collection system in Santiago, Chile.

The travelling salesman problem (TSP) method was commonly used between researchers for the same matter. Das and Kr. Bhattacharyya (2015) focused on the problem of minimizing the length of each municipal waste and collection route and proposed a heuristic solution that provided an optimal method of municipal solid waste collection and transportation using TSP. The result was a reduction of 30% of the total waste collection path length. Jakubiak (2016) also tried to improve the collection of municipal waste by analyzing four routes carried out by the Municipal Cleaning Service in Krakow, Poland. The author focused on minimizing the distance covered by the collection trucks and used the TSP solution method to find that it is possible to significantly shorten the covered distance with an optimized routing schedule.

M. Ombuki-Berman et al. (2017) studied the waste collection vehicle routing problem with time window (VRPTW) and went a step further by implicating the multiple disposal trips that happen in the real waste collection system and the driver's lunch breaks which made the problem more challenging. The team presented a multi-objective genetic algorithm for the waste collection problem relying on benchmarked data from the real world. Farrokhi-Asl et al. (2018) solved a multi-objective sustainable waste collection problem. They formulated three objective functions that included both operational and social costs and the model was used to evaluate the fuel consumption and CO_2 emissions and the impact on the environment. They were one of the few researchers that took into consideration the waste collection process's impact on the environment.

The waste collection problem is getting more attention than ever before and many research papers tackled the problem in many different perspectives for various objectives.

All the papers mentioned tried to find a solution for a periodic review collection problem but now with the involvement of the information technology (IT) and the IoT, the following section will present the researchers that tried to find a more efficient IoT enabled collection process.

2.5. IoT Enabled Collection Policy

For different reasons, the planned route cannot be achieved in the waste collection process. The amount of waste can change suddenly due to an unforeseen event or unexpected deviations. The truck drivers could deviate from the planned route for any reason which will affect the scheduled time and distances. All these reasons make the idea of considering an IoT enabled collection policy compelling. Furthermore, with the help of the available IT, IoT, and sensors it is possible to reach a realistic IoT enabled collection solution. The researchers in this field are well aware of the advantages the IoT can bring into the waste collection problem and during the recent years, their focus turned toward finding a solution considering it as a dynamic vehicle routing problem DVRP. " DVRP implies that not all information relevant to the vehicle routing process is known to the person who planned the route before beginning the routing process and information related to the route can be changed after the initial formation of the first route" (Milić & Jovanović, 2011).

Many methods were used to model the IoT enabled system and find an optimal solution for it. For instance, Rovetta et al. (2009) implemented a network of waste bins equipped with sensors all linked to a data management system in Pudong, China to monitor the overall and the bin specific waste generation as well as identifying the types of the waste material. This helped to identify potentially hazardous materials and the data collected was used to optimize the truck collection routes to minimize the cost related to the collection process. Mes et al. (2014) worked on developing an IoT enabled collection policy for underground containers equipped with sensors. They proposed a heuristics involving various tunable parameters. These parameters are tuned depending on the needs using optimal learning techniques along with the simulation. An important part of their work was that they divided the containers into three different groups based on the level of waste; MustGo containers, MayGo containers, and NoGo containers. As their name indicates, a MustGo container needs to be emptied as soon as possible and it should be incorporated in the same day routing plan. A MayGo container can be emptied if it is on the MustGo route plan or nearby and holding a sufficient amount of waste. And NoGo container shouldn't be incorporated in the same day routing plan. They tested their solution on waste collection company in Netherland and found that the cost savings can be as high as 40% with optimized parameters.

Milić and Jovanović (2011) developed a measuring system on the collection trucks that use mobile technology to monitor the current load in real-time. The collected data are then used to identify better routes to enhance the efficiency of the collection process. The team found that this dynamic collection methodology also gives a more flexible routing strategy which ensures better collection solutions that can accommodate instant changes. Faccio et al. (2011) worked on introducing an innovative vehicle routing model combined with the real-time traceability data to find an optimized solid waste collection solution. These real-time data were collected using different technologies such as volumetric sensors, RFID, weighting system, and vehicle traceability software application. The paper had three objectives; minimize the number of vehicles per fleet, minimize travel time and minimize total distance covered. The authors conducted an economic feasibility study as well which proved that the benefits of using the optimized routing method cover the costs of implementing the traceability technology.

Anagnostopoulos et al. (2015) introduced a new approach by defining high priority bins that are present in predetermined critical areas in the city of Saint Petersburg in Russia. Such areas can be hospitals, touristic areas, or municipality town hall, and they require time-critical waste collection. The authors developed four different models to ensure the speedy collection of these high priority bins. The dedicated trucks model, the detour model, the minimum distance model, and the reassignment model. These proposed models aim to minimize the collection time needed to reduce the possible negative effects of overfilled bins on citizens. Their performance was compared and a summary of the cases where each model performs the best was presented at the end. Another study was done by Shah et al. (2018) in which they developed a stochastic optimization model based on chance-constrained programming to optimize the waste collection process planning. The authors focused on minimizing the total transportation costs with maximum recovery of value within the waste bins. Sharmin and Al-Amin (2016) developed a cloud-based system that uses Ant Colony Optimization method to find the optimal waste collection route. They used sensors to monitor the waste level in bins and to establish a usage pattern for better waste collection planning. The system is also flexible and dynamic and can handle changes in the waste generation pattern or road activities. M. Johansson (2006) examined the effect of different scheduling and routing strategies for solid waste collection. He assessed four collection policies; Static scheduling and static routing, Dynamic scheduling and dynamic routing to full containers, Dynamic scheduling and dynamic routing to almost full containers, and Static scheduling and dynamic routing to almost full containers. The study concluded that the dynamic scheduling and routing policies present lower operating costs and shorter collection distances if compared with the static policies.

Other researchers presented review papers on the IoT enabled collection policy studies recently established. Esmaeilian et al. (2018) studied the future of waste management in smart and sustainable cities by reviewing existing studies on IoT enabled waste management practices and presenting a conceptual framework to overcome the recent gaps in waste recovery. The paper concluded that the transition from smart cities to zero-waste sustainable cities demanded four inter-related strategies; waste prevention, upstream waste separation, on-time waste collection, and collected waste value recovery.

As a conclusion, the number of studies focusing on solving the IoT enabled collection problem is growing reflecting the increased interest in finding smarter waste management strategies.

2.6. Research Gaps

From the reviewed papers, three points can be concluded. The first point is that the interest in finding the best way of collecting waste especially in the big crowded cities became widely spread. Many studies were conducted in different countries presenting various properties but the ultimate objective focused on finding the optimal route to collect the domestic waste with the least cost possible. The problem was looked at from mainly two perspectives periodic review policy and IoT enabled policy.

The second point is that most of the studies targeted the financial part of the problem and set objectives to minimize the collection cost and optimize the process. A few papers included the environmental impact of optimizing the waste collection process but it was not the main focus and it was rarely quantified.

The last point to mention is that no study took into consideration the impact on the inhabitants. The waste generation and its collection is a problem that is directly related to the lifestyle of the people living in the area. Finding a way to quantify the society satisfaction rate of the municipality's waste collection strategy is an important factor in the development of that city and can help raise awareness on other issues such as recycling waste and minimizing waste generation. If habitants have a positive perspective on their municipality's waste collection strategy, they will be more likely to cooperate in other initiatives such as waste segregation and recycling.

For that matter, this research will focus on analyzing the performance of the periodic review strategy against the IoT enabled collection strategy from all three aspects economic, environmental and citizen satisfaction. Thus this thesis has the following contributions:

- ✓ Both the environmental and the citizen satisfaction impact will be quantified.
- ✓ Assessment of both strategies will be presented and will be based on the three performance measures: Economic, Environmental and Citizen Satisfaction.

CHAPTER 3: MODEL DEVELOPMENT

From the detailed discussion presented in the previous chapters, it is evident that implementing an efficient waste collection process that takes into account the environment and the citizen satisfaction rate is crucial for the development of any country and especially for rapidly growing countries such as Qatar. Any country that aims to take a closer step into developing smart cities has to include in its strategy the smart domestic waste management.

In this chapter, the model development steps will be demonstrated. Simulation modeling will be used to consider the stochastickness nature of the waste collection system. Anylogic software will be presented and will be used to model both the waste generation process and the collection system. Finally, the developed model will be validated and verified by comparing its results with manual calculation results.

3.1. Problem Definition

The considered problem in this study is the performance analysis of the periodic review and IoT enabled waste management models from the three aspects economic, environmental and citizen satisfaction. To achieve this goal, simulation modeling will be used to build two waste collection models the periodic review model and the IoT enabled collection model. These two models will be simulated for a period of one year using different waste generation scenarios. And finally, the collected results will be analyzed and each model performance will be evaluated.

3.2. Model Description

The waste collection process is a complex and challenging system. To evaluate it, data needs to be collected over a long period to detect waste generation behavior and evaluate the methods used by the municipality to collect this waste. Data acquisition from the concerned party was not possible due to time limitation and company privacy policies and for those reasons, it was decided to simulate both the waste generation and collection plans.

Simulation modeling is a powerful tool that presents many advantages. It offers a safer way to test and explore different scenarios that help in making the right decision before applying the changes in the real world. It saves money and time as well since virtual experiments are less expensive and take shorter times than experimenting with real world assets. Simulation modeling also allows a clear observation of the way the system behaves over time at any level of detail, increases accuracy and helps in a more precise forecast. Another important advantage is its ability to handle uncertainty in operations times and outcomes which will help in measuring risks and find ways to minimize them (Anylogic).

3.2.1. Anylogic Software Presentation

The simulation modeling was performed using simulation software called Anylogic. The release of the first Anylogic version was in year the 2000 by the Distributed Computer Network research group at Saint Petersburg Polytechnic University as a result of the big success of previously developed software that allowed graphical modeling notation for system structure and behavior. That tool was named “COVERS” for Concurrent Verification and Simulation.

The new software was named Anylogic because it can model systems through all three well-recognized approaches system dynamics, discrete event simulation and agent based simulation (AnyLogic, 2019).

Many improvements were made on the software and now famous companies such as Airbus, Google, DHL, and Ford use and trust Anylogic in simulating and optimizing their processes. Now Anylogic simulation software is used in various industries. In the supply chain industry, it is used in supply chain design, policy evaluation, and risk assessment. In Manufacturing, it is widely used for production planning, process improvement, and layout optimization. In transport, it has a role in logistics planning, fleet management, and risk analysis. In warehouse operations, it is used in layout design, picking optimization and staffing policies. For the Mining industry, it is helpful for forecasts and analysis, excavation planning and fleet optimization. It is even used in the Oil and Gas industry for operation planning, storage management, and oil transfer and in Ports and Terminals management for container and bulk resource management and risk assessment.

Anylogic stands out from other simulation software in its ability to model systems through one of the three modeling methods; system dynamics, discrete event modeling and agent based modeling. And by being more flexible in simulating more complex systems using multi method simulation via incorporating two or even all three modeling approaches simultaneously, Anylogic gives a considerable advantage to its users. Another particularity of this software is that it provides industry specific libraries such as; Process modeling library, Fluid library, Rail library, Pedestrian Library, Road traffic library and Material Handling library (Anylogic).

System dynamics is a simulation approach developed in the fifties to assist managers in understanding industrial processes. These processes are complex systems that present a nonlinear behavior that is easier to understand using the simulation tools that system dynamics offer such as stocks, flows, table functions, time delays, and internal feedback loops. This modeling approach is highly abstract and ignores the detailed individual properties present in the modeled system (System dynamics, 2019).

Discrete Event Modeling approach looks to the modeled system as a sequence of events that happen in time. Each event changes the state of the system when it occurs in a predefined instant of time. There is no change in the system between two consecutive events thus the model can jump to the next event starting time. This simulation approach is broadly used in various industries such as manufacturing, healthcare, and logistics (Discrete-event simulation, 2019).

Agent Based Modeling describe or model the system based on actions and interactions between independent agents. These agents can be in a form of individuals, like a person or a vehicle, or collective entities such as a group of individuals that have common properties or organizations. This modeling approach assesses the effect of these interactions between these agents on the modeled system. This means that the model simulates the system using the detailed properties of the entities constituting it which provides a unique advantage compared to system dynamics and discrete event approach.

In this research work, the agent based modeling approach was used to model the municipal waste collection system. Three types of agents were created, one single agent to model the collection facility where the collection truck will start the routing and complete it. Another single agent was created to model the collection truck and a population of agents was created to model the waste bins. Details on these agents will be presented in the following section of this chapter.

3.2.2. Model Overview

The model developed includes two parts. The waste generation process is the first part. Figure 5 shows a general flow chart of the waste generation. The first step is the arrival of citizens to bins and disposing of waste. Then the disposed waste is accumulated over time in the bins. The next step depends on the policy being modeled. In the case of the periodic review policy, all bins send messages for collection to the collection facility. Whereas, in the case of IoT enabled collection policy only the bins reaching the level threshold send messages for collection.

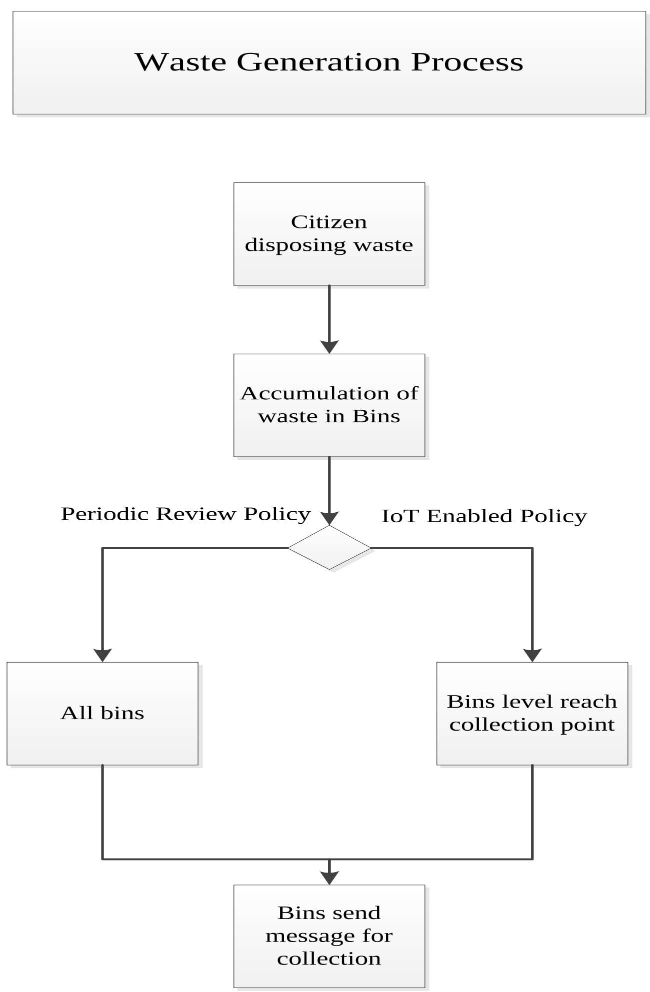

Figure 5. Waste generation general flow chart

The second step is the waste collection process presented by the flow chart in Figure 6. At the start of the model, the truck is stationed at the collection facility waiting for the scheduled collection period. Once the period is attained the truck will start moving. If the periodic review collection policy is being modeled, the truck will collect waste from all bins and go back to the collection facility. If the IoT enabled collection policy is being modeled, the truck will route to the identified bins only and collect the waste. Once all identified bins are serviced the vehicle will go back to the collection facility. At this step the total waste collected, the total traveled distance and the total estimated CO_2 emissions are registered and a new cycle begins. All the performance measures are initialized back to zero when the new cycle starts.

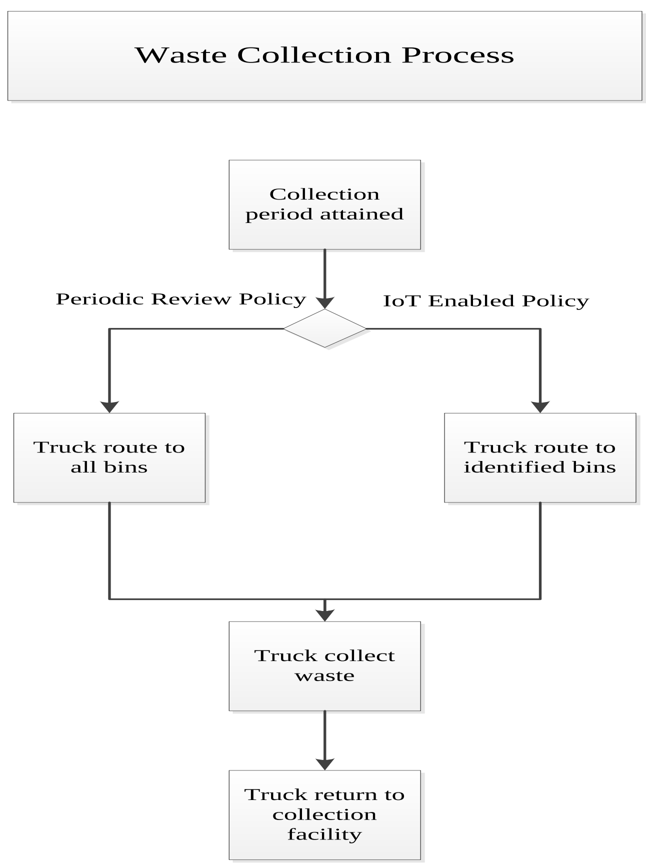

Figure 6. Waste collection general flow chart

3.2.3. Population of Agents 'Bins'

The model consists of 50 bins that present different waste generation behavior depending on certain parameters. The choice of this number is based on truck's maximum capacity as one truck is used in the model with unlimited capacity. Therefore, to keep the model close to the real system the number of bins was limited to this maximum capacity. These bins are located randomly on the actual map of Qatar with the actual real distances and roads between them. This is one advantageous particularity of Anylogic as the user can drag and drop a GIS map from the space and markup palette that represents the actual country or region with a high level of details such as districts and junctions. Figure 7 shows the GIS map of Doha in the model. The blue houses represent the bins. The red animation represents the collection facility where the truck is at the start and the end of each collection cycle.

Figure 7. GIS map of Doha in the model

Bins properties and behavior:

The bins modeled have certain properties and behavior as shown in Figure 8. Each bin has two states in the model, an 'idle' state in which the bin is collecting waste disposed by citizens of that area at a certain rate. This rate varies from a bin to another. And a 'waiting' state in which the bin is waiting for the truck to come and collect the accumulated waste.

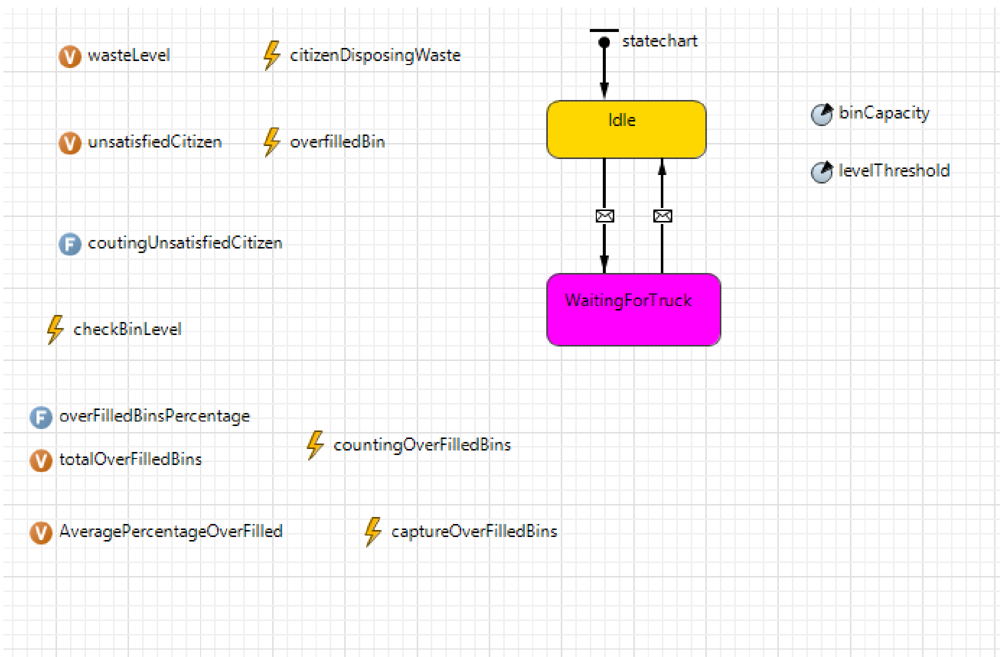

Figure 8. Bins properties and statechart

The transition between these two states is governed by messages. Depending on the collection strategy being modeled, the transition from idle to waiting is triggered either as soon as the waste is thrown into the bin, in case the periodic review collection model is being simulated, or when the bin level reaches a pre-specified level threshold in case the IoT enabled collection model is being simulated. Thus when the bin moves to the 'waiting' state it sends a message to the collection facility to include it in the collection plan of that day.

Once the collection truck reaches the bin and collects its waste the bin waste level comes back to zero and a message ‘bin emptied’ from the collection facility is sent to the bin that changes the state of the bin back to idle. These transitions are happening continuously while the model is running.

Figure 9 illustrates the event called ‘check Bin Level’. This event is scheduled at the end of each day and has as objective to check the status of all the bins at that time of the model and identify all the waste bins that require collection. In other words, this event iterates through all the bins and if their level is above the threshold it changes their state into ‘waiting’. This is done using the code presented in the action box.

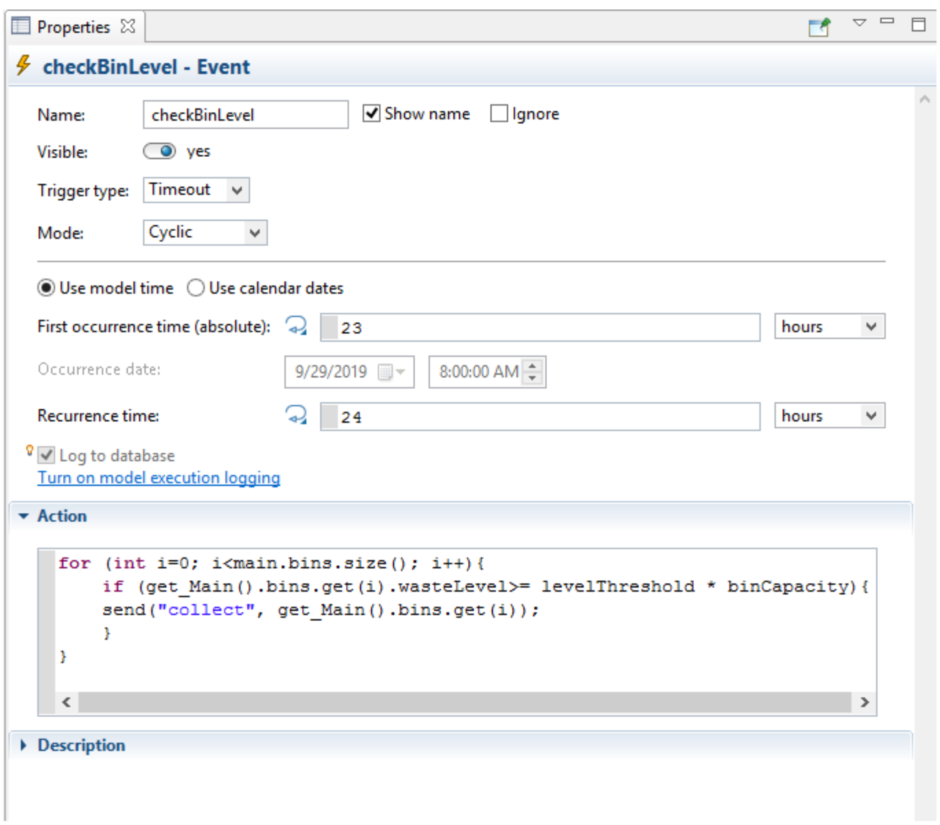

Figure 9. Check Bin Level event in Anylogic

Another event that is happening continuously while the model is running called 'over Filled Bin'. This event checks the bins waste level and if the bin has reached its maximum capacity before it is emptied the event count that bin as overfilled which translates into an unsatisfied citizen. Along with this event, another one has the purpose of summing all the overfilled bins over time and gives the average percentage of overfilled bins daily. This part of the model gives a quantifiable metric that will help assess the citizen satisfaction rate between different waste collection policies.

3.2.4. Agent 'Truck'

The truck routing logic was developed using the state chart presented in Figure 10. There are six states the truck goes through to collect waste from all the bins that are in the waiting state. In the first state, the truck is positioned at the collection facility and it is in idle state. Then an event that is triggered depending on the collection policy set (once per week, twice per week, three times per week or every day) transitions the truck to the state 'waiting for start'. In this state, the truck waits to receive the message sent from the bin confirming that it reached the level threshold and needs collection. Between this state and the next one 'moving to bin', there is a conditional transition called 'check Bin Filled'. This conditional transition has a purpose to check if at this waiting stage no bin needs collection the truck will go back to the first state but if the truck receives the message that a group of bins need collection it will first find the nearest bin to its current location using the nearest neighbor routing logic and then proceed to the 'moving to bin' state.

The truck will keep transitioning between the three states 'moving to bin' 'at bin' and 'emptying bin' until it services all the required bins while choosing every time the closest bin. When all bins are serviced the conditional transition ‘check all bins serviced’ will be satisfied and the truck will move back to the collection facility.

When the truck is at the ‘emptying bin’ state the truck will send the message ‘Bin emptied’ and the bin level will go back to zero, the waste weight collected will move from the bin to the truck, the CO_2 emission and the traveled distance are calculated as well using ‘CO_2 emission’ function and the built-in ‘distanceByRoute’ function respectively.

When the truck reaches back to the collection facility all the waste collected will be emptied and captured in the ‘cumulative total waste’ variable, the total emissions and traveled distance will be captured in ‘cumulative CO_2’ and ‘cumulative distance’ variables as well. After that, the truck will go back to idle condition waiting for ‘start routing’ event to trigger another collection cycle.

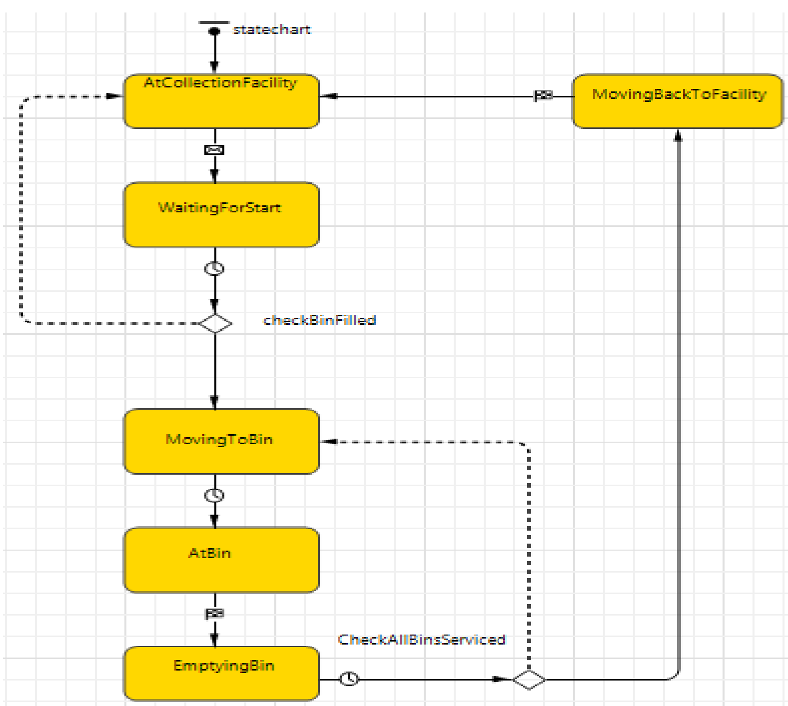

Figure 10. Truck statechart

3.2.5. Model Parameters and Formulas

3.2.5.1. Model Parameters

The parameters related to Bins that were used to run the simulation are as follow:

- The waste generation was modeled using two events; the arrival of citizens disposing of waste and the capture of the waste weight disposed of every time. The arrivals of citizens was modeled using a Poisson distribution with the rate of occurrence Lambda λ= 45 minutes. The Poisson process describes a situation where a series of discrete events happen in which the average time between the events is known but the exact timing when the event happens is random. And these occurring events are independent of each other (Koehrsen, 2019). The Poisson distribution description matches the model scenario where the exact time of arrival of the citizen to dispose of its waste is not known and the first event of citizen disposing waste does not affect the one right after. Thus it is a good estimation for proper simulation results.

  Every time the citizen throws his waste the bin gets full by a certain amount of waste weight which is modeled by a normal distribution with an average waste weight of 6 kg and a standard deviation of 2 kg. These numbers were chosen based on the study made by Ahmad (2016) in which waste generation data of 84 households in Doha was collected for three months between February 2015 and April 2015 to find a waste generation pattern.
- The bins capacity is 660 Liters.
- The domestic waste specific weight/ density 481 kg/m^3 = 0.481 kg/Liter (Density of Garbage).

- The bins locations were chosen randomly across the city of Doha.

The parameters related to the trucks are as follow:

- Truck's average speed is 15 km/hour. This average speed is estimated taking into account the truck speed between two bins, the distance between these two bins, and the stops for collecting the bins waste (Apaydin & Gonullu, 2011).
- The truck capacity was kept unlimited to simplify the model.
- Empty truck weight is 15 tons (Smith , 2017).

Table 3 summarizes these simulation parameters.

Table 3. Simulation Parameters

Parameter	Value
Citizen arrival rate	Poisson distribution (λ=45)
Waste weight	Normal distribution (6,2)
Bins capacity	660 Liters
Waste density	0.481 kg/Liter
Truck average speed	15 km/hour
Truck capacity	Unlimited
Truck empty weight	15 tons

3.2.5.2. Model Formulas:

The distance between different bins and the collection facility used in the model were directly computed by Anylogic. The latter has an integrated GIS map that included all the routes, regions along with their names and locations which made getting real distances between the random locations of the bins possible. The map is downloaded in real-time from OpenStreetMap online map services.

The carbon dioxide emission was calculated using Equation 1:

Equation 1: Vehicle CO2 Emission Equation

$$EM_{ij} = FE * FC_{ij} \quad (1)$$

where:

FE: is the Fuel Emission factor defined as the amount of carbon emissions per liter of fuel used. It measures the truck efficiency by converting fuel consumption into carbon emissions. The fuel emission factor is a constant set to be equal to 2.62 kg/Liter (Li, Lu, & Fu, 2015).

FC_{ij} : is the total amount of fuel consumed between two bins constituting the arc 'ij'. Many studies estimated the fuel consumption relying on distance only but this formula takes into account the truck weight, its load and the speed at which it is moving on top of the distance traveled by the collection truck. The fuel consumption is calculated using Equation 2 (Li, Lu, & Fu, 2015).

Equation 2: Fuel Consumption Equation

$$FC_{ij} = \left(\alpha_{ij}\left(\omega + y_{ij}\right) + \beta v_{ij}^2\right)d_{ij} \quad (2)$$

where:

α_{ij} : is an arc specific constant related to acceleration, road gradient, and rolling resistance.

ω : is the empty truck weight.

y_{ij} : is the load carried by the collection truck between the two bins 'i' and 'j'.

β : is a vehicle speed constant dependent on air density and frontal surface area of the truck.

d_{ij} : is the distance covered by the truck between bin 'i' and 'j' in kilometers.

Table 4 demonstrates the numerical values used to calculate the CO_2 emissions.

Table 4. Numerical Values used in CO_2 Emissions Calculation

Symbol	Value
FE	2.62 kg/Liter
αij	0.09
ω	15 tons
β	1

Figure 11 shows the function called ‘CO_2 emission’ developed in Anylogic model with two arguments, the total waste collected and the total distance between two consecutive bins. This function is called every time the truck reaches a bin and collects waste and the ‘cumulative CO_2 emission’ variable aggregates all calculated values.

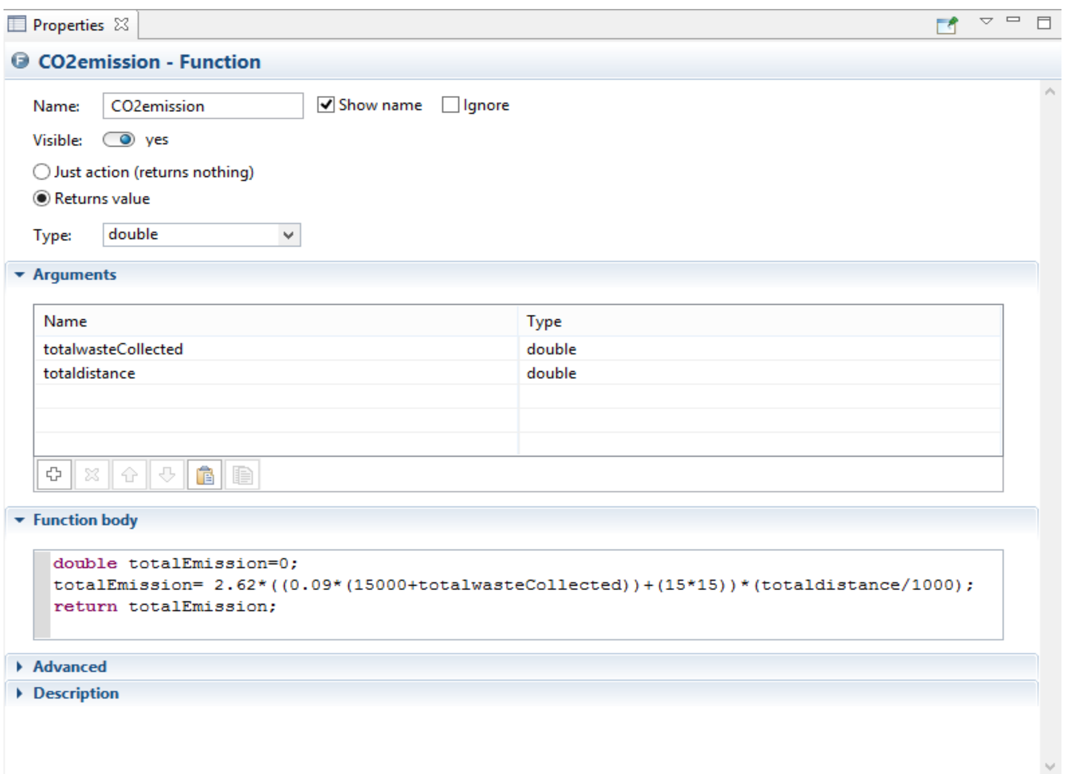

Figure 11. CO_2 emission function in Anylogic

3.3. Model Verification and Validation

Before proceeding to model experiments, a crucial step of verifying and validating the built simulation model is essential. There is a fine difference between verification and validation. Model verification is the process of proving that the built model is represented correctly and that it compiles without any bugs or coding mistakes. Moreover, the model needs to satisfy all the representation requirements, rules, and constraints. Whereas Model validation is the process of showing that the built model represents the real system and that it behaves similarly with an acceptable level of accuracy (Brade, 2003).

The main difference between verification and validation is that in the verification process the reference to the real system and envisioned purpose of use is not subject to verification (Brade, 2003).

Building the waste collection model in Anylogic was done through numerous steps. At each step, the model was tested that it compiled first and that the intended results were met. The first part was to build the waste generation process in the model and defining the behavior of the bins ('idle' state or 'waiting for truck' state). The waste generation needed to be specific for each bin meaning that at a certain point of time in the model each bin will have a different fill rate and accordingly will have a different state. The software visual capabilities made the process of verifying straightforward by identifying the bins in the 'waiting for truck' state with a red dot. Furthermore, when the model is paused, it was possible to check the fill rate of each bin individually and it was confirmed that it was different for each bin. The following figures show a paused model. Figure 12 shows all the bins along with their state (the bins with red dots are in the state of 'waiting for truck'). Figures 13 and 14 show two different bins with different fill levels and states at the same paused model time.

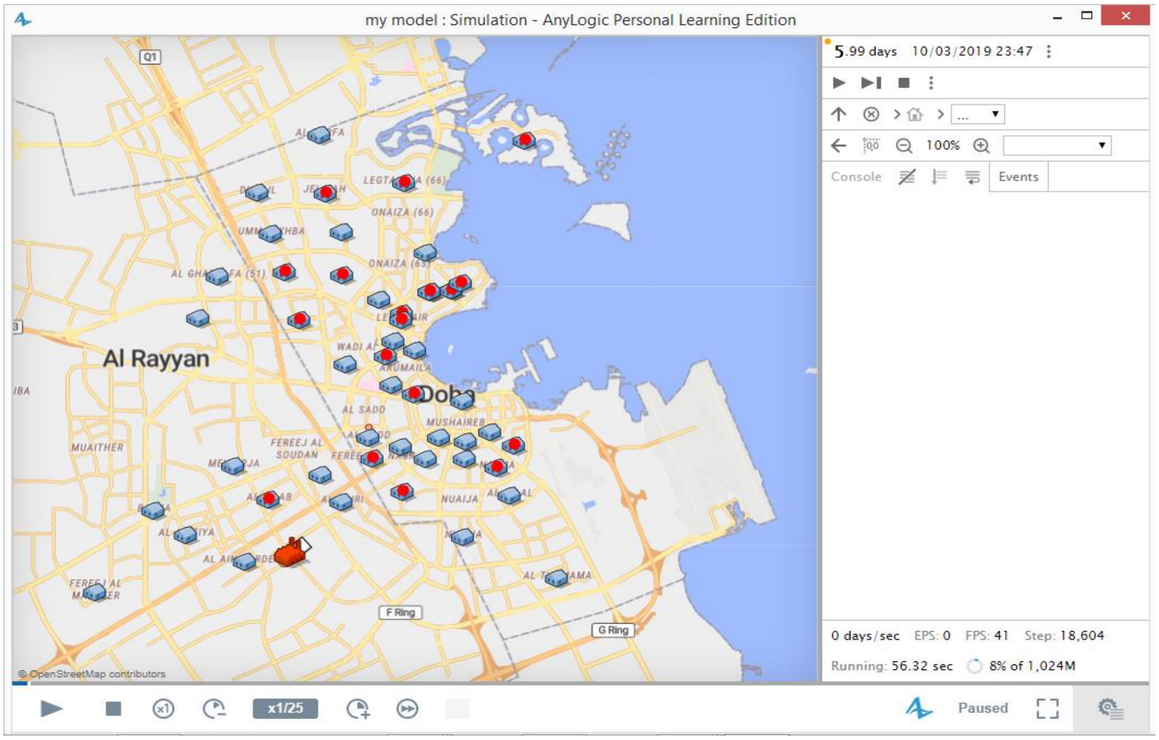

Figure 12. Paused model overview

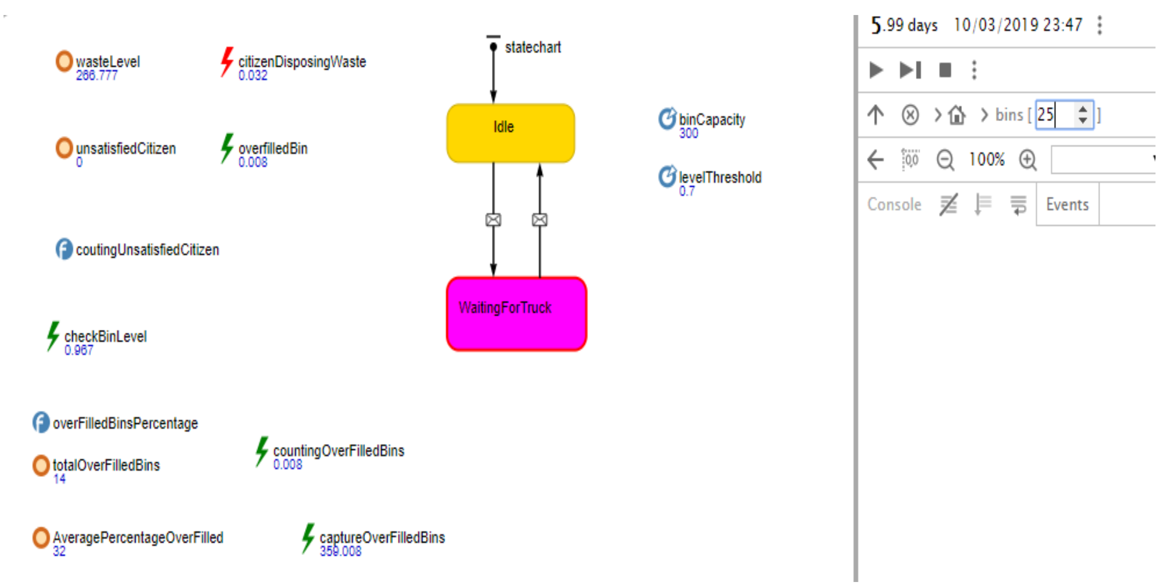

Figure 13. Bin 25 in waiting for truck state in the paused model

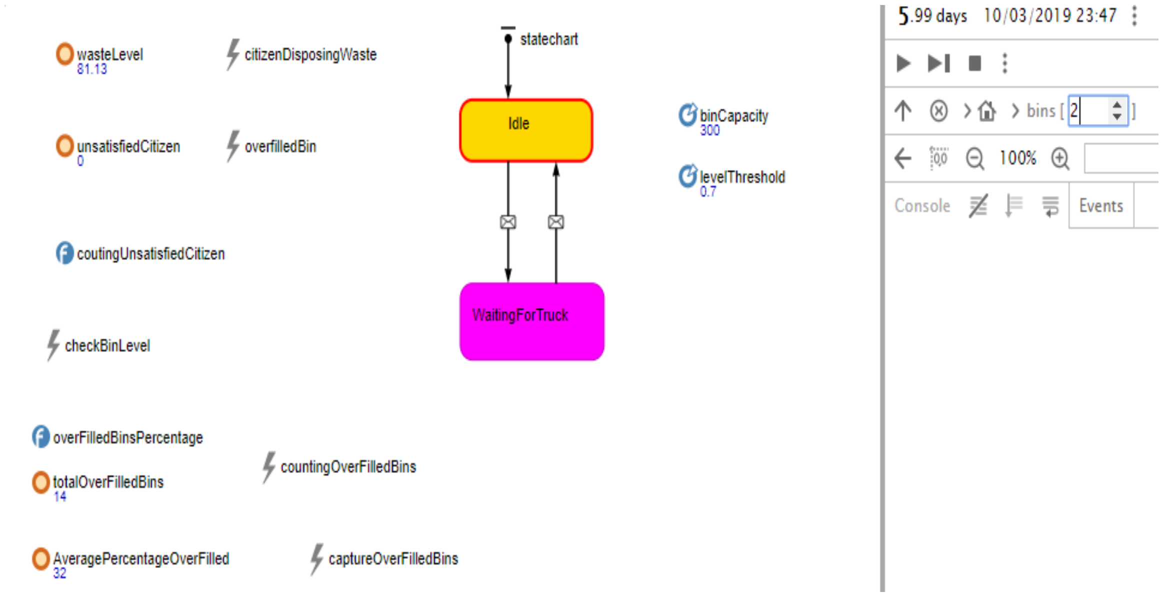

Figure 14. Bin 2 in idle state in the paused model

The second part of the model included the waste collection truck routing logic which was defined by a statechart that was explained in the model description section. The model was run and the statechart was carefully examined and all model errors and misbehaviors were identified and corrected. Then for the validation part, the same model, but smaller in size with 5 bins, was tested for a week and was compared to manual calculations done with Microsoft Excel. Three collection policies were tested, the once per week, twice per week and everyday periodic review collection policies. The model results were captured and compared to the manual calculation results to find the percentage error between both. Three types of data were collected; the total waste weight collected, total distance traveled by the collection truck and the total CO_2 emissions. The validation process was performed this way due to a lack of real-world data.

Tables 5, 6 and 7 below summarize the comparison results between simulation models and manual calculations along with the percentage error for everyday, twice per week and once per week periodic review collection policy respectively.

Table 5. Validation Result of Everyday Periodic Review Collection Policy

Everyday Periodic Review Collection Policy			
	Manual Calculation	Model Simulation	Error
Total Weight (kg)	6,586.17	6,760.78	2.65%
Total Distance (km)	204.722	204.733	0.01%
Total CO2 (kg)	871.657	880.389	1.00%

Table 6. Validation Result of Twice per Week Periodic Review Collection Policy

Twice per week Periodic Review Collection Policy			
	Manual Calculation	Model Simulation	Error
Total Weight (kg)	6,642.34	6,726.95	1.27%
Total Distance (km)	58.492	58.495	0.01%
Total CO2 (kg)	268.462	276.761	3.09%

Table 7. Validation Result of Once per Week Periodic Review Collection Policy

Once per week Periodic Review Collection Policy			
	Manual Calculation	Model Simulation	Error
Total Weight (kg)	7,217.15	6,716.44	6.94%
Total Distance (km)	29.246	29.247	0.01%
Total CO2 (kg)	149.926	156.090	4.11%

All percentage error results do not exceed 10% which gives a good confidence level for the built model accuracy.

3.4. Summary

In this chapter, the waste collection problem definition was elaborated. The simulation model was described in detail. Anylogic software used for building the model was presented as well. Agent based modeling approach was used in building the waste collection model. Both the population of agents ‘Bins’ and the agent ‘Truck’ parameters and behavior were described. All the parameters and equations used in the model were defined and presented. And finally, the built model was verified and validated by comparing the model output of three waste collection policies (once per week, twice per week, and every day) with manual calculations. It was perceived that the percentage error of the model results did not exceed 10% and concluded that the model represents the real system with sufficient accuracy. In the following chapter, the model will be executed for different experiments and the results will be analyzed for insightful conclusions.

CHAPTER 4: EXPERIMENTS AND RESULTS ANALYSIS

This chapter is divided into three sections. In the first section, the performance measures that will be used for comparing the traditional method of waste collection with the IoT enabled method will be set. The second section presents all the performed experiments. The experiments' results will be summarized in tables and analysis of these results will be made in the third section to discover the advantages and disadvantages of both waste collection models.

4.1. Performance Measures

Most of the previous studies published in the literature review concerning the waste collection problem focused on analyzing the proposed waste collection solutions from an economical point of view solely. And a few studies included the effect of a better waste collection policy on the environment. In this research, the comparison between the periodic review collection policy and the IoT enabled collection policy will include three performance measures.

The economic performance is always important for the municipalities as the waste collection process cost, as mentioned earlier in the literature review chapter, presents 80% of the total municipal waste management budget (Hoornweg & Bhada-Tata, 2012). Many studies showed that the collection cost increases linearly with the traveled distance of the collection vehicles. Therefore in this study, the economic performance indicator monitored in the different scenarios is the total traveled distance. The number of trucks used in the collection process as well as the employees involved has also an impact on the cost but was assumed negligible since one truck was included in the model.

The second performance indicator that was studied is the environmental aspect of the collection process. The focus was on the carbon dioxide emissions of the collection trucks. Equations 1 and 2 were used in the model to estimate the truck CO_2 emissions. These equations, as mentioned in the previous chapter, highlighted the importance of not only the traveled distance but also the load carried by the vehicle and its speed.

The third and last performance indicator was not taken into consideration by the previous research papers and is a contribution of this study. It is the citizen satisfaction rate as a result of the policy used by the municipalities in collecting the waste. This performance was estimated by recording the percentage of overfilled bins. Citizens passing by overfilled bins or citizens that are going to dispose of their waste and finding the bin full will be displeased. A neighborhood where the bins are frequently overfilled will cause unhappy citizens in terms of smell and the aesthetic of the public place. Thus it was considered that the more often the bins are overfilled the worse the model is performing in terms of citizen satisfaction rate.

4.2. Design of Experiments

After assuring that the built model is representing the real system with an acceptable level of accuracy, it is important to carefully experiment with the model by changing the inputs parameter and recording the outputs to get insightful observations.

Two different collection models were tested. The periodic review collection model in which the collection truck will route to all the bins, independently of the bins fill rate, every time the specified period is reached. This collection model depicts the traditional waste collection method that is commonly used by most of the municipalities. The other collection policy is the IoT enabled collection model in which the truck will service only the bins reaching a certain waste level and ignore the remaining ones. This method is modeling the use of smart bins equipped with level sensors and communicating with a central collection facility that decides the bins that need servicing.

For the periodic review policy, the model was tested with four different collection frequencies. Periodic collection performed once per week, twice per week, three times per week and every day. Whereas the IoT enabled collection policy was tested with three different bin waste level thresholds based on bin capacity. These three thresholds are 70%, 80%, and 90%.

Two scenarios related to the waste weight variability were tested as well. Low waste weight variability scenarios modeling a homogeneous neighborhood in which citizens have similar waste generation patterns. And high waste weight variability scenarios that model a heterogeneous neighborhood where citizens come from different backgrounds and lifestyles and have different waste generation patterns.

Three different waste fill rates were also tested based on the citizen arrival rate; high arrival rate, low arrival rate, and variable arrival rate. This is to accommodate the different periods of the year in which the waste is generated in different patterns. During the holiday season and summer seasons, for example, the generated waste is usually lower than the normal due to expatriates leaving back to their native countries. On the other hand, during special events such as a big sports event a considerable flow of incoming tourists into the country will increase the waste generation rate. Table 8 shows all the parameters along with their related experimented values.

Table 8. Parameters Experiment Values

Parameter	Classification	Value
Fill rate	(High, low, variable)	Poisson (45), Poisson (60), (Uniform 45-120)
Waste weight variability	(High, Low)	Normal (6,4), Normal (6,2)

Parameter	Classification	Value
Periodic Review Policy		(1/week, 2/week, 3/week, 7/week)
IoT Enabled Policy threshold		(70%, 80%, 90%)

All these parameters were combined and the scenarios were simulated for a year with 30 replications. The replications were necessary due to the stochastic nature of the model. The total time required to run all the simulation scenarios was around three hours and the results will be presented and discussed in the coming part of this chapter.

4.3. Results Discussion and Analysis

This section of the thesis will present the simulation results. These results will be analyzed and evaluated based on the three performance indicators previously mentioned.

4.3.1. Evaluation of the Periodic Review Collection Model

The results of the total collected waste weight, the total traveled distance, the CO_2 emissions and the percentage of overfilled bins were plotted and analyzed in this section of the chapter.

The total waste weight is almost constant in each simulation. Nevertheless, it was noticed that the higher the arrival rate the more waste is collected which is logical as the waste generation is directly related to the arrivals of citizens disposing it. The variable arrival rate yielded to the lowest waste amounts with an average of 1910 tons per year compared to an average of 3489 tons per year for high arrival rates. This is explained by the fact that the variability range in the model was wide leading to a lower total number of citizens disposing waste.

The second observation is related to the waste weight variability. Increasing the variability of the waste weight disposed from a standard deviation of 2 kg to 4 kg with a mean of 6 kg has a negligible impact and does not affect the total waste amount as much as the arrival rate. This observation is valid for all other measures as well. The effect of increasing the variability of waste weight on the total distance, total CO_2 emissions and the percentage of overfilled bins is negligible. Therefore the following performance analysis of the periodic review model will include the scenarios with low waste weight variability solely.

Figure 15 demonstrates that the total traveled distance is greatly affected by the choice of the collection period. It is clear from the graph that the more frequent the collection is performed during the week the higher is the total traveled distance registered for the collection truck. This distance does not change with varying the arrival rate or with the different waste weight variability since the traveled distance is independent of the generated waste. The truck is scheduled to pass by all the bins every time leading to the same total traveled distance in all scenarios.

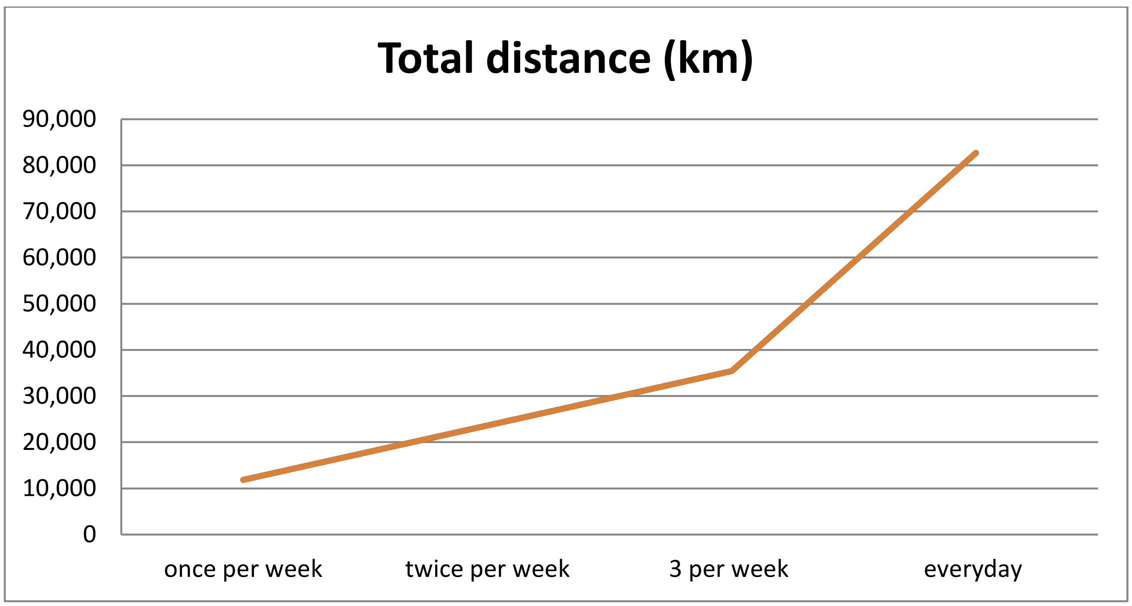

Figure 15. Total distance results for periodic review collection model

Figure 16 shows that the CO_2 emissions increase with the increase in the frequency of collection. This CO_2 emissions increase is the direct result of the significant increase in the truck traveled distance. The percentage increase is significantly high for all the scenarios with an average of 65% increase in the emissions.

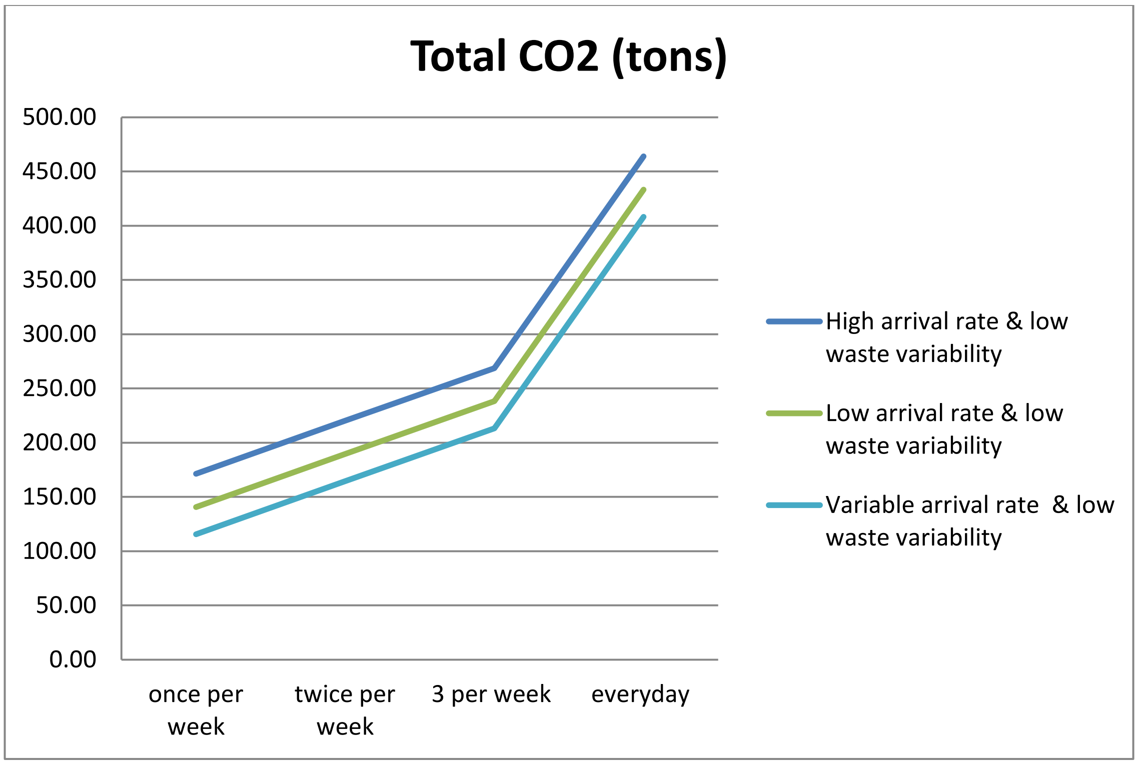

Figure 16. Total CO2 emissions results for periodic review collection model

On the other hand, for all scenarios, when the frequency of collection is increased the percentage of overfilled bins reduces until it reaches zero for every day periodic review collection model as shown in Figure 17. The lower the arrival rate the lower is the chances of finding an overfilled bin and since the variable arrival rate leads to the lowest amount of waste, it is obvious that it will lead to the lowest percentage of overfilled bins compared to the high and low arrival rate scenarios.

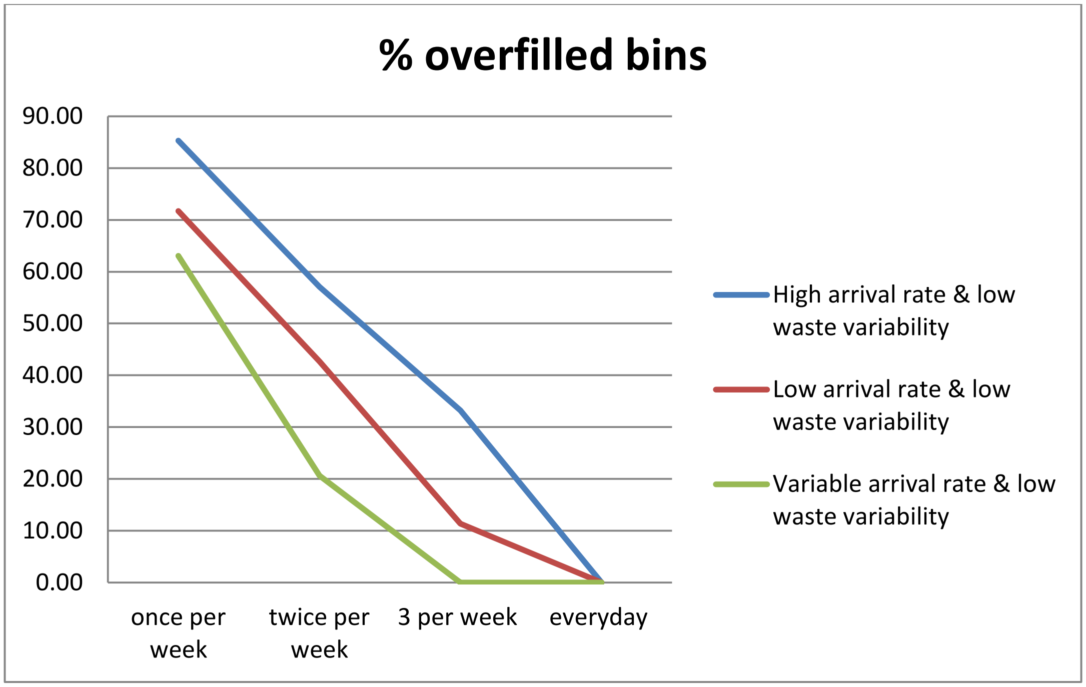

Figure 17. Percentage overfilled bins results for periodic review collection model

4.3.2. Evaluation of the IoT Enabled Collection Model

The same steps will be followed in evaluating the IoT enabled collection model. The total amount of waste collected in the case of this model is similar to the periodic review collection model.

A general observation for almost all scenarios presented in Figure 18 is that the total distance changes with the change of the specified threshold and decreases with the increase of the bin level threshold. This is because the truck only visits the bins reaching the level threshold, therefore when this threshold is increased the truck visits fewer bins yielding to a lower total traveled distance.

In the 'low arrival rate and low waste weight variability' and 'low arrival rate and high waste weight variability' scenarios the total distance has decreased by 7% and 9% respectively. The highest percentage decrease achieved was in the variable arrival rate scenarios with almost 10% decrease in traveled distance. This is because in the variable arrival rate, as previously noticed, the waste generation is the lowest and the lower the waste generation the higher is the impact of changing the level threshold.

The total distance has decreased for the high arrival rate scenarios as well but the drop was not significant, from 42,547 km down to 42,108 km for the 'high arrival rate and low waste weight variability' scenario. The reason is that changing the level threshold with a high waste generation rate does not affect much the number of bins that need to be serviced. In other words, bins, after being emptied by the truck, reach faster the level threshold the next day and are included in the routing schedule of that day which eventually does not reduce the total distance.

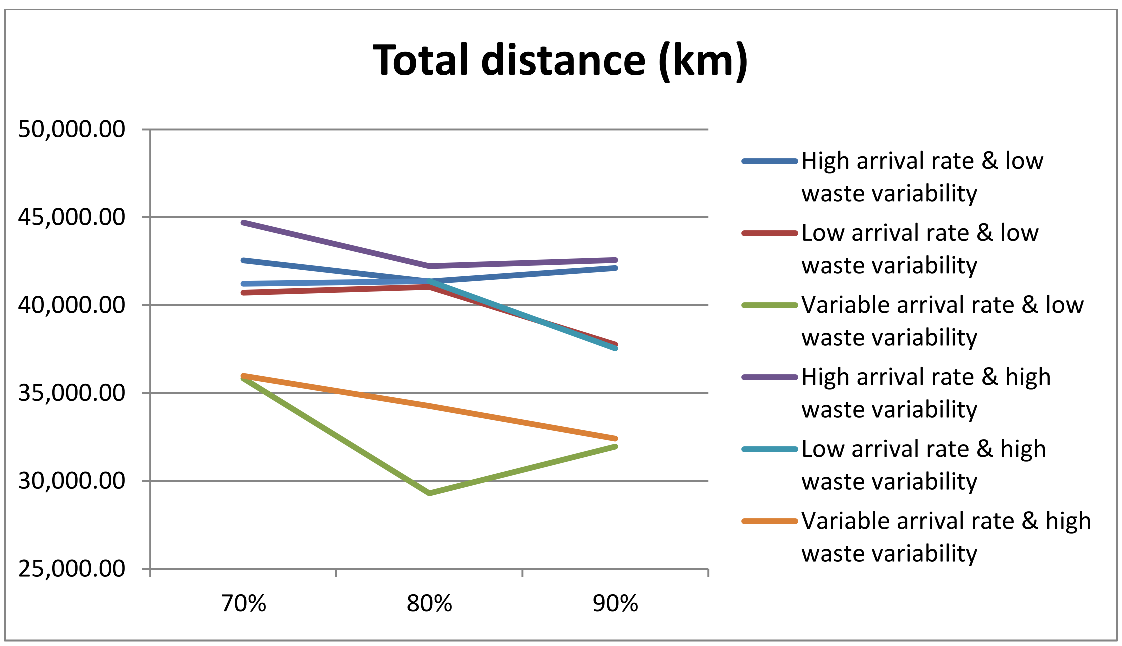

Figure 18. Total distance results for IoT enabled collection model

The total CO_2 emissions are directly related to the distance traveled and the waste generation. The less the traveled distance the less carbon dioxide is emitted. Figure 19 shows that increasing the level threshold reduces CO_2 emissions. The lowest CO_2 emissions are registered with the variable arrival rate scenarios that generate the lowest amount of waste.

The emissions decrease in the high waste generation scenarios with increasing the level threshold is not significant as a result of a limited decrease in distance and a high amount of waste.

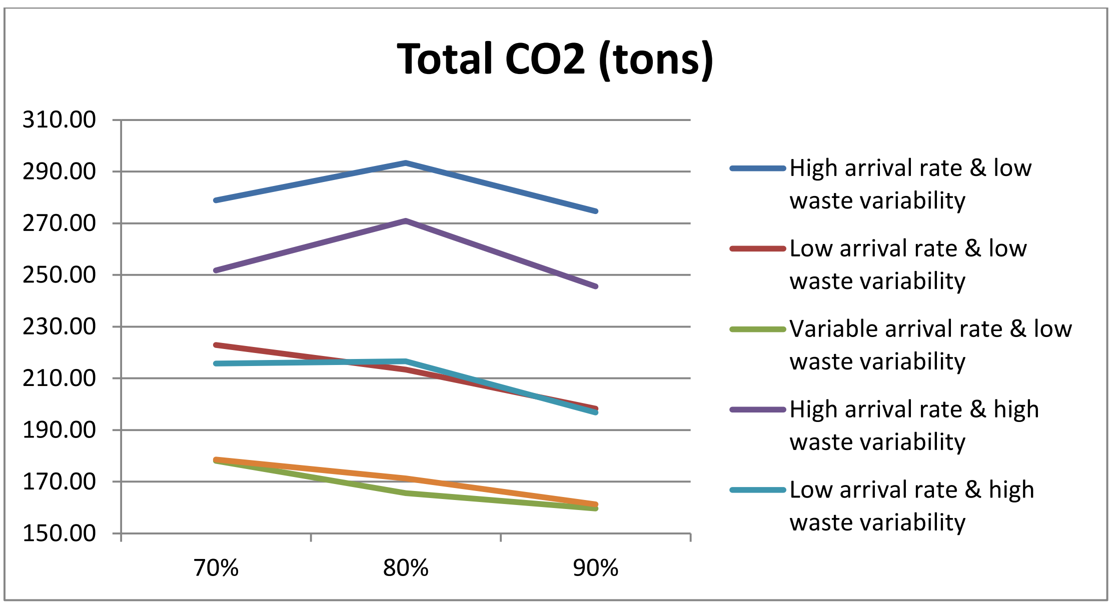

Figure 19. Total CO_2 emissions results for IoT enabled collection model

Figure 20 shows that there is no significant change in the percentage of overfilled bins with changing the level threshold for the high arrivals scenarios. On average, almost half of the bins get overfilled and changing the level threshold does not improve the results.

Whereas, changing the level threshold has an impact on the percentage of overfilled bins for the low arrival rate and variable arrival rate. The lower the level threshold set the better the results. This is because when the level threshold is increased the risk of bins getting overfilled is higher. The best results were reached with a 70% level threshold in the 'low arrival rate and low waste weight variability' scenario with a percentage of overfilled bins close to zero.

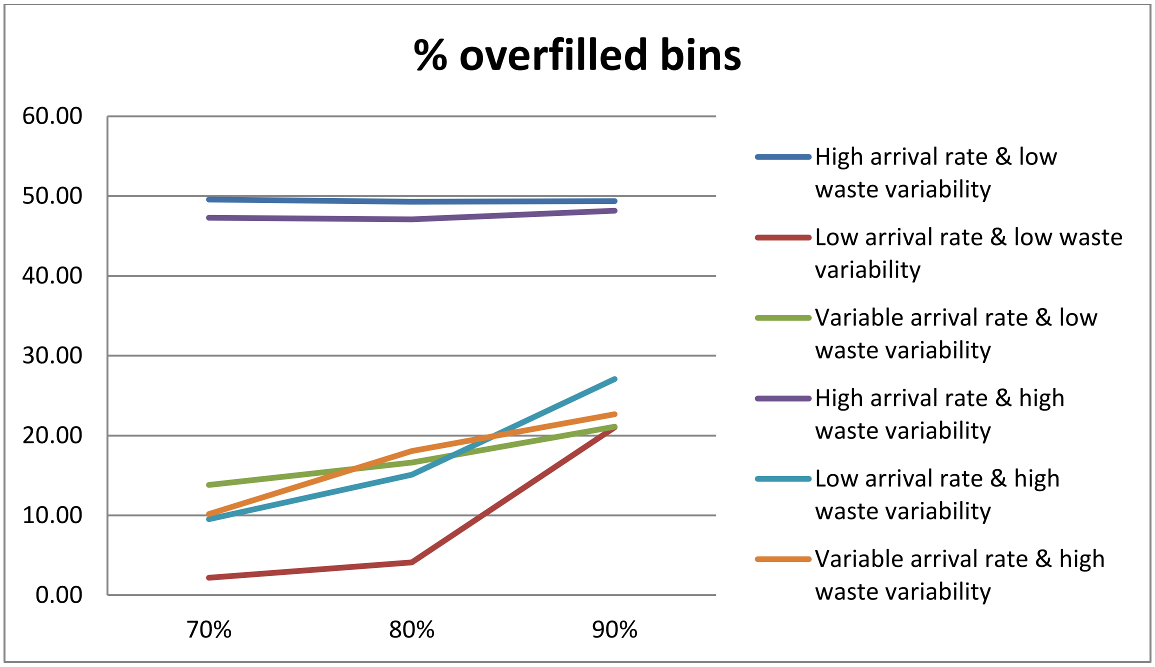

Figure 20. Percentage overfilled bins results for IoT enabled collection model

4.3.3. Periodic Review Collection Model and IoT Enabled Collection Model Comparison

Comparing both models will give more insightful observations on what advantages and disadvantages each model presents. The total waste generated will not be included in this comparison as it is independent of the collection method used and the focus is on analyzing the performance of each method.

Furthermore, it is worth mentioning that from analyzing each collection model separately it was concluded that the waste weight variability does not have a significant impact on the final results for the periodic review collection model and yield to similar results for the IoT enabled collection model. Thus only the scenarios with low waste weight variability will be analyzed. The conclusion attained from analyzing these scenarios will be assumed valid for the high waste weight variability as well.

4.3.3.1. High Arrival Rates

Figure 21 illustrates that the highest travel distance is reached with the everyday periodic review collection model which can be considered the worst performing model in terms of the total distance. All IoT enabled collection model results are comparable to each other and the three per week periodic review model. The lowest distance is registered for once per week periodic collection. The same results are observed for the total CO_2 emissions as well.

On the other hand, although it resulted in the lowest distance and emissions, the once per week collection presents the highest percentage of overfilled bins with more than 80%.

The best result in terms of overfilled bins is found in the everyday periodic review model with zero overfilled bins. The second best results are attained in the three collections per week model with around 30% overfilled bins. All the scenarios of the IoT enabled model yielded similar results that are slightly worse than the three collections per week model with an average of 50% overfilled bins.

In the case of high arrival rates, it is a good strategy to choose the periodic review policy with a frequency of three collections per week as it is the best performing model economically and environmentally and yield to a higher citizen satisfaction rate.

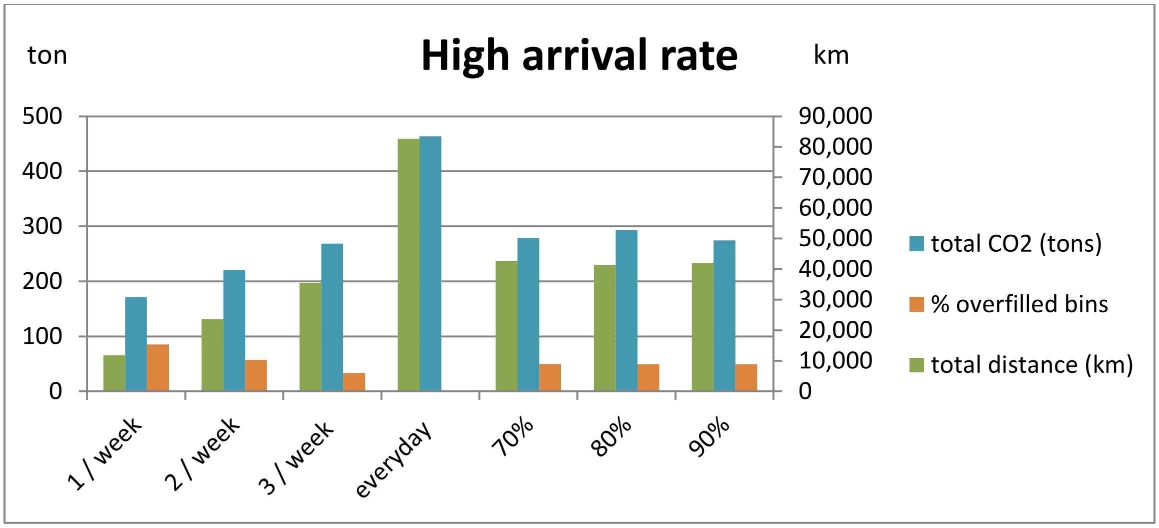

Figure 21. High arrival rate results comparison

4.3.3.2. Low Arrival Rates

Figure 22 summarizes the low arrival rate scenarios results. It appears that the total traveled distance results are similar to the high arrival rate scenarios. Nevertheless, the results of the CO_2 emissions are slightly different. Here the IoT enabled collection model, including all the level threshold tested, yield to a 16% lower total emissions compared to the three per week periodic review model.

In terms of overfilled bins, the everyday periodic review model is still the best with zero overfilled bins but the IoT enabled collection models results are also positive with 2%, 4%, and 22% of average overfilled bins per year for 70%, 80%, and 90% level threshold respectively.

Thus for the low arrival scenarios, the IoT enabled collection model results are the most promising particularly with a 70% level threshold. The results of this model present a minimized total distance, total CO_2 emissions, and the percentage of overfilled bins simultaneously.

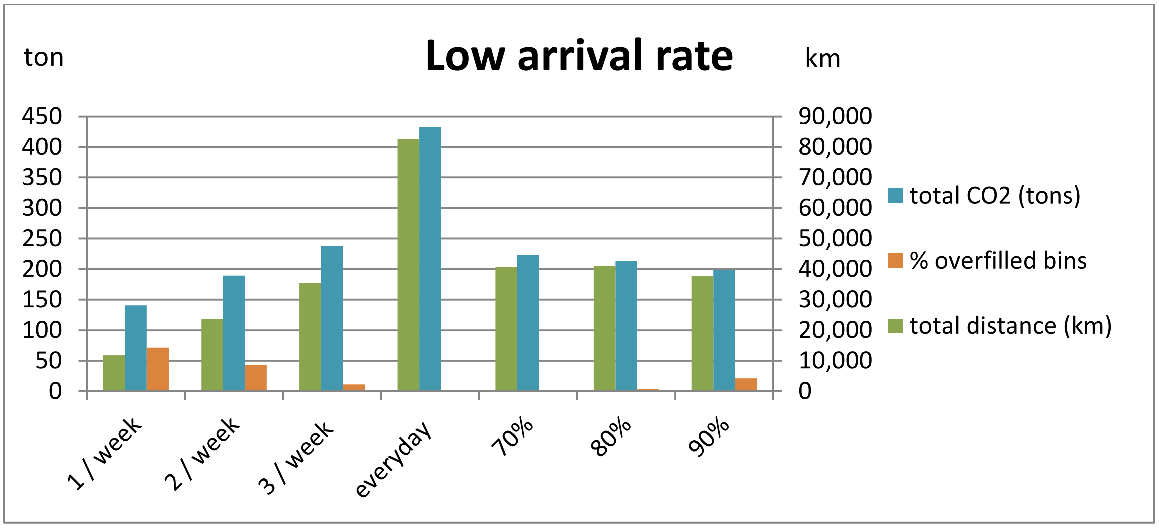

Figure 22. Low arrival rate results comparison

4.3.3.3. Variable Arrival Rates

The variable arrivals rate scenarios results represented in Figure 23 show that the best option for such scenarios is either the three per week periodic review model or the 70% level threshold IoT enabled collection model. Both models perform closely in terms of the total distance (35,432 km and 35,838 km). The periodic review model presents a better result in the percentage of overfilled bins with near to 0% compared to 14% for the IoT enabled model. Nevertheless, the IoT enabled model has 16% lower total CO_2 emissions. Thus for this scenario, the optimal model will be based on the priorities fixed by the municipalities. If the latter prioritizes the citizen satisfaction rate, the three per week review model will be the best option. Otherwise, if the priority is set for the environmental effect of the waste collection, the IoT enabled collection model with a 70% level threshold will be a better strategy.

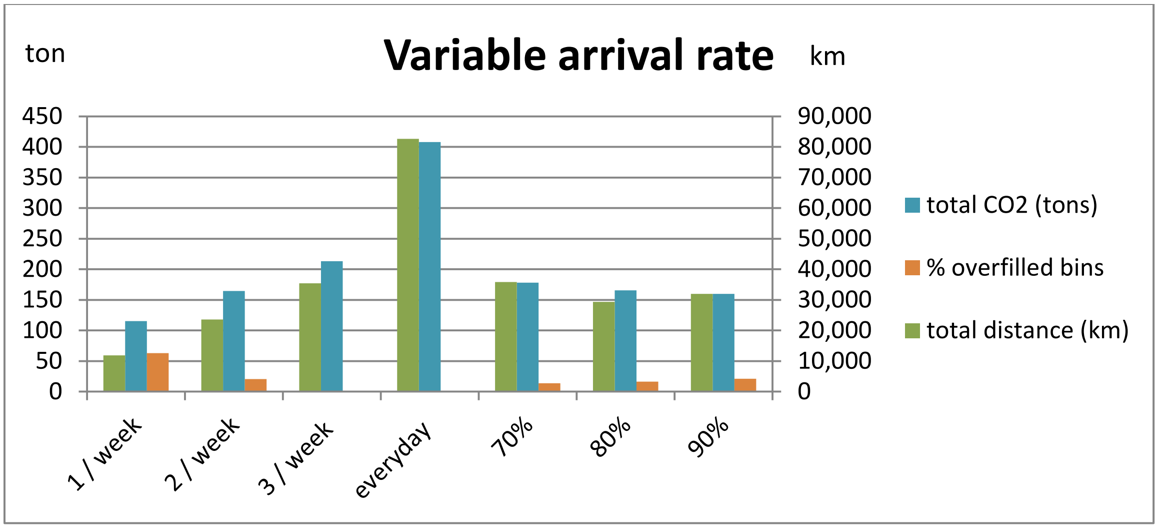

Figure 23. Variable arrival rate results comparison

CHAPTER 5: CONCLUSION AND FUTURE WORKS

Following the detailed analysis of all the results obtained from the different models and scenarios, conclusions will be summarized in this chapter. The future works will be presented too.

5.1. Conclusion

Tables 9, 10 and 11 summarize the results observed from the different models and scenarios for all the performance measures by giving the order from 1 to 7: 1 being the best result and 7 the worst.

Table 9. Summarized Results for Economic Performances

Total distance		Periodic review model				IoT enabled model		
		1/week	2/week	3/week	everyday	70%	80%	90%
Low waste variability	High arrival	1	2	3	7	6	4	5
	Low arrival	1	2	3	7	5	6	4
	Variable arrival	1	2	5	7	6	3	4
High waste variability	High arrival	1	2	3	7	6	4	5
	Low arrival	1	2	3	7	5	6	4
	Variable arrival	1	2	5	7	6	4	3

Table 10. Summarized Results for Environmental Performances

Total CO_2		Periodic review model				IoT enabled model		
		1/week	2/week	3/week	everyday	70%	80%	90%
Low waste variability	High arrival	1	2	3	7	5	6	4
	Low arrival	1	2	6	7	5	4	3
	Variable arrival	1	3	6	7	5	4	2
High waste variability	High arrival	1	2	3	7	5	6	4
	Low arrival	1	2	5	7	4	6	3
	Variable arrival	1	3	6	7	5	4	2

Table 11. Summarized Results for Citizen Satisfaction Performances

% overfilled bins		Periodic review model				IoT enabled model		
		1/week	2/week	3/week	everyday	70%	80%	90%
Low waste variability	High arrival	7	6	2	1	5	3	4
	Low arrival	7	6	4	1	2	3	5
	Variable arrival	7	6	2	1	3	4	5
High waste variability	High arrival	7	6	2	1	5	3	4
	Low arrival	7	6	3	1	2	4	5
	Variable arrival	7	6	2	1	3	4	5

This study was the first of its kind that incorporates the three performance measures; economic, environmental and citizen satisfaction in assessing both the traditional waste collection process, commonly implemented by municipalities, and the IoT enabled collection policy that exploits the technological advances with applying the concept of IoT and sensors in the waste management strategies.

Important conclusions can be made from the attained results to help in enhancing the waste collection strategies that municipalities implement for a greener and less expensive collection process with higher citizens' satisfaction.

The following are the reached conclusions:

- In the case where the waste generation is considerably high setting a traditional waste collection strategy with three times per week periodic review will yield better results than switching from the traditional collection model to the IoT enabled one.
- In the case where the waste generation is moderate switching to the IoT enabled collection policy gives a promising added value in the waste management process in all economic, environmental and citizen satisfaction measures.
- In the case where the waste generation is highly variable, the decision to switch from the periodic review policy to the IoT enabled policy will depend on the government priorities. Setting a 70% IoT enabled collection policy has a positive environmental impact on the whole process reducing vehicle emissions but the citizen satisfaction rate will be higher if the collection method is the three times per week periodic review.
- Furthermore, it was observed that in the case the disposed waste weight variability increases the impact on the total amount of waste is not significant when the system is studied for a period of a year.

5.2. Future Works

This thesis is a good initial assessment of the impact of changing the waste collection strategy and can be used as a baseline for future works aiming to further investigate this crucial part of the waste management problem in the state of Qatar. The results can be refined by collecting real historical data on the waste generation pattern. The existing number of bins available in the streets, their exact location and capacity will also help in getting more accurate results. Furthermore, the citizen satisfaction rate was quantified based on the percentage of overfilled bins solely. The quantification of this performance indicator can be enhanced by incorporating a metric that measures the intensity of the bin smell on top of capturing the number of overfilled bins.

The model in this study was developed using one truck with unlimited capacity that services only the capital of Qatar Doha. The challenges of extending this model to incorporate the remaining cities and a fleet of trucks with specified capacities can be part of future work. The state of Qatar can be divided into sectors and the fleet of trucks can be allocated to service each sector. Investigating the different strategies to allocate the trucks and the impact of the different waste collection policies on the entire state can provide insightful conclusions.

Another extension that can be considered is evaluating the truck routing logic. A comparative study between the nearest neighbor routing logic and TSP can be performed. Additionally, a hybrid model that includes both routing logic can be analyzed. This can be done by identifying which routing logic is performing better in each sector and allocating this routing policy accordingly. The waste collection model will include all the sectors along with their respective fleet of trucks and routing logic.

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APPENDICES

APPENDIX A: EVERY DAY PERIODIC REVIEW MODEL VERIFICATION TABLES

Table 12. Distance Matrix (Meter)

Distance matrix						
	bin 1	bin 2	bin 3	bin 4	bin 5	Collection facility
bin 1	0	2957	3419	7535	3788	4166
bin 2	4158	0	1075	5348	6353	6773
bin 3	3281	1021	0	5731	5876	7161
bin 4	7456	5436	5678	0	11170	8676
bin 5	3653	5510	5631	11133	0	3788
Collection facility	4525	5534	7228	8889	4592	0

Table 13. Every Day Model Waste Generation Data of the First Collection (Kg)

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
1	3.85	1	3.73	1	7.05	1	4.41	1	5.02
2	7.60	2	7.99	2	8.83	2	3.99	2	5.91
3	6.01	3	4.97	3	7.90	3	2.85	3	6.49
4	9.79	4	2.86	4	6.75	4	4.88	4	3.56
5	7.47	5	5.22	5	5.28	5	7.62	5	0.90
6	6.06	6	6.01	6	11.33	6	5.29	6	3.92
7	3.15	7	5.37	7	7.52	7	9.01	7	7.64
8	8.43	8	9.20	8	2.92	8	7.68	8	6.69

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
9	6.13	9	2.71	9	3.00	9	5.37	9	4.57
10	6.30	10	6.07	10	5.77	10	5.66	10	3.84
11	5.38	11	-0.16	11	4.49	11	5.84	11	3.47
12	4.06	12	5.78	12	5.29	12	9.11	12	6.09
13	6.31	13	3.22	13	7.38	13	4.80	13	8.61
14	5.41	14	6.58	14	10.55	14	3.94	14	2.59
15	3.91	15	5.58	15	4.36	15	7.44	15	6.57
16	7.91	16	5.58	16	3.51	16	4.55	16	4.55
17	5.85	17	6.99	17	1.92	17	7.33	17	4.78
18	6.39	18	8.63	18	8.01	18	4.99	18	4.00
19	6.50	19	5.42	19	6.64	19	4.62	19	6.28
20	5.87	20	5.13	20	4.91	20	9.76	20	3.64
21	6.49	21	7.65	21	5.48	21	7.93	21	3.60
22	6.34	22	5.93	22	5.42	22	6.25	22	5.14
23	7.05	23	3.31	23	7.46	23	1.77	23	2.43
24	5.78	24	4.92	24	7.62	24	9.26	24	0.72
25	5.40	25	5.23	25	4.29	25	4.33	25	7.13
26	6.64	26	5.35	26	6.94	26	2.54	26	5.02
27	3.70	27	3.47	27	5.51	27	8.95	27	9.35
28	4.21	28	11.10	28	4.29	28	10.81	28	3.97
29	2.98	29	8.41	29	4.87	29	6.66	29	6.05
30	4.78	30	7.51	30	4.97	30	6.25	30	6.74
31	2.85	31	7.43	31	6.47	31	6.49	31	4.46
32	7.82	32	5.93	32	7.63	32	7.07	32	5.97
total	186.44	total	183.10	total	194.36	total	197.45	total	159.70

Table 14. Every Day Model Waste Generation Data of the Second Collection (Kg)

Collection 2									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
1	7.53	1	4.27	1	5.77	1	6.72	1	3.67
2	4.15	2	2.86	2	6.81	2	7.09	2	5.47
3	3.63	3	7.23	3	3.19	3	7.14	3	5.08
4	6.84	4	4.20	4	5.38	4	4.32	4	5.52
5	3.87	5	4.70	5	6.97	5	7.22	5	6.32
6	5.53	6	6.35	6	1.94	6	7.10	6	9.03
7	7.42	7	5.89	7	5.89	7	7.71	7	8.73
8	5.39	8	6.48	8	7.53	8	3.08	8	4.51
9	9.01	9	2.52	9	6.48	9	5.09	9	5.63
10	4.68	10	6.59	10	7.67	10	10.25	10	9.07
11	2.59	11	6.80	11	4.64	11	3.05	11	5.60
12	8.29	12	7.59	12	2.43	12	6.24	12	6.13
13	6.70	13	7.27	13	7.35	13	4.11	13	7.79
14	3.26	14	5.18	14	9.11	14	7.61	14	5.70
15	5.61	15	4.44	15	6.86	15	7.37	15	3.06
16	7.57	16	4.24	16	6.25	16	7.50	16	6.91
17	3.14	17	7.94	17	8.48	17	4.29	17	3.08
18	5.31	18	6.58	18	2.10	18	5.57	18	4.83
19	9.39	19	6.24	19	7.36	19	3.29	19	6.08
20	5.66	20	4.85	20	6.34	20	6.70	20	5.02
21	5.36	21	6.59	21	7.50	21	5.52	21	6.85
22	4.24	22	7.84	22	5.79	22	5.87	22	3.58
23	6.22	23	0.08	23	8.01	23	9.45	23	5.18
24	5.61	24	4.03	24	10.20	24	4.43	24	5.43

Collection 2									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
25	4.98	25	3.43	25	14.29	25	2.68	25	5.74
26	4.85	26	6.66	26	9.16	26	8.67	26	7.95
27	6.55	27	5.90	27	5.56	27	4.75	27	7.95
28	7.12	28	4.07	28	9.86	28	8.04	28	3.26
29	5.35	29	5.61	29	8.64	29	5.12	29	3.38
30	7.73	30	7.63	30	6.66	30	9.12	30	6.04
31	2.37	31	4.55	31	5.94	31	2.50	31	5.10
32	4.50	32	5.51	32	4.49	32	5.64	32	6.81
total	180.47	total	174.10	total	214.63	total	193.23	total	184.51

Table 15. Every Day Model Waste Generation Data of the Third Collection (Kg)

Collection 3									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
1	3.99	1	8.58	1	4.45	1	5.76	1	5.92
2	7.29	2	5.75	2	6.09	2	8.62	2	9.64
3	7.24	3	5.56	3	8.14	3	8.81	3	7.75
4	6.84	4	5.27	4	7.12	4	6.55	4	3.46
5	7.74	5	7.51	5	4.88	5	8.24	5	6.07
6	4.54	6	7.58	6	6.94	6	2.33	6	7.13
7	5.34	7	8.15	7	5.74	7	8.38	7	2.10
8	5.53	8	4.57	8	6.74	8	7.38	8	9.99
9	7.51	9	6.30	9	9.76	9	6.54	9	4.87
10	8.52	10	2.30	10	4.20	10	5.69	10	0.64

Collection 3									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
11	6.63	11	5.44	11	7.82	11	7.43	11	2.14
12	5.98	12	2.89	12	7.00	12	4.59	12	5.96
13	5.49	13	3.29	13	6.27	13	8.01	13	8.04
14	6.76	14	8.44	14	5.84	14	6.30	14	7.85
15	0.97	15	5.57	15	5.75	15	4.84	15	5.76
16	4.35	16	4.64	16	5.45	16	0.21	16	5.81
17	4.56	17	7.74	17	2.24	17	3.24	17	9.18
18	3.09	18	5.55	18	5.57	18	4.56	18	2.95
19	8.14	19	7.80	19	6.20	19	6.26	19	7.06
20	5.02	20	2.76	20	4.25	20	3.01	20	7.79
21	5.85	21	5.56	21	5.56	21	5.85	21	6.13
22	5.18	22	6.06	22	1.98	22	4.09	22	5.13
23	8.53	23	7.93	23	7.67	23	5.16	23	5.87
24	8.43	24	8.03	24	7.68	24	8.47	24	4.57
25	6.48	25	9.79	25	4.64	25	3.99	25	4.74
26	6.07	26	7.59	26	7.09	26	5.42	26	7.97
27	5.70	27	5.69	27	6.81	27	9.49	27	5.82
28	5.77	28	7.51	28	4.82	28	1.17	28	4.98
29	9.04	29	7.38	29	6.46	29	5.20	29	2.33
30	8.85	30	7.64	30	4.13	30	5.97	30	7.46
31	4.82	31	6.64	31	6.53	31	6.37	31	6.50
32	2.61	32	3.64	32	4.49	32	3.34	32	5.08
total	192.83	total	199.16	total	188.31	total	181.29	total	186.69

Table 16. Every Day Model Waste Generation Data of the 4th Collection (Kg)

Collection 4									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
1	5.30	1	7.81	1	7.92	1	6.63	1	9.85
2	7.86	2	5.52	2	6.09	2	5.15	2	8.27
3	4.86	3	5.88	3	6.24	3	6.90	3	5.87
4	4.51	4	2.62	4	6.42	4	8.89	4	5.67
5	6.76	5	5.24	5	6.48	5	6.68	5	1.79
6	5.23	6	5.15	6	7.95	6	2.80	6	4.06
7	1.02	7	8.15	7	5.18	7	8.65	7	3.70
8	6.15	8	8.77	8	6.70	8	4.56	8	7.46
9	4.11	9	7.84	9	3.63	9	6.23	9	7.48
10	3.74	10	5.45	10	7.38	10	5.16	10	7.91
11	8.37	11	8.51	11	9.59	11	5.57	11	3.71
12	7.41	12	4.04	12	4.53	12	5.63	12	5.94
13	5.98	13	5.18	13	2.71	13	5.86	13	4.91
14	1.17	14	10.15	14	6.47	14	5.90	14	5.41
15	6.70	15	3.08	15	5.07	15	3.53	15	10.63
16	5.89	16	5.14	16	7.59	16	5.39	16	6.40
17	5.69	17	6.52	17	7.92	17	8.09	17	6.62
18	8.13	18	9.08	18	3.34	18	3.34	18	2.57
19	5.12	19	8.94	19	5.07	19	6.14	19	8.52
20	4.28	20	5.29	20	7.46	20	7.76	20	8.58
21	8.67	21	7.15	21	8.46	21	4.54	21	5.44
22	9.22	22	5.64	22	5.41	22	4.13	22	5.05
23	8.24	23	3.29	23	6.83	23	6.18	23	7.54

Collection 4									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
24	9.81	24	5.06	24	8.11	24	8.77	24	2.32
25	7.92	25	5.24	25	6.46	25	6.44	25	7.28
26	5.05	26	8.85	26	4.18	26	2.20	26	5.74
27	4.62	27	5.78	27	6.36	27	2.04	27	5.02
28	1.73	28	5.79	28	7.95	28	7.48	28	5.04
29	2.73	29	2.00	29	5.82	29	7.94	29	6.69
30	4.65	30	5.23	30	6.54	30	5.91	30	2.77
31	5.37	31	4.66	31	6.43	31	3.66	31	4.58
32	6.56	32	5.68	32	4.06	32	7.77	32	5.89
total	182.84	total	192.74	total	200.34	total	185.93	total	188.70

Table 17. Every Day Model Waste Generation Data of the 5th Collection (Kg)

Collection 5									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
1	7.25	1	7.21	1	7.58	1	6.76	1	5.52
2	6.77	2	6.73	2	7.09	2	6.05	2	4.91
3	8.32	3	6.79	3	7.15	3	3.87	3	7.79
4	4.72	4	6.84	4	4.93	4	6.74	4	7.05
5	5.31	5	7.72	5	3.70	5	6.70	5	7.27
6	4.32	6	2.55	6	5.92	6	6.00	6	5.41
7	6.10	7	8.67	7	5.79	7	1.74	7	4.44
8	6.70	8	3.89	8	3.43	8	6.08	8	5.81
9	5.80	9	8.67	9	4.39	9	5.33	9	7.80

Collection 5									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
10	5.38	10	4.61	10	1.51	10	8.48	10	8.26
11	7.98	11	2.41	11	6.45	11	7.46	11	5.98
12	5.56	12	9.28	12	2.51	12	7.97	12	3.14
13	1.72	13	7.03	13	6.65	13	10.09	13	7.55
14	9.76	14	5.84	14	7.88	14	7.01	14	3.23
15	5.87	15	3.88	15	6.00	15	6.10	15	3.01
16	8.72	16	9.96	16	5.66	16	7.79	16	5.96
17	7.22	17	8.25	17	10.99	17	6.04	17	4.77
18	8.63	18	5.05	18	5.77	18	7.22	18	2.37
19	12.15	19	5.16	19	7.36	19	5.01	19	2.18
20	1.92	20	3.05	20	4.74	20	7.37	20	7.14
21	6.71	21	3.60	21	6.27	21	6.61	21	4.15
22	2.59	22	7.66	22	10.49	22	7.13	22	12.36
23	7.21	23	6.31	23	5.60	23	7.08	23	5.90
24	1.70	24	3.85	24	7.07	24	4.34	24	6.93
25	2.25	25	5.32	25	8.58	25	4.59	25	6.97
26	9.14	26	7.66	26	6.60	26	4.94	26	6.47
27	0.91	27	6.89	27	6.36	27	5.63	27	9.34
28	5.89	28	3.92	28	5.85	28	2.68	28	3.35
29	9.38	29	6.81	29	3.47	29	6.64	29	6.27
30	7.58	30	9.07	30	5.56	30	4.94	30	4.69
31	8.19	31	5.93	31	9.41	31	7.05	31	7.36
32	6.45	32	7.21	32	3.84	32	9.62	32	7.32
total	198.21	total	197.80	total	194.61	total	201.04	total	190.71

Table 18. Every Day Model Waste Generation Data of the 6th Collection (Kg)

Collection 6									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
1	5.80	1	8.50	1	3.38	1	6.95	1	5.79
2	7.10	2	2.46	2	9.91	2	4.63	2	5.16
3	8.38	3	3.75	3	3.04	3	3.95	3	0.09
4	6.96	4	9.23	4	5.57	4	5.22	4	5.40
5	2.72	5	7.11	5	5.65	5	5.69	5	6.02
6	4.69	6	6.31	6	6.05	6	6.10	6	3.90
7	5.75	7	8.34	7	4.73	7	5.59	7	5.42
8	6.23	8	5.11	8	8.26	8	3.64	8	7.37
9	5.93	9	5.01	9	6.89	9	8.52	9	6.39
10	2.28	10	7.15	10	0.08	10	6.97	10	5.52
11	6.50	11	1.24	11	1.35	11	6.37	11	5.03
12	6.83	12	5.93	12	6.33	12	4.79	12	6.29
13	6.08	13	4.70	13	4.21	13	6.46	13	5.60
14	4.06	14	4.81	14	5.67	14	2.79	14	4.91
15	6.42	15	5.36	15	7.45	15	8.88	15	1.60
16	6.37	16	2.61	16	5.99	16	5.80	16	4.05
17	5.01	17	6.38	17	5.82	17	7.04	17	6.76
18	8.90	18	4.51	18	3.91	18	3.86	18	6.73
19	8.40	19	5.57	19	6.09	19	3.18	19	11.76
20	6.70	20	7.45	20	6.21	20	7.69	20	5.22
21	7.31	21	8.62	21	6.28	21	6.53	21	9.25
22	3.79	22	4.99	22	5.45	22	4.02	22	4.20
23	7.04	23	5.90	23	8.14	23	6.09	23	5.90
24	6.00	24	2.78	24	5.34	24	4.46	24	2.72

Collection 6									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
25	8.14	25	5.05	25	7.14	25	7.39	25	4.10
26	7.65	26	9.00	26	5.19	26	5.15	26	6.40
27	5.35	27	8.02	27	8.02	27	1.92	27	5.81
28	7.65	28	4.05	28	7.58	28	3.92	28	5.79
29	6.35	29	4.93	29	6.98	29	4.63	29	8.92
30	4.59	30	7.35	30	5.33	30	5.78	30	5.34
31	3.96	31	8.71	31	10.55	31	5.14	31	5.49
32	7.16	32	7.28	32	4.63	32	3.92	32	6.98
total	196.12	total	188.21	total	187.21	total	173.08	total	179.91

Table 19. Every Day Model Waste Generation Data of the 7th Collection (Kg)

Collection 7									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
1	3.92	1	2.35	1	7.30	1	2.61	1	7.28
2	7.08	2	4.82	2	5.17	2	10.14	2	9.13
3	11.72	3	3.03	3	7.04	3	5.24	3	7.97
4	7.59	4	6.83	4	7.23	4	6.97	4	6.72
5	6.47	5	5.43	5	6.01	5	7.71	5	4.67
6	8.16	6	4.25	6	9.41	6	6.21	6	5.43
7	8.71	7	6.73	7	9.50	7	5.01	7	4.64
8	4.40	8	3.85	8	7.20	8	6.63	8	11.10
9	5.43	9	3.79	9	5.29	9	7.40	9	4.42
10	5.31	10	7.67	10	7.33	10	6.68	10	5.82

Collection 7									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
11	6.89	11	5.07	11	2.79	11	6.34	11	7.23
12	9.01	12	5.76	12	4.65	12	4.04	12	4.68
13	8.36	13	5.28	13	6.12	13	2.99	13	5.65
14	6.29	14	5.00	14	7.42	14	5.84	14	7.37
15	6.01	15	8.14	15	4.26	15	4.60	15	8.19
16	6.21	16	5.26	16	5.45	16	2.88	16	4.35
17	5.60	17	4.75	17	5.60	17	3.24	17	4.67
18	4.60	18	2.84	18	3.04	18	7.61	18	3.19
19	8.37	19	3.78	19	5.38	19	5.44	19	2.91
20	5.63	20	5.90	20	8.63	20	5.49	20	9.63
21	7.04	21	3.93	21	4.73	21	4.76	21	2.23
22	3.60	22	6.05	22	6.07	22	4.02	22	4.83
23	10.53	23	4.27	23	1.06	23	6.33	23	6.84
24	4.07	24	7.36	24	8.27	24	6.33	24	5.61
25	9.28	25	7.37	25	3.22	25	6.02	25	6.34
26	7.98	26	6.24	26	3.80	26	5.25	26	9.51
27	6.55	27	6.93	27	7.65	27	8.75	27	5.46
28	5.58	28	7.28	28	4.14	28	8.56	28	5.59
29	9.29	29	5.32	29	9.53	29	7.53	29	7.20
30	6.50	30	4.26	30	9.95	30	6.12	30	5.53
31	4.02	31	6.40	31	5.89	31	6.63	31	5.78
32	4.72	32	6.37	32	2.63	32	12.88	32	4.44
total	214.90	total	172.32	total	191.76	total	196.25	total	194.40

Table 20. Every Day Model CO2 Emission Calculation (Kg)

CO2 emission	Collection 1	Collection 2	Collection 3	Collection 4	Collection 5	Collection 6	Collection 7
F to 1	18.672	18.672	18.672	18.672	18.672	18.672	18.672
1 to 2	12.332	12.327	12.336	12.329	12.340	12.338	12.351
2 to 3	4.529	4.525	4.535	4.531	4.536	4.533	4.534
3 to 4	24.411	24.418	24.433	24.427	24.447	24.421	24.431
4 to 5	48.098	48.101	48.098	48.099	48.178	48.054	48.134
5 to F	16.453	16.476	16.478	16.480	16.508	16.456	16.497

APPENDIX B: TWICE PER WEEK PERIODIC REVIEW MODEL VERIFICATION TABLES

Table 21. Twice per Week Waste Generation Data of First Collection (Kg)

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
1	2.21	1	2.30	1	9.13	1	8.97	1	3.10
2	8.92	2	7.01	2	6.67	2	6.36	2	6.48
3	3.69	3	6.28	3	4.88	3	4.27	3	3.18
4	6.59	4	7.32	4	6.64	4	5.34	4	6.61
5	8.02	5	7.22	5	8.23	5	11.18	5	4.72
6	6.51	6	4.86	6	6.18	6	9.47	6	9.43
7	5.11	7	6.40	7	9.13	7	6.61	7	6.42
8	6.63	8	8.94	8	3.22	8	5.26	8	7.93
9	2.82	9	6.66	9	8.66	9	4.75	9	8.12
10	6.46	10	6.26	10	0.51	10	5.49	10	6.45
11	5.61	11	5.93	11	4.98	11	7.84	11	6.25
12	7.59	12	4.12	12	3.46	12	3.85	12	5.28
13	5.73	13	8.32	13	8.82	13	2.36	13	10.49
14	7.72	14	3.39	14	3.25	14	9.24	14	7.03
15	6.41	15	5.15	15	7.07	15	5.11	15	5.74
16	8.39	16	5.82	16	5.32	16	6.45	16	6.13
17	6.52	17	6.69	17	6.78	17	6.91	17	6.32
18	8.33	18	6.44	18	5.35	18	4.20	18	5.04
19	7.67	19	5.22	19	6.57	19	7.44	19	3.92
20	6.25	20	1.67	20	9.35	20	8.77	20	7.17
21	5.23	21	5.73	21	6.22	21	10.28	21	6.35

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
22	4.93	22	8.26	22	5.32	22	6.23	22	7.48
23	9.34	23	5.84	23	4.25	23	2.89	23	6.15
24	9.50	24	2.15	24	6.51	24	4.52	24	3.47
25	5.50	25	8.64	25	6.20	25	3.17	25	5.81
26	5.71	26	8.73	26	10.23	26	6.02	26	3.18
27	9.14	27	2.24	27	6.77	27	7.11	27	6.01
28	8.62	28	4.90	28	7.08	28	7.00	28	4.96
29	5.28	29	2.94	29	5.16	29	6.08	29	5.48
30	6.36	30	5.27	30	5.49	30	6.20	30	2.84
31	7.52	31	7.81	31	6.78	31	8.59	31	7.37
32	6.93	32	4.49	32	4.72	32	5.05	32	7.87
33	6.52	33	5.87	33	6.84	33	4.60	33	5.33
34	3.80	34	4.60	34	7.41	34	2.49	34	6.87
35	5.86	35	8.23	35	6.21	35	4.11	35	6.86
36	4.30	36	4.64	36	7.82	36	7.34	36	7.53
37	4.97	37	5.12	37	7.42	37	9.86	37	4.82
38	2.14	38	8.34	38	3.28	38	3.80	38	8.27
39	7.70	39	6.71	39	7.81	39	1.78	39	7.90
40	8.76	40	8.16	40	7.45	40	5.30	40	5.73
41	7.84	41	6.81	41	5.61	41	2.96	41	5.79
42	5.96	42	4.36	42	3.84	42	4.16	42	6.41
43	7.50	43	7.48	43	8.07	43	9.49	43	5.25
44	3.83	44	1.18	44	9.07	44	3.93	44	6.26
45	3.70	45	5.20	45	5.65	45	7.04	45	10.96
46	5.98	46	7.72	46	4.82	46	7.62	46	7.31

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
47	5.88	47	9.23	47	6.81	47	4.46	47	7.35
48	8.14	48	5.30	48	1.15	48	6.14	48	0.11
49	8.93	49	8.62	49	5.99	49	6.45	49	9.23
50	2.64	50	3.54	50	6.27	50	6.36	50	2.78
51	3.92	51	6.45	51	3.27	51	5.27	51	6.69
52	2.94	52	5.32	52	4.74	52	7.62	52	5.80
53	4.69	53	8.47	53	4.41	53	5.53	53	4.73
54	4.31	54	5.47	54	3.34	54	6.92	54	5.42
55	5.25	55	4.08	55	8.87	55	6.58	55	5.61
56	7.62	56	4.10	56	8.06	56	5.01	56	4.38
57	6.62	57	6.31	57	4.18	57	5.98	57	7.49
58	5.70	58	5.42	58	6.87	58	6.31	58	6.05
59	2.41	59	6.73	59	8.02	59	2.84	59	4.35
60	5.58	60	5.53	60	5.91	60	7.20	60	3.12
61	7.93	61	4.07	61	4.55	61	4.31	61	4.50
62	5.81	62	7.99	62	5.53	62	2.32	62	5.63
63	7.83	63	4.39	63	7.30	63	7.97	63	9.20
64	8.24	64	3.47	64	6.44	64	3.29	64	5.17
65	7.56	65	3.96	65	4.32	65	4.64	65	6.90
66	7.89	66	3.10	66	6.48	66	5.62	66	5.46
67	6.60	67	6.57	67	3.77	67	8.05	67	6.95
68	7.70	68	1.27	68	6.82	68	4.82	68	3.31
69	2.59	69	5.88	69	7.68	69	8.08	69	7.86
70	3.49	70	6.39	70	5.26	70	5.72	70	3.67
71	4.42	71	6.84	71	3.73	71	5.45	71	5.20

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
72	6.63	72	1.64	72	5.40	72	8.85	72	9.08
73	6.54	73	7.06	73	7.03	73	3.91	73	5.33
74	8.03	74	5.73	74	5.97	74	6.00	74	6.86
75	7.69	75	5.48	75	6.50	75	3.87	75	8.67
76	4.92	76	4.67	76	6.54	76	5.19	76	6.32
77	7.80	77	4.66	77	7.70	77	6.91	77	7.16
78	6.23	78	6.84	78	6.06	78	7.17	78	6.91
79	4.37	79	3.28	79	6.48	79	6.82	79	6.56
80	5.27	80	6.72	80	7.09	80	3.35	80	9.02
81	5.76	81	4.91	81	6.05	81	3.06	81	7.96
82	6.98	82	4.16	82	5.72	82	5.59	82	8.75
83	4.24	83	5.85	83	7.70	83	7.14	83	3.91
84	5.81	84	5.84	84	4.93	84	3.48	84	2.45
85	4.93	85	4.81	85	4.52	85	6.40	85	5.48
86	2.75	86	10.04	86	5.99	86	6.82	86	8.85
87	4.80	87	6.75	87	4.77	87	8.84	87	4.52
88	6.86	88	3.68	88	4.32	88	8.30	88	5.35
89	9.36	89	7.67	89	9.07	89	6.66	89	4.56
90	4.30	90	3.80	90	5.77	90	6.94	90	6.93
91	4.24	91	5.18	91	4.97	91	8.41	91	4.83
92	0.06	92	8.79	92	4.45	92	8.95	92	8.17
93	1.19	93	6.62	93	3.28	93	7.06	93	2.84
94	4.53	94	5.84	94	4.46	94	2.55	94	5.64
95	6.94	95	4.37	95	7.33	95	6.95	95	5.50
96	5.32	96	3.33	96	7.15	96	6.90	96	5.48

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
97	6.32	97	5.17	97	6.93	97	2.04	97	4.75
98	4.22	98	6.21	98	5.66	98	9.47	98	6.55
99	7.63	99	3.75	99	8.35	99	5.29	99	4.62
100	4.68	100	8.97	100	5.63	100	6.84	100	4.67
101	6.25	101	4.48	101	7.08	101	-0.45	101	4.18
102	8.51	102	7.29	102	5.49	102	6.53	102	5.83
103	6.08	103	6.73	103	4.87	103	11.18	103	5.90
104	6.82	104	5.13	104	7.77	104	4.40	104	6.27
105	6.20	105	6.54	105	7.35	105	9.51	105	6.74
106	6.17	106	4.58	106	5.38	106	5.53	106	4.31
107	3.13	107	4.60	107	8.10	107	8.57	107	3.70
108	1.29	108	6.39	108	4.39	108	4.29	108	8.18
109	7.06	109	9.26	109	9.91	109	4.32	109	3.61
110	5.42	110	8.71	110	5.95	110	8.57	110	4.38
111	6.64	111	8.64	111	10.66	111	2.12	111	4.38
112	5.17	112	7.84	112	4.26	112	5.05	112	3.83
Total	661.97	Total	647.95	Total	687.05	Total	669.82	Total	664.07

Table 22. Twice per Week Waste Generation Data of Second Collection (Kg)

Collection 2									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
1	7.68	1	4.16	1	4.66	1	7.39	1	4.34
2	4.65	2	4.67	2	6.17	2	9.64	2	5.39

Collection 2									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
3	5.51	3	7.63	3	6.39	3	2.99	3	3.64
4	9.33	4	4.18	4	6.27	4	2.30	4	5.76
5	8.29	5	5.95	5	5.83	5	7.44	5	5.50
6	8.39	6	2.59	6	4.98	6	5.13	6	3.19
7	4.44	7	9.08	7	2.86	7	3.48	7	7.63
8	6.34	8	8.45	8	7.35	8	6.76	8	4.59
9	8.28	9	6.90	9	4.84	9	3.08	9	4.31
10	6.01	10	6.15	10	2.56	10	7.70	10	5.17
11	7.14	11	5.49	11	6.92	11	3.15	11	4.95
12	4.13	12	7.53	12	5.22	12	3.88	12	6.95
13	9.99	13	8.80	13	7.24	13	6.47	13	2.94
14	5.55	14	9.53	14	5.23	14	5.33	14	8.51
15	5.60	15	5.34	15	4.68	15	1.79	15	5.85
16	5.74	16	7.91	16	7.05	16	6.36	16	6.14
17	5.42	17	5.07	17	4.24	17	6.36	17	2.90
18	5.43	18	7.58	18	2.94	18	8.75	18	4.81
19	5.01	19	8.13	19	7.16	19	5.27	19	6.08
20	4.66	20	4.69	20	7.54	20	5.77	20	8.50
21	0.37	21	6.33	21	5.42	21	5.82	21	5.84
22	6.81	22	8.02	22	6.29	22	7.94	22	5.30
23	7.74	23	7.68	23	6.09	23	7.23	23	5.71
24	4.34	24	2.12	24	6.16	24	6.53	24	5.39
25	4.13	25	5.19	25	8.10	25	5.13	25	3.91
26	6.19	26	3.99	26	7.09	26	4.57	26	4.63
27	7.41	27	3.59	27	6.20	27	7.16	27	6.75

Collection 2									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
28	6.00	28	3.16	28	5.15	28	1.96	28	4.84
29	7.21	29	5.02	29	9.09	29	3.94	29	7.28
30	6.78	30	2.88	30	7.63	30	7.34	30	6.90
31	8.86	31	6.93	31	4.30	31	6.06	31	5.67
32	5.09	32	7.55	32	5.44	32	10.44	32	9.32
33	7.52	33	4.72	33	6.83	33	4.16	33	4.30
34	6.50	34	4.74	34	7.07	34	5.17	34	6.27
35	10.62	35	6.87	35	4.98	35	8.61	35	2.63
36	5.34	36	5.62	36	5.94	36	4.63	36	3.53
37	2.60	37	6.10	37	2.46	37	3.29	37	5.46
38	8.10	38	4.81	38	5.81	38	5.87	38	6.82
39	6.24	39	6.28	39	8.47	39	6.78	39	5.06
40	6.17	40	7.33	40	5.99	40	5.46	40	3.81
41	7.76	41	6.07	41	5.50	41	7.19	41	7.70
42	6.25	42	3.72	42	8.80	42	7.62	42	2.17
43	6.84	43	3.06	43	4.50	43	6.47	43	10.00
44	10.37	44	6.89	44	7.52	44	5.32	44	4.13
45	2.88	45	4.47	45	10.11	45	8.99	45	7.11
46	2.82	46	1.03	46	6.32	46	5.07	46	6.12
47	8.03	47	2.84	47	6.79	47	3.74	47	5.72
48	3.69	48	7.34	48	2.24	48	4.02	48	7.47
49	6.19	49	7.43	49	4.46	49	7.33	49	6.76
50	4.07	50	7.27	50	2.48	50	5.84	50	7.99
51	8.84	51	7.60	51	7.71	51	5.84	51	6.19
52	1.68	52	9.71	52	5.95	52	8.50	52	5.66

Collection 2									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
53	6.61	53	8.25	53	7.50	53	6.84	53	5.11
54	7.98	54	4.20	54	5.04	54	5.51	54	6.87
55	4.92	55	4.52	55	8.32	55	5.58	55	9.75
56	5.33	56	8.03	56	7.42	56	7.73	56	7.15
57	5.26	57	5.85	57	7.15	57	7.06	57	2.15
58	7.85	58	7.52	58	5.25	58	6.95	58	8.45
59	7.70	59	4.99	59	8.25	59	6.89	59	7.05
60	3.91	60	6.20	60	7.62	60	3.27	60	5.38
61	5.12	61	5.00	61	5.00	61	7.28	61	4.90
62	5.15	62	6.28	62	9.39	62	5.79	62	4.49
63	7.41	63	3.83	63	5.52	63	5.15	63	3.98
64	4.14	64	6.80	64	4.62	64	8.37	64	8.55
65	6.52	65	5.41	65	6.45	65	10.23	65	6.96
66	7.81	66	7.05	66	4.98	66	5.29	66	8.74
67	7.59	67	3.52	67	3.84	67	5.14	67	5.70
68	6.65	68	7.43	68	7.69	68	7.00	68	6.14
69	7.63	69	5.33	69	7.96	69	2.46	69	7.51
70	3.45	70	6.77	70	2.83	70	6.92	70	6.32
71	4.60	71	7.30	71	8.74	71	6.41	71	6.78
72	6.59	72	5.44	72	6.77	72	8.18	72	4.44
73	7.57	73	4.66	73	8.10	73	8.25	73	7.99
74	6.47	74	7.46	74	4.88	74	8.58	74	5.29
75	10.71	75	6.76	75	9.07	75	4.13	75	3.79
76	5.21	76	5.70	76	2.04	76	5.89	76	8.05
77	4.61	77	4.62	77	4.75	77	5.63	77	5.52

Collection 2									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
78	5.83	78	8.39	78	6.53	78	4.74	78	8.88
79	7.75	79	7.41	79	5.65	79	8.30	79	6.30
80	11.31	80	5.58	80	5.32	80	7.78	80	4.26
81	11.33	81	9.04	81	5.85	81	7.67	81	8.74
82	6.91	82	4.94	82	5.57	82	4.80	82	5.59
83	5.12	83	2.37	83	5.78	83	5.49	83	6.71
84	6.85	84	6.04	84	5.72	84	7.24	84	9.99
85	6.26	85	7.80	85	9.44	85	5.52	85	7.25
86	3.35	86	2.18	86	5.22	86	8.86	86	8.18
87	6.21	87	8.37	87	4.18	87	3.64	87	7.71
88	7.63	88	5.22	88	6.64	88	4.76	88	8.50
89	3.36	89	5.45	89	10.15	89	7.44	89	6.02
90	3.25	90	6.26	90	7.18	90	6.63	90	4.69
91	6.29	91	5.28	91	7.55	91	5.48	91	7.45
92	5.97	92	6.16	92	6.79	92	8.09	92	7.10
93	6.64	93	2.98	93	8.77	93	4.84	93	7.65
94	4.33	94	6.20	94	7.91	94	5.93	94	7.27
95	7.39	95	2.58	95	6.91	95	6.18	95	3.35
96	5.61	96	6.53	96	3.78	96	5.20	96	4.41
97	3.76	97	4.02	97	5.86	97	3.54	97	8.70
98	4.77	98	3.79	98	8.17	98	6.80	98	4.77
99	9.81	99	3.02	99	6.79	99	5.08	99	3.71
100	6.80	100	5.41	100	5.90	100	10.01	100	3.04
101	3.79	101	4.16	101	1.68	101	9.94	101	7.93
102	8.86	102	8.33	102	8.41	102	4.28	102	3.71

Collection 2									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
103	3.32	103	6.80	103	7.28	103	4.27	103	6.16
104	5.18	104	3.90	104	1.70	104	4.65	104	9.85
105	5.94	105	5.43	105	4.68	105	6.85	105	7.54
106	6.52	106	7.48	106	10.15	106	2.88	106	7.14
107	6.09	107	7.21	107	4.85	107	5.27	107	7.28
108	7.35	108	8.15	108	5.29	108	9.51	108	5.96
109	5.41	109	6.71	109	6.86	109	4.38	109	6.81
110	4.53	110	2.20	110	5.52	110	6.01	110	7.21
111	6.86	111	4.34	111	5.50	111	8.91	111	5.36
112	2.50	112	7.12	112	7.51	112	6.61	112	6.63
Total	690.69	Total	651.96	Total	687.28	Total	681.19	Total	682.51

Table 23. Twice per Week Model CO2 Emission Calculation (Kg)

CO2 emission	Collection 1	Collection 2
F to 1	18.672	18.672
1 to 2	12.663	12.683
2 to 3	4.768	4.776
3 to 4	26.347	26.392
4 to 5	53.117	53.233
5 to F	18.606	18.662

APPENDIX C: ONCE PER WEEK PERIODIC REVIEW MODEL VERIFICATION TABLES

Table 24. Once per Week Model Waste Generation Data (Kg)

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
1	8.47	1	5.96	1	5.92	1	8.24	1	6.12
2	3.60	2	5.00	2	4.37	2	4.22	2	3.63
3	3.58	3	4.49	3	7.20	3	8.15	3	7.97
4	6.98	4	5.71	4	9.43	4	6.45	4	4.67
5	2.28	5	9.86	5	7.01	5	7.09	5	4.10
6	5.66	6	5.54	6	9.43	6	7.95	6	5.24
7	6.93	7	2.85	7	5.44	7	4.93	7	9.51
8	5.07	8	5.28	8	10.02	8	8.81	8	5.24
9	7.03	9	4.73	9	6.95	9	8.11	9	6.24
10	6.09	10	7.14	10	8.80	10	5.93	10	9.74
11	6.16	11	6.47	11	5.91	11	2.97	11	11.09
12	8.13	12	4.88	12	9.46	12	4.73	12	7.19
13	5.46	13	3.36	13	6.57	13	4.44	13	3.13
14	5.54	14	5.85	14	5.89	14	4.55	14	4.75
15	7.54	15	5.75	15	6.75	15	8.02	15	5.81
16	6.17	16	6.80	16	5.48	16	3.56	16	8.15
17	5.65	17	7.52	17	3.91	17	8.33	17	1.80
18	6.12	18	4.94	18	3.29	18	7.04	18	3.41
19	5.49	19	4.18	19	5.28	19	7.46	19	5.39
20	5.54	20	3.46	20	7.74	20	2.60	20	7.58
21	1.43	21	7.78	21	8.47	21	4.67	21	10.25

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
22	7.04	22	8.18	22	8.62	22	4.39	22	9.41
23	8.75	23	6.97	23	6.87	23	4.63	23	6.33
24	5.56	24	5.29	24	7.11	24	5.51	24	6.42
25	8.40	25	4.57	25	8.11	25	7.43	25	6.40
26	4.00	26	6.68	26	6.21	26	6.78	26	5.96
27	8.33	27	4.56	27	4.22	27	5.00	27	4.07
28	6.66	28	7.63	28	4.72	28	4.64	28	2.06
29	3.27	29	9.10	29	7.69	29	5.44	29	4.40
30	3.92	30	6.61	30	5.04	30	8.42	30	6.45
31	5.85	31	6.96	31	7.79	31	6.16	31	5.54
32	4.26	32	4.11	32	8.90	32	4.17	32	7.34
33	7.64	33	7.18	33	3.04	33	5.70	33	4.00
34	4.54	34	4.52	34	5.49	34	6.43	34	1.20
35	6.72	35	5.05	35	3.78	35	3.09	35	3.89
36	4.82	36	5.31	36	4.72	36	8.54	36	5.29
37	4.62	37	8.25	37	5.51	37	5.40	37	6.99
38	3.75	38	5.61	38	5.29	38	5.75	38	4.00
39	6.97	39	8.57	39	7.72	39	7.22	39	7.30
40	4.39	40	5.76	40	7.12	40	7.52	40	1.97
41	9.80	41	7.60	41	5.56	41	6.14	41	7.13
42	5.11	42	7.01	42	6.77	42	9.49	42	5.93
43	6.50	43	5.27	43	6.12	43	5.48	43	6.26
44	7.38	44	6.00	44	6.58	44	8.45	44	4.81
45	10.47	45	6.27	45	8.61	45	3.82	45	8.44
46	3.11	46	4.17	46	0.76	46	7.83	46	4.39

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
47	5.41	47	8.12	47	10.51	47	7.53	47	5.72
48	4.23	48	7.31	48	8.61	48	6.90	48	4.50
49	8.71	49	6.11	49	5.55	49	6.19	49	4.33
50	2.47	50	2.69	50	4.52	50	4.39	50	7.06
51	7.64	51	6.30	51	4.08	51	5.29	51	1.38
52	7.23	52	8.31	52	5.61	52	3.58	52	6.63
53	4.61	53	3.55	53	8.07	53	5.59	53	8.64
54	4.72	54	5.93	54	2.03	54	1.88	54	7.72
55	7.21	55	10.63	55	2.65	55	4.50	55	6.72
56	4.77	56	7.61	56	2.43	56	4.94	56	2.39
57	7.59	57	8.26	57	4.27	57	7.41	57	4.43
58	6.27	58	7.34	58	11.36	58	4.02	58	9.51
59	6.51	59	3.91	59	6.45	59	8.02	59	8.39
60	5.90	60	4.97	60	3.77	60	3.07	60	5.09
61	9.19	61	5.51	61	6.06	61	4.97	61	6.58
62	4.66	62	8.40	62	5.87	62	9.43	62	7.08
63	5.91	63	3.65	63	3.58	63	6.77	63	7.36
64	4.64	64	8.70	64	5.98	64	6.35	64	5.54
65	2.63	65	5.68	65	2.65	65	5.58	65	5.86
66	6.69	66	4.40	66	7.58	66	4.67	66	1.55
67	7.89	67	7.34	67	-0.27	67	6.56	67	2.52
68	3.77	68	7.84	68	4.91	68	5.81	68	6.19
69	4.76	69	3.63	69	4.71	69	3.64	69	4.68
70	5.04	70	-0.29	70	7.96	70	8.30	70	5.46
71	6.13	71	6.42	71	5.53	71	5.62	71	7.00

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
72	8.85	72	8.99	72	4.77	72	4.32	72	9.42
73	6.70	73	6.48	73	4.08	73	7.09	73	5.26
74	6.18	74	3.27	74	6.35	74	4.34	74	7.07
75	5.44	75	8.25	75	5.14	75	10.68	75	8.68
76	8.28	76	6.23	76	4.59	76	7.43	76	5.55
77	3.19	77	3.55	77	0.36	77	4.08	77	4.53
78	5.02	78	4.87	78	6.38	78	2.05	78	4.45
79	5.69	79	7.46	79	3.30	79	8.36	79	5.94
80	3.98	80	7.59	80	3.67	80	6.11	80	4.62
81	6.27	81	8.93	81	7.30	81	8.96	81	7.58
82	6.10	82	6.22	82	7.20	82	3.35	82	5.01
83	7.95	83	3.38	83	10.10	83	5.07	83	6.08
84	5.82	84	6.62	84	4.24	84	9.43	84	4.14
85	9.21	85	3.07	85	6.81	85	7.46	85	10.57
86	4.27	86	5.74	86	5.43	86	8.42	86	7.60
87	5.61	87	6.32	87	4.51	87	7.06	87	2.83
88	2.63	88	4.94	88	5.45	88	1.51	88	6.51
89	11.08	89	8.95	89	7.38	89	6.30	89	5.58
90	6.98	90	4.35	90	5.50	90	5.64	90	4.39
91	5.45	91	4.82	91	5.83	91	5.90	91	4.77
92	3.37	92	5.13	92	4.93	92	3.14	92	5.17
93	5.44	93	4.08	93	4.63	93	7.79	93	4.88
94	5.48	94	9.20	94	9.57	94	1.39	94	4.54
95	5.85	95	4.10	95	5.20	95	10.51	95	5.32
96	7.89	96	7.36	96	5.51	96	3.94	96	6.39

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
97	8.67	97	8.19	97	5.86	97	3.38	97	8.55
98	4.12	98	4.79	98	5.36	98	5.89	98	10.26
99	5.17	99	4.24	99	5.53	99	6.79	99	7.51
100	6.77	100	2.92	100	6.05	100	6.76	100	5.44
101	2.97	101	2.86	101	8.76	101	2.65	101	3.73
102	8.83	102	3.93	102	5.62	102	5.78	102	4.74
103	6.40	103	8.10	103	5.44	103	4.87	103	8.70
104	8.33	104	3.43	104	5.01	104	4.83	104	6.01
105	2.36	105	5.86	105	5.58	105	3.83	105	4.55
106	7.84	106	5.50	106	2.85	106	5.18	106	5.81
107	2.09	107	7.14	107	5.88	107	7.74	107	4.51
108	3.85	108	7.04	108	4.74	108	7.42	108	6.50
109	5.62	109	3.27	109	7.26	109	5.72	109	2.78
110	9.10	110	7.62	110	8.47	110	2.64	110	5.04
111	5.36	111	2.08	111	4.65	111	8.21	111	2.97
112	7.52	112	0.69	112	5.36	112	8.22	112	7.55
113	6.28	113	5.50	113	6.09	113	11.88	113	5.04
114	9.01	114	3.43	114	3.55	114	4.78	114	6.83
115	4.46	115	4.48	115	6.98	115	8.75	115	9.00
116	5.82	116	8.43	116	6.22	116	5.84	116	4.23
117	8.14	117	7.17	117	7.10	117	5.13	117	2.18
118	5.36	118	6.48	118	4.02	118	5.26	118	7.84
119	6.97	119	6.06	119	6.79	119	9.35	119	5.06
120	6.62	120	6.61	120	7.99	120	3.34	120	8.24
121	8.58	121	4.84	121	3.75	121	4.24	121	4.04

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
122	9.08	122	5.29	122	3.40	122	6.33	122	8.55
123	5.15	123	5.72	123	5.46	123	3.38	123	6.81
124	7.68	124	7.93	124	5.38	124	7.36	124	3.86
125	4.37	125	9.86	125	6.49	125	7.79	125	6.11
126	7.50	126	5.91	126	7.04	126	6.70	126	3.41
127	3.59	127	2.59	127	6.70	127	5.85	127	8.37
128	8.24	128	5.27	128	2.45	128	6.65	128	3.37
129	8.60	129	8.15	129	3.18	129	10.12	129	6.24
130	8.86	130	5.68	130	4.70	130	4.60	130	5.33
131	6.53	131	2.18	131	1.24	131	8.60	131	4.36
132	6.55	132	7.41	132	4.85	132	6.11	132	6.33
133	7.15	133	6.09	133	7.20	133	8.99	133	6.16
134	6.59	134	5.57	134	9.57	134	7.89	134	7.91
135	8.23	135	7.76	135	5.26	135	7.20	135	8.12
136	5.85	136	4.97	136	4.80	136	7.75	136	4.18
137	4.69	137	4.62	137	7.23	137	3.88	137	8.97
138	6.63	138	6.33	138	4.23	138	4.80	138	9.25
139	8.10	139	2.70	139	7.09	139	4.27	139	7.93
140	5.25	140	5.18	140	6.14	140	5.87	140	4.33
141	4.60	141	6.72	141	6.26	141	6.83	141	7.48
142	4.73	142	6.27	142	9.94	142	5.88	142	9.34
143	7.52	143	3.69	143	7.71	143	8.73	143	5.05
144	5.53	144	10.22	144	7.58	144	4.49	144	6.29
145	5.39	145	3.45	145	5.34	145	5.16	145	5.11
146	3.56	146	5.47	146	3.32	146	6.54	146	8.83

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
147	3.18	147	3.07	147	8.40	147	6.38	147	6.60
148	7.92	148	6.59	148	7.90	148	7.12	148	4.68
149	8.83	149	5.80	149	6.59	149	9.98	149	6.52
150	3.99	150	8.33	150	7.27	150	4.63	150	6.81
151	6.36	151	5.01	151	5.28	151	5.13	151	3.74
152	4.20	152	5.07	152	7.52	152	9.64	152	2.84
153	4.95	153	6.07	153	6.64	153	7.80	153	3.30
154	7.35	154	5.72	154	6.83	154	6.17	154	9.07
155	7.21	155	1.03	155	3.82	155	7.27	155	4.16
156	7.43	156	7.54	156	6.41	156	6.45	156	8.08
157	5.23	157	8.63	157	8.09	157	2.31	157	8.66
158	6.63	158	8.47	158	2.56	158	5.67	158	8.04
159	6.87	159	5.60	159	8.73	159	2.66	159	4.30
160	4.13	160	4.07	160	5.60	160	6.89	160	8.03
161	3.99	161	6.34	161	2.12	161	4.86	161	5.31
162	6.03	162	6.54	162	4.97	162	5.78	162	8.74
163	8.42	163	3.81	163	8.59	163	6.92	163	5.64
164	3.77	164	4.50	164	6.26	164	7.55	164	8.58
165	3.39	165	7.95	165	5.07	165	6.42	165	6.61
166	10.50	166	8.31	166	6.10	166	6.69	166	3.70
167	8.13	167	4.75	167	1.81	167	6.03	167	5.04
168	10.85	168	3.41	168	3.66	168	4.19	168	7.35
169	6.89	169	10.31	169	2.91	169	7.77	169	7.00
170	4.07	170	2.60	170	3.29	170	2.55	170	4.95
171	8.61	171	4.50	171	4.04	171	7.24	171	5.65

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
172	8.99	172	5.80	172	4.52	172	5.18	172	3.53
173	6.47	173	7.20	173	6.76	173	5.25	173	8.29
174	5.56	174	8.86	174	8.35	174	6.99	174	5.07
175	5.78	175	6.97	175	5.10	175	6.80	175	3.04
176	3.65	176	6.70	176	3.44	176	6.73	176	3.16
177	8.19	177	2.26	177	6.79	177	4.83	177	7.34
178	5.50	178	6.49	178	6.24	178	5.90	178	5.41
179	7.46	179	2.93	179	4.42	179	7.82	179	3.65
180	4.18	180	5.80	180	7.00	180	3.25	180	6.08
181	3.49	181	5.19	181	2.67	181	6.96	181	7.00
182	2.74	182	5.60	182	5.12	182	5.70	182	3.45
183	9.99	183	3.20	183	1.68	183	7.15	183	4.52
184	3.91	184	7.44	184	4.26	184	6.56	184	7.69
185	3.28	185	9.11	185	5.51	185	8.18	185	6.36
186	12.16	186	4.57	186	4.25	186	8.96	186	4.82
187	2.77	187	6.44	187	5.07	187	6.68	187	3.77
188	3.66	188	7.28	188	4.37	188	7.85	188	7.56
189	6.70	189	4.97	189	2.74	189	6.40	189	6.10
190	6.26	190	5.93	190	5.86	190	7.68	190	7.17
191	9.92	191	9.73	191	5.75	191	5.75	191	5.38
192	3.68	192	5.46	192	6.63	192	7.01	192	3.86
193	3.86	193	5.01	193	4.19	193	3.62	193	5.90
194	6.23	194	3.48	194	5.02	194	8.45	194	6.41
195	7.17	195	5.76	195	7.41	195	6.93	195	6.40
196	6.80	196	7.26	196	8.10	196	5.95	196	7.56

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
197	6.67	197	4.90	197	5.43	197	5.04	197	2.95
198	6.20	198	6.57	198	6.98	198	5.84	198	7.55
199	6.77	199	3.92	199	4.92	199	5.50	199	6.27
200	6.70	200	5.63	200	8.93	200	6.79	200	9.20
201	5.22	201	10.31	201	6.33	201	5.96	201	7.18
202	6.58	202	6.07	202	7.07	202	7.97	202	3.20
203	6.47	203	6.21	203	2.86	203	3.88	203	6.00
204	9.31	204	7.98	204	8.74	204	7.86	204	4.12
205	7.72	205	9.11	205	8.88	205	2.14	205	5.21
206	9.81	206	5.14	206	8.00	206	8.39	206	3.29
207	5.21	207	6.88	207	8.27	207	9.03	207	9.51
208	2.13	208	4.90	208	4.50	208	7.75	208	4.26
209	3.93	209	4.17	209	7.13	209	6.04	209	7.12
210	5.23	210	3.80	210	6.21	210	6.20	210	6.89
211	8.26	211	3.97	211	6.10	211	6.20	211	3.93
212	6.36	212	6.29	212	9.64	212	2.73	212	6.34
213	7.12	213	2.55	213	10.32	213	6.54	213	7.71
214	4.86	214	3.49	214	4.59	214	6.03	214	4.74
215	8.47	215	5.04	215	3.25	215	4.51	215	7.92
216	3.81	216	6.27	216	6.52	216	5.80	216	5.72
217	4.69	217	3.32	217	3.16	217	5.36	217	5.95
218	8.08	218	5.48	218	9.59	218	5.26	218	6.71
219	7.58	219	4.24	219	3.94	219	6.22	219	8.22
220	3.98	220	6.54	220	8.75	220	6.04	220	6.98
221	7.57	221	6.29	221	8.80	221	8.80	221	3.63

Collection 1									
Bin1		Bin2		Bin3		Bin4		Bin5	
Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight	Citizen	waste weight
222	3.60	222	6.16	222	5.21	222	6.58	222	2.95
223	3.76	223	5.05	223	7.28	223	8.71	223	3.36
224	6.09	224	7.32	224	5.93	224	7.66	224	8.91
225	4.50	225	8.83	225	5.45	225	5.32	225	5.43
226	2.34	226	5.37	226	7.35	226	4.84	226	3.78
227	8.78	227	9.21	227	3.14	227	7.73	227	6.64
228	9.68	228	4.13	228	7.01	228	8.75	228	4.74
229	4.25	229	4.78	229	8.16	229	3.23	229	6.19
230	9.08	230	6.28	230	6.58	230	8.58	230	7.72
231	6.13	231	1.72	231	7.38	231	7.12	231	3.97
232	6.30	232	4.94	232	5.06	232	4.17	232	3.79
233	5.15	233	7.20	233	10.27	233	5.90	233	5.54
234	4.63	234	5.82	234	7.44	234	4.52	234	5.67
235	4.32	235	5.51	235	4.95	235	3.98	235	9.26
236	7.60	236	1.28	236	5.78	236	5.86	236	5.67
237	4.84	237	8.51	237	7.56	237	5.02	237	7.29
238	4.24	238	4.78	238	7.59	238	2.89	238	7.53
239	5.55	239	4.76	239	5.12	239	8.28	239	3.83
240	5.17	240	3.39	240	4.46	240	6.88	240	3.38
241	6.35	241	4.47	241	4.33	241	4.76	241	7.32
242	8.78	242	10.05	242	4.95	242	3.93	242	5.31
Total	1471	Total	1404	Total	1427	Total	1476	Total	1426

Table 25. Once per Week Model CO_2 Emission Calculation (Kg)

CO2 emission	Collection 1
F to 1	18.672
1 to 2	13.228
2 to 3	5.165
3 to 4	29.464
4 to 5	61.317
5 to F	22.068

APPENDIX D: PERIODIC REVIEW MODEL SIMULATION RESULTS

Table 26. High Arrival Rate and Low Waste Weight Variability Results (Periodic Review)

Periodic Review Collection model results (poisson 45 & normal (6,2))				
results	once per week	twice per week	3 per week	everyday
total waste (tons)	3,495.3697	3,495.7219	3,492.1237	3,497.4766
total distance (km)	11,810.8492	23,621.6984	35,432.5475	82,675.9443
total CO2 (ton)	171.3915	220.1636	268.7164	463.8555
%overfilled	85.3151	57.0795	33.2493	0.0000

Table 27. Low Arrival Rate and Low Waste Weight Variability Results (Periodic Review)

Periodic Review Collection model results (poisson 60 & normal (6,2))				
results	once per week	twice per week	3 per week	everyday
total waste (tons)	2,619.1034	2,621.6925	2,620.1616	2,622.5749
total distance (km)	11,810.8492	23,621.6984	35,432.5475	82,675.9443
total CO2 (ton)	140.6426	189.4667	238.1511	433.1848
%overfilled	71.6767	42.7014	11.3534	0.0000

Table 28. Variable Arrival Rate and Low Waste Weight Variability Results (Periodic Review)

Periodic Review Collection model results (uniform 45-120 & normal (6,2))				
results	once per week	twice per week	3 per week	everyday
total waste (tons)	1,904.7647	1,909.1059	1,908.7597	1,907.2403
total distance (km)	11,810.8492	23,621.6984	35,432.5475	82,675.9443
total CO2 (ton)	115.5611	164.4757	213.2228	408.0954
%overfilled	63.0575	20.6192	0.0055	0.0000

Table 29. High Arrival Rate and High Waste Weight Variability Results (Periodic Review)

Periodic Review Collection model results (poisson 45 & normal (6,4))				
results	once per week	twice per week	3 per week	everyday
total waste (tons)	3,495.1604	3,498.0205	3,499.2519	3,498.9552
total distance (km)	11,810.8492	23,621.6984	35,432.5475	82,675.9443
total CO2 (ton)	171.4089	220.2226	268.9553	464.0017
%overfilled	84.4822	57.2164	33.4247	0.0000

Table 30. Low Arrival Rate and High Waste Weight Variability Results (Periodic Review)

Periodic Review Collection model results (poisson60 & normal (6,4)				
results	once per week	twice per week	3 per week	everyday
total waste (tons)	2,620.8072	2,623.4758	2,623.1240	2,627.0275
total distance (km)	11,810.8492	23,621.6984	35,432.5475	82,675.9443
total CO_2 (ton)	140.6361	189.5333	238.2444	433.3753
%overfilled	72.8877	42.4822	11.6767	0.0000

Table 31. Variable Arrival Rate and High Waste Weight Variability Results (Periodic Review)

Periodic Review Collection model results (uniform 45-120 & normal (6,4))				
results	once per week	twice per week	3 per week sec	everyday
total waste (tons)	1,912.9723	1,905.5851	1,911.9398	1,909.8547
total distance (km)	11,810.8492	23,621.6984	35,432.5475	82,675.9443
total CO_2 (ton)	115.8413	164.3955	213.3347	408.1459
%overfilled	63.8521	20.4438	0.0877	0.0000

APPENDIX E: IOT ENABLED MODEL SIMULATION RESULTS

Table 32. High Arrival Rate and Low Waste Weight Variability Results (IoT enabled)

IoT enabled collection model result (poisson 45 & normal (6,2))			
Threshold	70%	80%	90%
total waste (tons)	3,493.9178	3,497.8432	3,493.7636
total distance (km)	42,546.8500	41,337.9721	42,107.9076
total CO2 (ton)	278.8438	293.3339	274.6468
%overfilled	49.5616	49.2712	49.3699

Table 33. Low Arrival Rate and Low Waste Weight Variability Results (IoT enabled)

IoT enabled collection model result (poisson 60 & normal (6,2))			
Threshold	70%	80%	90%
total waste (tons)	2,622.0182	2,618.8354	2,614.6740
total distance (km)	40,701.0581	41,039.2895	37,757.5830
total CO2 (ton)	222.9432	213.4393	198.2747
%overfilled	2.1699	4.1205	21.0411

Table 34. Variable Arrival Rate and Low Waste Weight Variability Results (IoT enabled)

IoT enabled collection model result (uniform 45-120 & normal (6,2))			
Threshold	70%	80%	90%
total waste (tons)	1,900.7738	1,900.5060	1,898.9434
total distance (km)	35,838.5219	29,301.5066	31,954.9051
total CO2 (ton)	178.1021	165.5444	159.6533
%overfilled	13.8082	16.5973	21.1178

Table 35. High Arrival Rate and High Waste Weight Variability Results (IoT enabled)

IoT enabled collection model result (poisson 45 & normal (6,4))			
Threshold	70%	80%	90%
total waste (tons)	3,499.4648	3,494.9895	3,491.5268
total distance (km)	44,691.9792	42,222.6779	42,562.2006
total CO2 (ton)	251.7068	271.0112	245.6135
%overfilled	47.2658	47.0849	48.1753

Table 36. Low Arrival Rate and High Waste Weight Variability Results (IoT enabled)

IoT enabled collection model result (poisson 60 & normal (6,4))			
Threshold	70%	80%	90%
total waste (tons)	2,619.6849	2,618.2181	2,612.1358
total distance (km)	41,224.3565	41,359.9416	37,540.2662
total CO2 (ton)	215.7604	216.6224	196.7867
%overfilled	9.5123	15.0849	27.0630

Table 37. Variable Arrival Rate and High Waste Weight Variability Results (IoT enabled)

IoT enabled collection model result (uniform 45-120 & normal (6,4))			
Threshold	70%	80%	90%
total waste (tons)	1,903.5183	1,904.1434	1,899.2986
total distance (km)	35,967.5912	34,270.0757	32,403.5384
total CO2 (ton)	178.5387	171.2265	161.2287
%overfilled	10.1699	18.0767	22.6521