Master's thesis

2020

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Master's thesis

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An IoT-based Smart and Sustainable Waste Management System for a Norwegian Municipality

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An IoT-based Smart and Sustainable Waste Management System for a Norwegian Municipality

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Masters in Simulation and Visualization

Submission date:	June 2020
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Summary

A solid waste management system (SWMS) is the backbone of a smart and sustainable city (SSC). The SWMS includes all the factors related to waste such as collection, sorting, transportation, and recycling. The core processes of waste collection and transportation remain the same for decades. With the help of IoT-based data driven and data transfer technologies, cameras, actuators and sensors, the waste collection process can be improved and modified. The smart waste collection triggers a transition from fixed collection to on-demand collection assigned by optimization algorithms and smart web-applications.

In this thesis, a Norwegian municipality is investigated as a case study. An overview of the current practices and infrastructure is presented and the currently faced issues are addressed. A conceptual model of a smart and sustainable waste management system along with optimized waste collection and transportation system is proposed to achieve the key performance indicators (KPIs) presented in EU agenda of United for Smart and Sustainable Cities (U4SSC) (ITU-T (2016)).

The proposed conceptual model illustrates the role of each stakeholder in the waste management system's development. An IoT-based smart waste bin is proposed to detect the waste material and the waste volume in a bin. It addresses the battery life problem in IoT-based devices. A smart waste bin application is presented to directly connect the citizens and services providers for the development of a solid waste management system (SWMS).

Regarding waste collection and transportation, various optimization techniques are proposed such as multi-objective traveling salesman problem (MOO-TSP), a conventional vehicle routing problem (VRP), and capacitated vehicle routing problem (CVRP). The proposed optimized solutions calculate routes for a various number of vehicles under different scenarios having specified constraints such as minimum traveling distance, minimum traveling time, vehicle capacity, waste volume in the bin and waste collection on demand. These solutions are cost-effective and time-efficient.

In MOO-TSP, the shortest possible route is calculated with objectives such as minimum traveling distance and minimum traveling time. The calculated route takes one vehicle at a time into consideration. The proposed optimization model is 34% cost saving as compared to the current practices.

In VRP, the shortest possible routes are calculated for various vehicles. The routes are calculated for different constraints such as minimum traveling time and minimum traveling distance. Furthermore, the CVRP adds several more constraints for route calculation such as capacity of a vehicle, volume of waste in each bin.

Pertaining to the visualization of optimized routes on a map. Google maps platform is used to visualize the calculated routes from a depot site to several bins and back to the depot site. For optimizing routes, the greedy descent algorithm is used to calculate the nearest possible neighbour in a routing problem. The routes on Google maps are differentiated by different colors for each vehicle.

The proposed optimal solutions for routing and vehicle allocation lead to a significant reduction in the overall cost of a waste management system. The results are obtained from

the data from the waste bins placed by the service providers in the investigated municipality. To calculate the optimal distance and optimal time for waste calculation, the Google Distance Matrix API is used.

The proposed solutions prove that IoT-based SWMS is the best replacement of current practices in order to achieve sustainable development goals (SDGs). This thesis achieves the SDG 11.6 and supports SDG 12.4, SDG 12.5. Where SDG 11 targets to make cities and human settlements inclusive, safe, resilient, and sustainable, and SDG 12 ensures sustainable consumption and production patterns (SGDs (2020)).

Acknowledgements

I am sincerely grateful to my supervisors; Anniken Th. Karlsen and Ibrahim A. Hameed for their strong support, essential guidance and dedicated supervision throughout the thesis. Their constructive criticism, invaluable suggestions and time have helped me to achieve all the steps of this research.
Besides my supervisors, I would like to thank the environmental company Årim for their great collaboration. They have shown a great interest in the project and been available for meetings and domain-knowledge. I want to direct a special thanks to Espen Mikkelborg for his assistance when collecting data from waste bins. Finally, I would like to thanks my family and friends for all the encouragement, support and motivation. This masters would have been impossible without them.

Preface

This masters thesis is submitted as the final work of the Master of Science in Simulation and Visualization program at the Department of ICT and Natural Sciences, Norwegian University of Science and Technology (NTNU). The research and report are done during the last year, from winter 2019 - spring 2020. The pilot project of this work has been done as a Specialization project course in winter 2019. It has been performed with the environmental company Årim as a collaborating partner, provided access to the data from the database. They are respected service providers for household waste management in Ålesund community.
This thesis aims to explore the waste management system using optimization algorithms and IoT technologies to achieve sustainable development goals specifically the solid waste key performance indicators (KPIs). It is investigated whether it has a potential to improve the current practices and infrastructure for waste management system in the investigated municipality. The main parts of the thesis are to use optimization techniques for solving routing problem for waste collection and to predict the waste volume in waste bins.
I was inspired to pursue this topic since I attended the U4SSC seminar held at NTNU. I am very much interested in finding better ways to monitor climate change and in applying my knowledge of artificial intelligence and data analysis towards a smart and sustainable environment. I also have a background of developing optimization algorithms particularly greedy algorithms.

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Abbreviations

IoT	=	Internet of things
SWMS	=	Solid waste management system
QoL	=	Quality of life
UC	=	Ubiquitous computing
M2M	=	Machine to machine
WSN	=	Wireless sensor network
U4SSC	=	United for smart and sustainable cities
SDG	=	Sustainable development goals
ICT	=	Information communication technology
SSC	=	Smart sustainable cities
KPI	=	Key performance indicator
LPWAN	=	Low Power Wide Area Networks
RFID	=	Radio Frequency Identification
OR	=	Operation research
TSP	=	Travelling salesman problem
VRP	=	Vehicle routing problem
CVRP	=	Constraints vehicle routing problem
SOP	=	Single-objective optimization problem
MOP	=	Multi-objective optimization problem
PS	=	Pareto-set

Chapter 1

Introduction

In this chapter, the background and motivation for this thesis work are introduced. Furthermore, the contribution and scope of the thesis in this particular research field is described. Finally, the outline of the thesis is stated.

1.1 Background

During the last century the world population has been tripled and massive relocation took place from rural to urban areas. Nowadays around 50% of the world's population lives in the cities and it is predicted that this digit will reach 70% by 2050 (Raina et al. (2017)). This drastic growth of urbanization caused production of a huge amount of waste. Since last few decades, many researchers proposed various number of solutions for waste maintenance and management. Pertaining to this dramatic urbanization from past few decades around the world makes smart sustainable cities the main concern. Operating all the cities authorities with the help of ICT made cities efficient in several aspects. Though incorporating ICT with city operations cannot fully interprets the smart cities concept. Generally a smart city is an urban environment that utilizes ICT and other related technologies to improve performance efficiency of regular city operations and quality of service (QoS) provided to urban citizens. Internet of Things (IoTs) crossover various areas/operations of a smart city. While a smart sustainable city can be defined as:(ITU-T (2016))

"*An innovative city that uses information and communication technologies and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to the economic, social, environmental and cultural aspects.*"

With the advent of smart devices and their recent advancements, the abstraction of connecting everyday objects via existing networks becomes extremely favorable. The Internet of things (IoTs) is an arrangement of web related items that can accumulate and exchange data. Evolution of conventional networks has resulted in linking billions of connected devices together. IoT defines a world where almost anything can connect and interact in a smart fashion than ever before (Kamm et al. (2020)). Technological advancements in

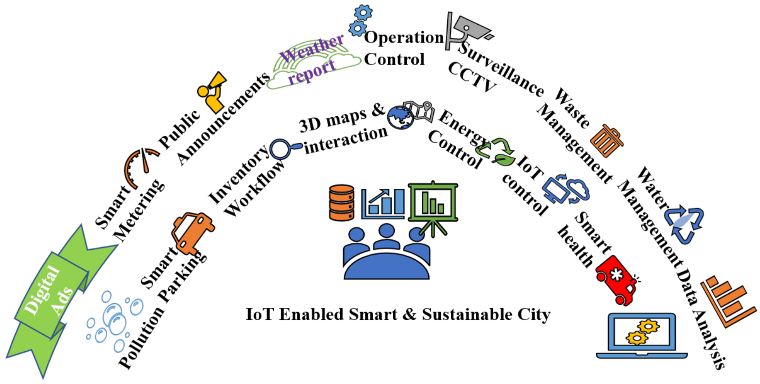

Figure 1.1: An IoT-based conceptual model of smart and sustainable city (Nasar et al. (2020a))

ubiquitous computing (UC), wireless sensor networks (WSN), and machine-to-machine (M2M) communication have further strengthened the notion of IoT (Silva et al. (2018)). Moreover, linked devices share their information and get access to the authorized information of other devices to support contextual decision making.

In **Fig. 1.1**, a conceptual model of IoT-based smart and sustainable city is illustrated. The deployment of wireless sensor networks in a smart and sustainable city infrastructure generates a large amount of data each day across a variety of domains with applications including health, environment, energy and transport monitoring. To take advantage of the generated data there is a need for new techniques and technologies that can assist in managing the utilization of resources smartly and dynamically (Gaur et al. (2015)). This research gives a conceptual model of how to utilize and manage the collected data for city's benefits specially waste management system.

Moreover, a smart waste management is the fundamental zone of a smart and sustainable city. Several solid waste management (SWM) projects have been executed worldwide in rural and urban areas. Different data handling techniques and data transfer technologies have been proposed as the solution for SWM (Kamm et al. (2020)). In this research, I have proposed an IoT-based smart and sustainable solid waste management system for a Norwegian municipality with the optimal solutions for selective waste collection, routing problem and vehicle allocation.

1.2 Motivation

We know that the climate change is a bitter reality of today's world and hearing few of the young activists talking openly and with a great responsibility towards climate change, motivates me to choose this topic for my master's thesis. Being a human and responsible citizen of a country, it is our duty to make world a better place for next generations and try to give them an improved lifestyle.

This thesis gets motivation from such a project with United for Smart and Sustainable Cities (U4SSC) to contribute in the development of a smart sustainable municipality and to achieve sustainable development goals (SDGs) proposed by U4SSC. United for Smart and Sustainable Cities (U4SSC) is an united nations initiative coordinated by ITU and UNECE and 14 other UN agencies in response of sustainable development goals (SDGs) i.e.,

"*Ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests*".

It advocates for the public policy to encourage the use of ICTs to facilitate and ease the transition towards smart and sustainable cities (ITU-T (2016)). This initiative has developed a set of key performance indicators (KPIs) for smart sustainable cities (SSC) to set the standards for evaluating the contributions of ICT in making cities smarter and more sustainable and to provide the means for self-assessment to cities (ITU-T (2016)). These

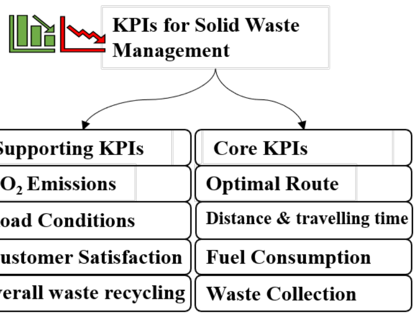

Figure 1.2: Solid waste management KPIs (Nasar et al. (2020a))

indicators have been developed to provide cities with a reliable and systematic framework for data collection and performance assessment as well as measure the progress towards smart and sustainable development goals (SDGs). These KPIs are structured in different dimensions. The solid waste management is a sub-dimension of environment dimension to achieve SDGs particularly SDG 11 and SDG 12. My contribution in this project is to develop a smart and sustainable waste management system for the investigated municipality. The solid waste key performance indicators (KPIs) have been achieved with the development of smart and sustainable waste management system (SSSWMS) for the investigated municipality described in **Fig. 1.2** (ITU-T (2016)).

1.3 Scope

The scope of this thesis is to investigate the IoT-based technologies for smart and sustainable solid waste management system (SWMS). Different optimal routing techniques are being used to solve the waste collection and transportation problem. The proposed SWMS is based on current practices and infrastructure. The aim of the thesis is to provide optimal solution for selective waste collection problem. The scope falls within the boundaries of IoT technologies, sustainable developments and waste management system as indicated in **Fig. 1.3**.

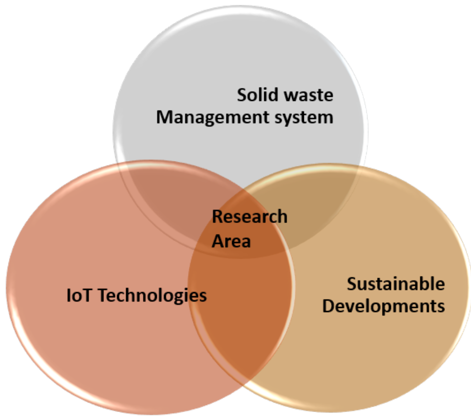

Figure 1.3: Venn diagram of thesis scope

1.4 Objective & Contributions

Pertaining to the development of a waste management system, waste collection and transportation are major challenges. Although various optimization algorithms have been used to solve the optimal routing problem, there are still many challenges to cater.(Gaur et al. (2015); Lundin et al. (2017); Yuan et al. (2013)). The overall goal and purpose of this thesis is therefore related to exploring the following questions for waste management system:

- What are the current practices and infrastructure?
  - A case study of the investigated municipality
- Are they efficient? If not, what to do?
  - Optimal Solutions
- What are the smart and sustainable solutions?
  - IoT-based waste management system

The objective of this thesis:

> Investigates the current practices and infrastructure of the waste management system for a Norwegian municipality and proposes solutions to the recent problems.

The proposed smart and sustainable waste management system (SWMS) is based on IoT technologies. These technologies inter-link the service providers and the customers for efficient and effective interaction. The google maps platform, especially Google Distance Matrix API, is used for geographical locations of waste bins scattered in the municipality. In this thesis following research questions are investigated and answered:

1. How can the current SWM system become smart and sustainable?

   The current practices are lacking optimal solutions for waste collection and vehicle allocation. This problem can be solved with the help of many optimization algorithms but in this thesis the following optimization algorithms such as multi-objective traveling salesman problem (MOO-TSP), vehicle routing problem (VRP) and capacitated vehicle routing problem (CVRP) are used to develop a smart and sustainable SWMS.

2. How can IoT- technologies be used in SWM system?

   Pertaining to the increasing urbanization, the cities are becoming smarter and more sustainable with the help of ICT technologies. The IoT- based SWM system interlinks all the concern parties/ stakeholders in a smart sustainable city. A conceptual model is proposed in this thesis that is based on IoT technologies to implement an improved smart and sustainable SWMS.

3. How to solve waste collection and transportation problem?

   With the help of optimization algorithms as MOO-TSP, VRP and CVRP, the waste collection problem is resolved by minimizing traveling time, traveling distance and traveling cost. This developed system gives optimized routes for vehicles allocation and waste collection, and schedule the trips for waste collection by analyzing the obtained waste bin data.

4. Are the proposed solutions applicable in real- life practices?

   To make the system adaptive and practical, I have studied the current infrastructure and practices for this municipality. The proposed solutions are based on the problems occurring in the current practices. For instance, there is no optimal solution present for waste collection's transportation and so on.

5. Have the solid waste key performance indicators (KPIs) been achieved?

   Pertaining to the solid waste KPIs provided by U4SSC to achievce SDGs, the proposed SWMS achieves all the core and supporting KPIs proposed as in **Fig. 1.2** specifically, SDGs 11 and SDGs 12 (ITU-T (2016); SGDs (2020)).

6. What are the proposed visualization tools for tracking the waste collection and vehicle allocation?

   There are several visualization tools that can be used by waste truck drivers to locate the route and location of the waste bins. In this thesis, I have used Google maps platform for optimization of routes.

1.5 Thesis Outline

The structure of this thesis is as follows:

- **Chapter 2 - Related Work:** Explores the research work related to this thesis. The chapter summaries the methods and techniques proposed by numerous researchers regarding to IoT-based smart and sustainable waste management system. An introduction to the proposed system is also presented.

- **Chapter 3 - Basic Theory:** Describes the relevant theory for this thesis. This chapter includes theory about smart and sustainable city, IoT technologies, SWMS, optimization algorithms. This chapter explains the approaches used in this thesis in detail.
- **Chapter 4 - IoT-based Conceptual Model:** Illustrates the proposed conceptual model for IoT-based SWMS. It describes the suggested solutions and models for smart and sustainable SWMS to connect all the stakeholders, in detail.
- **Chapter 5- Optimization Models:** Discusses the proposed solutions for waste collection and vehicle allocation. This chapters presents the achieved KPIs provided by SDGs. It illustrates data analysis and proposed optimization algorithms that are applied to solve waste collection and transportation problem from waste bins to disposal sites.
- **Chapter 6- Discussion & Conclusion:** Discusses the results for smart and sustainable SWMS, concludes this thesis and presents possible future work in smart and sustainable solid waste management system (SWMS).

1.6 List of Publications

1.6.1 Published Paper

- Wajeeha Nasar, Anniken Th. Karlsen, Ibrahim A. Hameed: **A Conceptual Model Of An IoT-Based Smart And Sustainable Solid Waste Management System: A Case Study Of A Norwegian Municipality**. – *ECMS*, 2020, Germany.

1.6.2 Submitted Paper

- Wajeeha Nasar, Anniken Th. Karlsen, Ibrahim A. Hameed, Saumitra Dwivedi: **An Optimized IoT-based Waste Collection and Transportation Solution: A Case Study of a Norwegian Municipality**. – submitted to *3rd International Conference on Intelligent Technologies and Applications (INTAP)*, 2020, Norway.

Chapter 2

Related Work

’Smart City’ term was first used by Van Bastelaer (1998) and has been getting attention from all around the world since then. The concept of smart city varies among practitioners and academia but in general the interlinked connection of ICT technologies with city operational fields with the help of IoTs can summarize the general concept of smart city as shown in **Fig. 1.1** (Silva et al. (2018); Gaur et al. (2015)). A lot of researchers use smart and sustainable terminology together when it comes to better living conditions and human rights (Mingaleva et al. (2019)).
All the aspects of both smart and sustainable concepts have mutual interests. Pertaining to that the waste management is an important factor in the concepts of both smart and sustainable cities to address problems such as responding to climate change in terms of smart protection systems, maintaining and sustaining the urban environment (Mingaleva et al. (2019)). This thesis focuses on the domestic solid waste management system (SWMS) for a smart and sustainable city.

2.1 IoT-based Smart and Sustainable City

The Internet of Things (IoT) is one of the main components of ICT infrastructure of SSC as an emerging solution to urban growth, owing to its tremendous potential for advancing environmental sustainability (Mingaleva et al. (2019); Ahvenniemi et al. (2017); Bibri and Krogstie (2017)). The term IoT is associated with data analytic as one of the predominant ICT visions or computing paradigms which is obviously on a penetrative pass across many urban environments to improve energy production and reduce environmental impacts. It primarily concerns the efficient use of natural resources, the intelligent management of infrastructures and facilities, and the increased provision of environmental support services. As such the IoT and associated data analysis technologies will play a key role in catalyzing and enhancing the sustainable development process (Bibri and Krogstie (2017)).
The use of ICTs for SSC provides urban stakeholders various values:

1. The value of productivity in urban operations and services

2. The enhancement of quality of life (QoL)

3. Environmental sustainability cultivation

In this regard, the U4SSC initiative has established a set of KPIs for SSC to create benchmarks for evaluating ICT's contributions to make cities smarter and more sustainable, and to provide them with the means for self-assessment to achieve the sustainable development goals (SDGs) (ITU-T (2016)). The KPIs are divided into three main domains in **Fig. 2.1**. SWM is an overlapping area of SDG 11 and SDG 12 (SGDs (2020)) and in this thesis the smart and sustainable SWMS based on IoTs technologies is proposed and developed. The IoT-based SWMS connects and interlinks all the stakeholders such as city administration, service provider companies, truck drivers and citizens. Through the advanced data driven and data transfer technologies, cameras, sensors, actuators and IoT controls, the current inefficient waste management practices can be replaced.

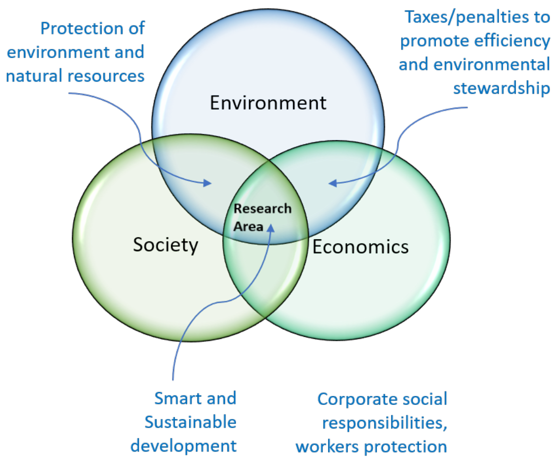

Figure 2.1: Sustainable developments domains with KPIs

2.2 Solid Waste Management System (SWMS)

'Waste' encompasses all materials that have reached the end of their useful existence and other process by-products such as processing, trading, construction and demolition. The waste that we receive at the end of a cycle of a material is indeed the tip of the iceberg. At this point the actual produced waste is a fraction of the materials used to manufacture and transport the product over its life cycle. All products and services can not be treated in the same manner. Each product and material has different life cycle and once that life cycle is over, it should be handled differently.

The environmental protection agencies have developed a waste management hierarchy and non-hazard waste material hierarchy. These hierarchies give recognition that waste material can not be handled in a single manner. There has to be various ways for the waste

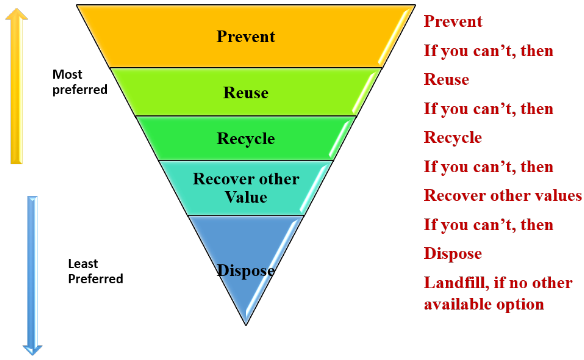

Figure 2.2: Solid waste management hierarchy (Nasar et al. (2020a))

management. **Fig. 2.2** describes the waste management hierarchy from the most preferred way for waste handling to the least preferred way.

According to Nagapan et al. (2012), waste should be regulated in the following order of preference: prevention, reuse, recycle, energy recovery, storage, containment, and disposal. The roles of city municipality, government, waste management companies have major influence on the development and dissemination of strategies that will help to operationalize the waste management hierarchy. Waste prevention means reduce waste at the source and it is the most environmentally-favorable strategy. It may take several different forms, including reuse or redistribution of products, bulk purchase, packaging reduction, product redesign, and toxicity reduction.

Recycling and compositing are the sets of activities that involve gathering used, reused, or discarded goods that might otherwise be regarded as waste; sorting and converting the recyclable products into raw materials; and reprocessing the recycled raw materials into new products.

Recover other values from waste involves the conversion of non-recyclable waste materials into usable oil, electricity or fuel by a range of methods, including combustion, gasification, anaerobic digestion and recovery of landfill gas. Treatment can help to reduce the quantity and toxicity of the waste before disposal. These treatments can be physical, chemical, or biological. Landfills are the most common method of waste disposal and constitute an important part of an integrated waste management system (Nagapan et al. (2012); Adeleke and Ali (2020)).

The solid waste management system (SWMS) includes waste sorting, collection, transportation and recycling, as shown in **Fig. 2.3**. In recent practices of Norwegian municipalities, different types of waste bins are provided to customers at household level for waste sorting. The collection, transportation and management for each type is different. For instance, food waste needs to be emptied more often than other type of wastes. Plastic and paper waste usually collected every 10^{th} week. Similarly treatment also varies from type-to-type. Waste transportation is a major issue in a waste management system. Different solutions and techniques have been proposed during last few decades.

Nirde et al. (2017) proposed an IoT-based solid waste management system for a smart city. In their research, a prototype is built with the help of ultrasonic sensors that are used to

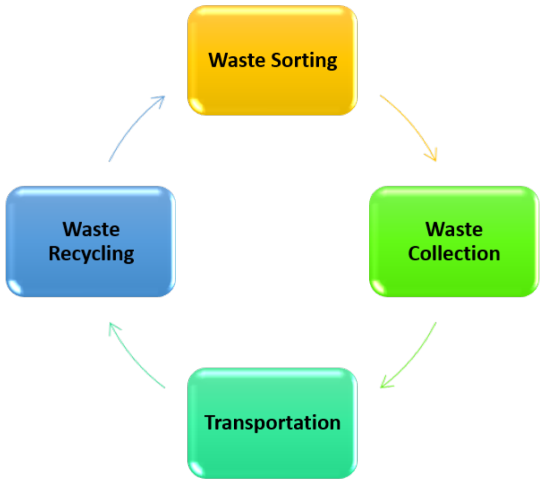

Figure 2.3: Smart and sustainable waste management system (Nasar et al. (2020a))

measure the waste volume in a bin. The data from these sensors help to prevent littering and service providers schedule the waste collection trips accordingly.
Murugaanandam et al. (2018); Lundin et al. (2017) propose an automatic smart bin or garbage collection system focused on warning the authorities such as corporate or local waste disposal team about waste volume so that they can efficiently control the full disposal of the waste.
Adeleke and Ali (2020) propose an efficient model for waste collection to reduce total number of waste sites and containers. Anagnostopoulos et al. (2017) provides a comprehensive survey of opportunities and challenges for the waste management in an IoT-enabled smart city where the authors described the current infrastructure of the city. This survey offers the possible solutions and opportunities by IoT technologies.
Hong et al. (2014) investigates a Korean city and proposes a smart garbage system (SGS) to reduce food waste. In the SGS, the battery-based smart garbage bins (SGBs) share information with each other using wireless mesh networks, and the router and server capture and analyze service delivery information.The proposed solution reduces 33% average amount of food waste. Various other techniques in the literature are used to optimize routing problems.

2.3 Selective Waste Collection and Transportation

2.3.1 Optimization Algorithms

Studies related to waste collection and transportation can be classified into different categories with respect to routes and number of disposal sites (Li et al. (2011)):

- Single route, single disposal site
- Single route, multiple disposal sites

- multiple route, multiple disposal sites

In earlier years of researches for transportation problem, traveling salesman problem(TSP) gained the major attention and most of the researchers have used TSP to solve waste trucks transportation problem (Fırıncı et al. (2009)).
With the advancement in ICT technologies, solving selective waste collection and transportation problem with TSP is not enough, specially, in case of multiple disposal sites and multiple routes (Yuan et al. (2013)). To address such cases, multiple traveling salesmen problem (mTSP) also known as vehicle routing problem (VRP) is used. Due to its crucial role in organizing distribution networks and logistics in many sectors such as garbage collection, mail delivery, snow ploughing and mission sequencing, the VRP has attracted immense interest from many researchers over the decades. Studies provides the exact methods based on linear programming techniques and guided local search, uses to solve VRP and its types such as VRP with time window (VRPTW), VRP with pick-up and delivery, and capacitated VRP (CVRP). The aim is to find a set of distribution routes that meets certain requirements or constraints and offer minimum total cost (Liong et al. (2008)). Furthermore, heuristic techniques have received broad interest of researchers in the attempts to solve VRPs on a large scale. Among others, the recently applied heuristic techniques such as genetic algorithm, evolution strategies and neural networks for optimization problems such as solving TSP and mTSP, gives promising results (Yuan et al. (2013); Liong et al. (2008); Hameed (2020); Singh et al. (2018); Jozefowiez et al. (2008)).
Hameed (2020) proposes a multi-objective genetic algorithm (MOGA) for searching efficient solutions for the optimal routes with minimum traveling distance and traveling time. In this research, an initial population is provided that is composed of an approximation to the highly supported efficient solutions. A Pareto local search is then extended to all initial population solutions. The approach is applied to a simulated problem and to a real-world problem where distances and actual estimates of travelling time are retrieved from the Google Maps Platform using a Google Distance Matrix API for multiple origins and destinations using different transport modes. It has been observed that solving a TSP as a multi-objective optimization problem will provide more practical solutions.
A novel approach with two part chromosomes crossover for mTSP through genetic algorithm (GA) is used by Yuan et al. (2013). The proposed approach minimizes the problem space and overcomes the limitations usually occurs to find optimal routes while implementing two chromosome crossover technique. Other than GA, some researchers used ant colony optimization (ACO) algorithm to solve TSP or mTSP (Othman et al. (2018)).
Othman et al. (2018) proposes ACO algorithm to solve VRP. The efficiency of algorithm is improved by reducing the parameters used for stopping criteria. The control parameters are analyzed to find the best value for each of them and evaluation of ACO' output on VRP is made. The good performance of the algorithm reflected on the importance of its parameters such as visibility, trial and pheromone decay.
Li et al. (2011) uses a hybrid GA and ACO approach to solve vehicle routing problem and find optimal route length with minimum distance. The objective features and constraints of VRP are defined with the objective of reducing the service costs without exceeding the vehicle capacity. In the proposed GA-ACO algorithm, genetic algorithm is performed by selection, crossover and mutation, and then ACO's pheromone update is performed to move away from the local optima. The proposed GA-ACO algorithm is intended to

improve the efficiency of genetic algorithms by integrating local search and optimization of ant colony. From the simulation results, it is observed that the proposed GA-ACO algorithm is performing satisfactorily.
Zhang and Lee (2015); Yao et al. (2017); Gomez and Salhi (2014) use artificial bee colony optimization algorithm (ABC) to solve the VRP and CVRP. Zhang and Lee (2015) solve the CVRP with the artificial bee colony algorithm (ABC), derived from the swarm intelligence. The application of the ABC algorithm to solve the CVRP has exploited the swarm intelligence's inherent features. Additionally, a routing directed ABC algorithm (RABC) is further proposed consisting of numerous improvements to enhance the ability of the conventional ABC algorithm to diversify and intensify search, which incorporates the useful routing information. The algorithm is tested with different test instances on the benchmark. Yao et al. (2017) uses improved artificial bee colony (IABC) algorithm to solve the VRPTW. This proposed algorithm's efficiency is enhanced by a local optimization based on a crossover process and a scanning technique. Subsequently, the IABC's effectiveness is measured on certain well-known metrics. The results states that the efficiency of the IABC algorithm in resolving the VRPTW.
Other techniques such as simulated annealing (SA) and a modified discrete firefly algorithm (MDFA)is proposed by Manliguez. et al. (2017). Manliguez. et al. (2017) studies the data from several sensors and the city's solid waste management system (SWMS) to improve waste collection and routing problem by using SA and MDFA. The proposed algorithm is used to solve travelling salesman problem (TSP) using the tanh function for discretization. The purpose of this analysis is to evaluate and compare MDF-SA and MDFA in terms of running time and service quality. Generally, the proposed hybrid algorithm has performed better than MDFA in terms of route selection for city's SWMS.
Baranwal et al. (2017) uses a maximum entropy principle based approach to solve mTSP and VRP with variant constraints. In the proposed solution, the TSP and its variants are presented as resource allocation constraints, where an ordered set of resources is associated with the cities, and the allocation is performed through an iterative algorithm in such a way that each city ultimately becomes associated with a resource.
Ibrahim et al. (2019) implement a reinforcement learning technique to locate optimal paths from a depot to the collection of customers while also considering the capacity of the vehicles to minimize the cost of goods and services transportation. The research solves the CVRP using an exact method, column generation, google's operation research tools and reinforcement learning, and compare their solutions. The objective is to solve an efficient routing problem for a large size of the vehicle.
The study of the great work and proposed solutions of numerous authors leads this thesis research towards right direction. This thesis approaches the defined problems for a smart and sustainable waste management system as:

- **Case I:** Pertaining to the development of a smart and sustainable waste management system, an IoT-based conceptual model is proposed and I write a research paper based on the proposed conceptual model, title: "A Conceptual Model Of An IOT-Based Smart And Sustainable Solid Waste Management System: A Case Study Of A Norwegian Municipality" (Nasar et al. (2020a)). In this paper, IoT-based conceptual model is proposed that connects all the stakeholders in the development and deployment of the smart sustainable city (SSC) technologies.

- **Case II :** For waste collection and transportation, a multi-objective TSP approach is proposed to find optimal shortest routes with minimum distance and time. It also uses the collected waste bin's data to predict the waste volume in each waste bin for future scheduling of waste trucks and drivers. I write another research paper based on the proposed approaches and title of the paper is : "An optimized IoT-based Waste Collection and Transportation: A Case Study of a Norwegian Municipality". The benefits of implementing this proposed system are illustrated along with comparison of existing practices and proposed solutions.

- **Case III:** The waste collection and transportation problem on a large scale, is generally addressed as multiple traveling salesman problem (mTSP) or vehicle routing problem (VRP). To solve the route length problem with multiple constraints and objectives, I proposed the solution to sovle the VRP and CVRP with greedy descent algorithm. For visualization of calculated routes with different numbers of vehicles, google maps API and google distance matrix API is used. I am planning to write a research paper based on these approaches.

Chapter 3

Basic Theory

3.1 IoT Technologies

Smart sustainable cities (SSC) paradigm uses internet of things(IoT) such as connected sensors, cameras,light and so on to collect and analyse every bit of information out there in order to increase production quality and achieve maximum resource usage to improve quality of citizen's life. Developing a smart waste management system is one of the major IoT application towards the development of SSC (Gaur et al. (2015); Silva et al. (2018); Dugdhe et al. (2016); Flammini and Sisinni (2014)).
According to Anagnostopoulos et al. (2017); Minoli et al. (2017), our physical world is becoming one interconnected information system, offering us countless opportunities and possibilities but many challenges are still present. Numerous initial obstacles and challenges regarding the size and costs of data transfer chips have already been solved nowadays (Kamm et al. (2020)). In particular, the development of minimum-cost and low-power transceivers, including the growth of flexible and open standard stacks, have made it easy for wireless sensor networks (WSNs) to be widely adopted for both home and industrial monitoring applications(Flammini and Sisinni (2014)). However, interconnected IoT devices require secure bi-directional signalling to facilitate communication, interaction and transmission of data across devices and gateways (Chen (2010)).
Some of the major challenges in this research area are scaling, reliability, bandwidth, protection and power consumption (Kamm et al. (2020)). One important factor regarding data transfer technologies, is the increase in the batteries utilization and the concerns associated with the battery life (Chen (2010)).Therefore choosing the correct data transfer technology is essential.

3.1.1 Data Transfer Technologies

In the initial developments of IoT devices, battery power IoT devices are limited in their operations by the capacity of their power supply. This limitation of batteries utility represents a ginormous barrier in the widespread of IoT applications (Miorandi et al. (2012)).

Therefore, reduction in energy consumption for transferring and inquiring data is essential (Lee and Lee (2015); Miorandi et al. (2012)). Pertaining to that the recent research projects focus on developing alternatives of batteries replacement with passive wireless sensor networks (WSN) and energy harvesting. However, reduction in energy consumption need to measure, transceive data is still a critical concern (Kamm et al. (2020)). **Figure. 3.1** illustrates an overview of data transfer technologies with respect to their range and power consumption. Every wireless network has its own strengths and weaknesses. 4G and 5G telecommunication technologies are optimized for transferring videos and stream large volumes of data in real time and have high energy consumption (Cox (2012)). Whereas Near-Field Communication (NFC) works with passive tags without direct energy source. Instead, they induce energy from the transmitted signals. Hence, they are limited to the power of the magnetic field of the transmitters. The range lies between a few millimeters (mm) up to a few meters (m) (Lee and Lee (2015)).

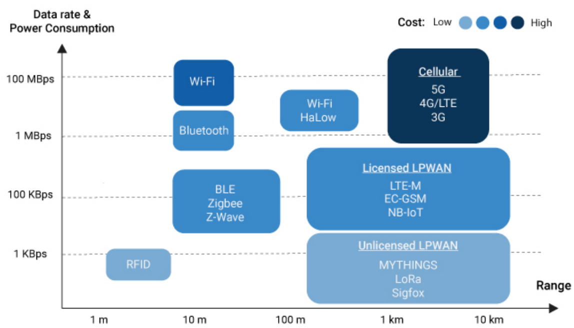

Figure 3.1: Overview of data transfer technologies [Adapted from BEHRTECH (2018)]

Low Power Wide Area Networks (LPWAN)

Low Power Wide Area Networks (LPWAN) are the trends in IoT applications and provide long range communication on small, inexpensive batteries. These technologies are designed to support large-scale IoT networks spanning over huge industrial and commercial campuses (Cox (2012)). LPWANs can connect all types of IoT sensors, enabling a wide range applications. However, LPWANs can only send small data blocks at a low rate and are therefore best suited for low bandwidth that are not time sensitive (Kamm et al. (2020)). The term LPWAN includes a number of different technologies, such as LoRa, NB-IoT and Sigfox.

LoRa

LoRa is a long-range, low-power, low-bit, wireless telecommunications network that is being marketed as an infrastructure solution for the Internet of Things (Tukade and Banakar

(2018)). LoRa is a secure wireless technology that allows a small amount of data to be transmitted over a long distance. The basic element of this technology is the modulation of spectrum distribution, which makes LoRa resistant to interference (SoS-Electronics (2017)). It provides device-gateway-server communication system through standard IP connection and end device uses single-hop wireless communication. The only drawback of this technology is low transmission speed (Tukade and Banakar (2018); SoS-Electronics (2017)).

Sigfox

Sigfox is data transfer technology for less amount of data transmission. It enables IoT devices to communicate over large distance and is secure and reliable. The devices using Sigfox consume less power, has long range and the battery life is up to 10 years. The drawbacks are one way communication and charge for data transfer by operators (SoS-Electronics (2017)).

NB-IoT

Narrowband-IoT (NB-IoT) is latest data transfer technology that uses LPWAN network. It enables users to communicate and connect a large number of devices via existing frequencies. It has low power consumption and fast networking. Being a new technology is its drawback (SoS-Electronics (2017)).

3.2 Current Practices and Infrastructure

In the investigated case, the solid waste management methods and facilities for domestic waste have three different sizes of waste bins for selective waste collection as shown in **Figure. 3.2**:

1. Normal waste bins.
2. Standard underground waste bins
3. Sensor-based underground waste bins

The sensors, mounted on the bins, monitor the volume of waste bins whether they are filled or empty to plan a trip for the waste collection truck drivers. The data transmits in real time through wireless networks to a BioEnable waste management network.
2G and 3G telecommunication systems are available with WCDMZ and GSM networks for data transfer. These data transfer technologies have certain drawbacks such as high energy consumption, low transmission speed. Due to these high energy consumption transmissions require battery replacement after a certain time which represents an enormous barrier to widespread the current practices. Besides this, one of the main challenge in today's domestic SWMS is lack of optimal solution for waste collection that impact the SSC objectives for SWMS. Due to which citizens have to face several problems such as delay in waste collection that cause non-friendly and unsanitary environment. The lack of optimal solutions also causes road congestion and unnecessary traffic.

Figure 3.2: Types of bins present in the investigated municipality

In addition to that the investigated municipality has specific type of waste trucks for each kind of waste bin. This leads towards another issue in current infrastructure where narrow and steep roads in the city center makes the waste collection task impossible. Other challenges is far away placed waste bins and open waste bins, as shown in **Figure. 3.3**. All these stated issues and challenges are addressed in this thesis research.

Figure 3.3: Challenges present in the current infrastructure

3.3 Multi-objective Optimization Travelling Salesman Problem

Waste collection and transportation problem referred as NP-hard combinatorial optimization problem in the literature (Adeleke and Ali (2020); Rutqvist et al. (2020); Fırıncı et al. (2009); Yuan et al. (2013)). These optimization problems are the class of integer constrained optimization problems that are intractable for optimal resolution in large scales. Robust approximation algorithms to common NP-hard problems have a range of potential applications and are the foundation of modern industries such as transport, supply chain, electricity, finance and scheduling (Joshi et al. (2019)). One of the well-known NP-hard problem the travelling salesman problem (TSP) that is used for single route, single depot site, states the following question:

> Given a list of N cities and the distance between each pair of cities, what is the shortest possible route that visits each city and returns to the origin city?

Besides distance, other notions such as time, cost etc. can be taken into account. For N cities, the number of tours/routes are finite, can stated as $1/2(N-1)!$, then the problem is how to obtain an efficient algorithm to find an optimal route. The TSP can be generalized as:

- Single-objective optimization problem TSP (SOP-TSP)
- Multi-objective optimization problem TSP (MOO-TSP)

3.3.1 Single-Objective TSP

The SOP-TSP finds the total minimized distance from one node to another. The SOP-TSP can be graphically represent as, shown in **Figure. 3.4**.

$$G = (V, E) \tag{3.1}$$

where $V = v_1, v_2, ..., v_N$ are nodes and E is a set of edges. For SOP-TSP, the problem is to find the shortest possible route length with minimum traveling distance. Let the possible route to visit all nodes are $P_1 = 1, 6, 5, 3, 2, 4, 1$ and $P_2 = 1, 4, 2, 3, 5, 6, 1$. The distance is $P_1 = 31\ and\ P_2 = 29$ covered in both cases. Therefore, the solution route will be P_2. The mathematical representation of SOP-TSP is:

$$min \left\{ \sum_{i,j=1, i \neq j}^{N} d_{ij} \right. \tag{3.2}$$

where d_{ij} is the distance between locations/nodes $i\ and\ j$.

3.3.2 Multi-Objective TSP

The MOO-TSP includes other notions such as cost, time etc. to final optimal shortest possible route. The graphical representation of MOO-TSP is same as SOP-TSP, as shown in **Figure. 3.5**:

$$G = (V, E) \tag{3.3}$$

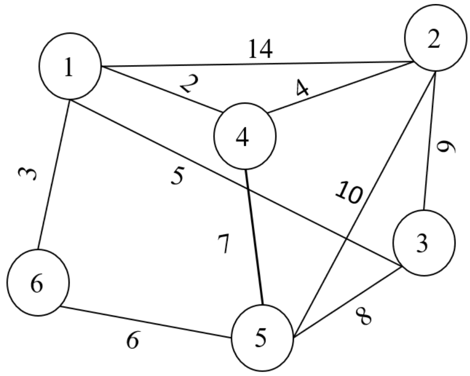

Figure 3.4: SOP-TSP graphical representation with weight (traveling distance) on its edges

where $V = v_1, v_2, ..., v_N$ are nodes and E is a set of edges. In MOO-TSP, traveling time and cost can be added along with traveling distance to find the optimal shortest route length. In the previous section, the optimal solution is focused on single weight where in MOO-TSP, the optimal solution is dependant on minimum distance, time, cost and so on. In this thesis, the optimal solution focused on minimum traveling distance and traveling time. The mathematical representation of MOO (Hameed (2020)):

$$MOO = \begin{cases} min\ F(x) = f_1(x), f_2(x), ..., f_n(x) \\ s.t.\ x \in S \end{cases} \tag{3.4}$$

where $F(x)$ is the objective vector and $n \geq 2$ is the number of objective functions/weights. $x = x_1, x_2, ..., x_N$ is the decision variable vector where N is number of cities/nodes and x is a permutation of integers from 1 through N to minimizes $F(x)$. S is the achievable solution space. The set $O = F(S)$ corresponds to the practical solution in the objective space and the solution can be represent as $y_i = f_i(x)$ where $Y = y_1, y_2, ..., y_n$. The multi-objective solution is the set of non-dominated feasible solutions called Pareto-set (PS).

Let the possible route to visit all nodes are $P_1 = 1, 6, 5, 3, 2, 4, 1$ and $P_2 = 1, 4, 2, 3, 5, 6, 1$. The distance is $P_1 = (31, 16)$ and $P_2 = (29, 15)$ covered in both cases. Therefore, the solution route will be P_2. The mathematical representation of MOO-TSP is:

$$min \begin{cases} f_1 = \sum_{i,j=1,i \neq j}^{N} d_{ij} \\ f_2 = \sum_{i,j=1,i \neq j}^{N} t_{ij} \end{cases} \tag{3.5}$$

where d_{ij} and t_{ij} are the travel distance and time between city pair $i\ and\ j$ respectively. x is a route permutation of N. $f_1(x)\ and\ f_2(x)$ are the total traveled distance and time for route P_2.

In this thesis, the classified waste collection and transportation problem is stated as:

- **Scenario I:** Single route and single depot is solved with MOO-TSP approach and write a paper, named " An optimized IoT-based Waste Collection and Transportation: A case Study of a Norwegian Municipality".

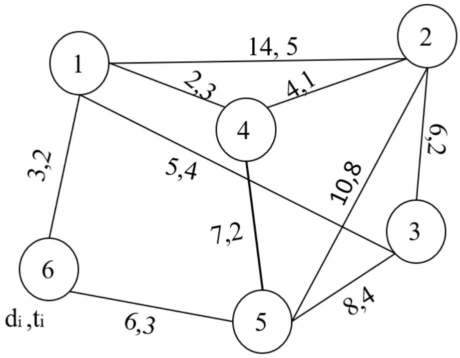

Figure 3.5: MOO-TSP graphical representation with weights (traveling distance, traveling time) on its edges

- **Scenario II:**Multiple routes and single depot is with vehicle routing problem (VRP) in the classical way and capacitated vehicle routing problem (CVRP) by adding constraints such as capacity of the vehicles.

- **Scenario III:** Multiple routes and multiple depots are usually occurs in big cities where different vehicles are allocated at multiple depots sites. This problem can also be solved with above techniques, for example, VRP and CVRP.

3.4 Vehicle Routing Problem (VRP)

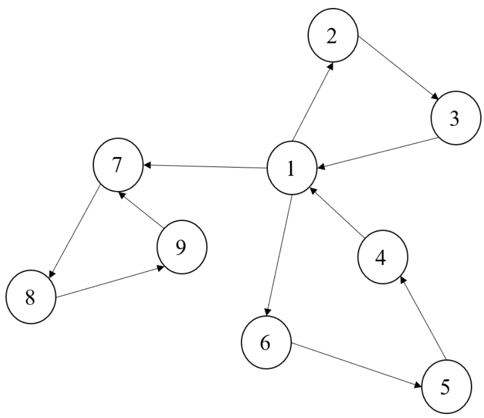

Figure 3.6: VRP graphical representation with weights (traveling distance or traveling time) on its edges

For cases such as multi-routes and single depot site, and multiple routes and multiple depot, the optimal possible routes are found by symmetric mTSP and single asymmetric

TSP(Li et al. (2011)). The mTSP is usually classified as VRP and in a classical VRP, the nodes are known and the traveling distance and time between each node is also given. The VRP can be defined graphically as shown in **Figure. 3.6**.
Let $G = (V, E)$ where $V = v_1, v_2, ..., v_N$ is a set of nodes representing cities with the depot location at node v_1 and E is the set of edges. With every edge (i, j) $i \neq j$ is associated with a non-negative distance matrix $C = c_{ij}$. In some cases, c_{ij} can be interpreted as traveling time or traveling cost. In addition, assume that there are N available number of vehicles based at the depot. The mathematical representation of VRP (Dugdhe et al. (2016)):

Let x_{ij} be an integer variable which may take value $\{0, 1\}, \forall\{i.j\} \in E\{\{0, j\} : j \in V\}$ and value $\{0, 1, 2\}, \forall\{0, j\} \in E, j \in V$. Note that $x_{0j} = 2$ when a route including the single city j is selected in the solution. The VRP can be formulated as the following integer program:

$$Min \sum_{i \neq j} x_{ij} d_{ij} \tag{3.6}$$

Subject to:

$$\sum_{j} x_{ij} = 1, \forall i \in V, \tag{3.7}$$

$$\sum_{i} x_{ij} = 1, \forall i \in V, \tag{3.8}$$

$$\sum_{i} x_{ij} \geq |S| - v(S), S : S \subseteq V1, |S| \geq 2, \tag{3.9}$$

$$x_{ij} \in 0, 1, \forall i, j \in E; i \neq j \tag{3.10}$$

In the above equations (3.6), (3.7), (3.8) and (3.10) define a modified assignment problem i.e. assignments on the main diagonal are prohibited. Constraints in equation (3.9) are sub-tour elimination constraints: $v(S)$ is an appropriate lower bound on the number of vehicles required to visit all nodes of S in the optimal solution.

3.5 Capacitated Vehicle Routing Problem (CVRP)

The classical VRP find optimal solutions for multiple vehicles with minimum distance or minimum time. This approach can be modified by adding constraints such as capacity of the vehicles along with other constraints. The method to find optimal routes with such constraints is known as capacitated vehicle routing problem (CVRP). The CVRP can be described as follow (Ibrahim et al. (2019)):
Let $G = (V, E)$ is an undirected graph of VRP where $V = v_0, v_1, v_2, ...v_N$ is the set of $n + 1$ nodes and E is the set of edges. Node v_0 represents the depot and the nodal set $V = v_0$ corresponds to N customers. A non-negative cost c_{ij} is associated with each edge $\{i, j\} \in E$, the q_i units are supplied at depot v_0. A k set of vehicles with capacity Q is stationed at depot v_0 and use to facilities the customers. A route for CVRP is defined as a least cost simple cycle of graph G passing through depot v_0 such that the total demand of the visited nodes do not exceed the vehicle capacity.
The mathematical representation of CVRP is as follow (Ibrahim et al. (2019)):

Let $G = (V, E), d, q\ and\ Q$ define a CVRP instance having nodes v_0 as the depot and the remaining nodes in N as customers.

$$Minimize \sum_{e=(u,v)\in E} d(e)x_e \tag{3.11}$$

Subject to:

$$\sum_{e\in\sigma(\{v\})} x_e = 2, \forall u \in N\{0\}, \tag{3.12}$$

$$\sum_{e\in\sigma(\{0\})} x_e \geq 2k^* \tag{3.13}$$

$$\sum_{e\in\sigma(S)} x_e \geq 2k(S), \forall S \in N\{0\}, \tag{3.14}$$

$$x_e \leq 1, \forall e \in E\sigma(\{0\}) \tag{3.15}$$

$$\sum_{l=1}^{P} q_l^e \lambda_l - x_e = 0, \forall e \in E, \tag{3.16}$$

$$x_e \in \{0, 1, 2\}, \forall e \in E, \tag{3.17}$$

$$\lambda_l \geq 0, \forall l \in \{1, ..., p\} \tag{3.18}$$

where x_e represents the number of times that edge e is traversed by a vehicle and its value is assumed 2 if e is adjacent to the depot, corresponding to a route with a single customer. λ_l usually associated with possible routes. Each λ_l parameter is associated with one of all the possible $q - routes$ satisfying the capacity constraint. While a $q - route$ is the distance between depot and the node with maximum demand value Q and back to the depot. Equation (3.12) states that each node is served by exactly one vehicle and equation (3.13) states that we need to assign back-and-forth route to k^* vehicles from depot to different customers. The minimum number of vehicles for route assigning are calculated by Bin-packing problem. The rounded capacity constraint use $k(S) = \sum_{u\in S} q(u)/Q$ stated in (3.14) as a lower bound on the minimum number of vehicles need to service the customers in set $S \subset N$. The equation (3.16) describes x to be a linear combination of $q - routes$. All the stated constraints in above equations complete CVRP formulation.

3.5.1 Other applications of vehicle routing problem (VRP)

Compared to SOP-TSP and MOO-TSP, the VRP or mTSP is more appropriate for particular practical scenarios and real-life applications. These applications are mostly related to various routing and scheduling problems. Some major applications are described below (Bektas (2006)):

- *Print Scheduling*– The problem of printing scheduling consists of relying on which method should run and the duration of each run. The costs of plate adjustments are the inter-city costs in the VRP terminology. In a similar sense, the VRP can also be used to establish a development schedule for pre-printed insert ads for newspapers (Carter and Ragsdale (2002)).

- *Workforce Planning*– The problem such as *Interview Scheduling* described by (Gilbert and Hofstra (1992)), mTSP with time constraint where the issue here is of arranging interviews between tour brokers and tourism industry vendors. Each broker corresponds to a salesman who is needed to visit a given set of vendor booths identified by a set of T cities.

- *Transportation Planning*– Angel et al. (1972) discusses the issue of scheduling buses as a variant of the mTSP with certain side constraints. The purpose of the scheduling is to achieve a bus loading pattern such that the number of routes is reduced, the overall distance covered by all busses is held to a minimum, no bus is overloaded and the time taken to reach each route does not exceed a maximum permissible level.

- *Mission Planning*– Mission planning typically occurs in the sense of autonomous mobile robots, where construction, military identification, warehouse automation, post-office automation and planetary exploration cover a range of applications. The mission plan is to decide the best route for each robot to achieve the mission's goals in the shortest amount of time possible. The application of VRP in mission planning in an unstructured environments discussed in Brummit and Stentz (1998).

- *Production Planning*– In the iron and steel industry, orders have to be placed for a production change on the hot strip rolling mill so as to reduce the overall transfer (setup) cost in the production series. Tang et al. (2000) have provided a recent application of modeling such a problem encountered in China's iron and steel complex as a VRP.

- *Satellite Systems*– A very interesting use of the VRP, as investigated by Saleh and Chelouah (2004), occurs in the architecture of global networks surveying satellite navigation systems (GNSS). A GNSS is a space-based satellite network that offers coverage for all locations around the world, and is essential in real-life applications such as early warning and disaster management, environmental monitoring, and monitoring of agriculture etc.

3.6 Operation Research Tools (OR-Tools)

Several methods are used to optimize the route length for a routing problem over the decades. In this thesis, the operation research tools (OR-tools) are being used to find optimal possible routes for MOO-TSP, VRP and CVRP techniques. OR-tools is an open source platform available for solving optimization problems. The major applications suitable for OR-tools are routing problem, constraint programming, flows problem, integer programming and so on (Ibrahim et al. (2019)).

The main objective of this platform to my thesis is that it enables me to find the optimal routes and their lengths for routing problem using python libraries.
OR-tools use the Manhattan distance to compute the distance between two points; (x_1, y_1), (x_2, y_2). The Manhattan distance sums up the absolute distance of $x \; and \; y$ coordinates

respectively. The mathematical formula can be written as:

$$S = |x_1 - x_2| + |y_1 - y_2| \tag{3.19}$$

3.6.1 Routing Options

These following options can be used by routing solvers (Google-Developers (2020b)):

Search Limits

Search limits terminate the solver after it has exceeded a defined limit, such as the maximum time or the number of solutions found.

1. *Solution Limit*– indicates the limit of solutions generated during the search.
2. *Time Limit.Seconds*– indicates the time limit of search in seconds.
3. *lns Time Limit.Seconds*– describes the time limit in seconds for the completion search for each local search neighbour.

First Solution Heuristic

There is a vast variety of first solution heuristics that are used to find the initial solution. The following first solution heuristic are provider by Google-Developers (2020b):

1. *Automatic Heuristic Strategy*– It allows the solver detect which heuristic strategy is best to use according to the requirement of the model.
2. *Path Cheapest Arc Strategy*– In this heuristic solution, the solver starts from a route ”start” node and find the cheapest possible route to connect it to the other node then it extends the route by iterating on the last node added to the route.
3. *Path Most Constrained Arc Strategy*– It is similar to path cheapest arc, however arcs are evaluated with a comparison-based selection that first favors the most restricted arc. Use the method **ArcIsMoreConstrainedThanArc()**to create a selector for the routing model.
4. *Evaluator Strategy*– It is also similar with path cheapest arc, however the arc costs are calculated using the **SetFirstSolutionEvaluator()** function passed to.
5. *Savings Strategy*– For multiple-vehicle problems, the trade between more vehicles with shorter routes and fewer vehicles with longer routes is very significant (IBM (2009-2010)). The savings of serving node a and node b in the same route, denoted $savings\ (a, b)$. and the savings heuristic generates a solution based on the given equation:

   $$savings\ (a, b) = cost(a, Depot) + cost(Depot, b) - cost(a, b) \tag{3.20}$$

   It follows the given principles:

(a) Choose an arbitrary visit, usually the depot(O), and for all pairs of nodes (i, j) to visit, compute the savings function:

$$savings_(i, j) = cost(i, O) + cost(O, j) - cost(i, j) \tag{3.21}$$

(b) Sort the arcs between nodes (i, j) according to savings (i, j) in a descending order and put them in a list.

(c) If all nodes as scheduled are visited, the goal succeeds.

(d) If there are unscheduled nodal visits, select *an untried vehicle v* from the system. If there are no untried vehicles, the unexpected nodal visits are constrained to be unperformed. If one of these visits must be performed, the goal fails.

(e) Scan the list to find an arc that can be used to create an initial partial route for *vehicle v*. If no such legal arc can be found, go to step above, otherwise remove the chosen arc from the list.

(f) Scan the list to find an arc that can be added to the start or end of the route. If no such arc can be found, go to step (c), otherwise remove the arc from the list, and repeat step (f).

6. *Sweep Heuristic Strategy*– The sweep strategy follows the given steps to build a route by sweeping around the depot (IBM (2009-2010)):

   (a) Let depot O be a site from where the vehicles leave and let A is another depot site which serves as a reference.

   (b) Sort all the nodes N in the routing plan by increasing angle $\angle AOS$ and put them in the list.

   (c) In that order the nodal visits corresponding to the depot sites in the list will be assigned to the vehicles as long as the constraints are respected.

   (d) If all vehicles have been used, the remaining visits will be required to be ineffectual. If it is important to make one of those trips, the target fails.

7. *Christofides Heuristic Strategy*– The objective of Christofides's-2/3 approximation for metric TSP algorithm is to find Hamiltonian cycle of minimum length. The algorithm builds up on the given steps (Frieze (1979)):

   (a) Construct a minimum spanning tree T.

   (b) Start the tour at an arbitrary point X and visits the nodes around the spanning tree T once counterclockwise.

   (c) Mark the visited nodes and add them to T.

   (d) Then find the Euler tour and remove the nodes visited twice.

8. *All Unperformed Strategy*– Let inactive all nodes. Only seeks a solution if nodes are optional (a disjunction constraint with a finite penalty cost is an element).

9. *Best Insertion Heuristic Strategy*– The best insertion heuristic solves the routing problem by inserting each visit, in the same manner as they were created, at the best possible place in terms of cost (IBM (2009-2010)). It is build up on the following steps:

   (a) Let all the vehicles v have empty routes and L be the list of unassigned visits.

   (b) Take a visit S in L.

   (c) Insert S in a most suitable route where the cost is minimum. If there is no feasible position, then the goal fails.

   (d) Remove S from L list and if L is not empty then go to step (b).

10. *Parallel Cheapest Insertion Solution Strategy*– This strategy build a solution by inserting the cheapest node at its cheapest position; the cost of insertion is based on the arc cost function and is much faster than best insertion heuristic strategy (Google-Developers (2020b)). The solution is made regardless of the order in which the nodes are created.

11. *Local Cheapest Insertion*– It builds up a solution by inserting cheapest node and the cost is based on arc cost function. The advantage of this strategy over parallel cheapest insertion is that the solution order is based on the manners in which the nodes are created (Google-Developers (2020b)).

12. *Global Cheapest Arc Strategy*– It connects the two nodes with cheapest route segment (Google-Developers (2020b)).

13. *Local Cheapest Arc Strategy*– It selects the node with an unbound successor and link it to the node with the cheapest route segment (Google-Developers (2020b)).

14. *First Unbound Min Value Strategy*– This solution selects an unbound node and link it to the first available node. This strategy is a combination of two heuristics strategies, choose first unbound and assign min value (Google-Developers (2020b)).

Local Search Algorithms

The local search algorithms can be applied directly to problems of satisfaction, provided we choose the appropriate function of the evaluation. These are the following local search options provider by Google-Developers (2020b) for solving routing problems are as follow:

1. *Automatic Local Search Algorithm*– The solver selects the meta-heuristic to solve the routing problem (Google-Developers (2020b)).

2. *Greedy Descent Local Search Algorithm*– In greedy descent, a neighbour is chosen to reduce an evaluating function. It is also known as hill climbing. On the other hand, if the objective is to maximize evaluation function then it is called greedy ascent. Hill climbing or greedy local search finds a better neighboring state without looking ahead of where to go next. While greed is considered one of seven cardinal sins, it turns out that greedy algorithms also perform very well.

Hill climbing usually makes fast progress towards a solution since repairing a bad state is generally relatively straightforward. At each step of the search algorithm, the current node is replaced by the best neighbor; in this case, that means if a heuristic cost estimate h is used, then find the least minimum heuristic value h (Russell (2010)).

Algorithm 1: Greedy Descent Local Search Algorithm (Russell (2010))

Result: returns a state that is local minimum
$current \leftarrow MAKE - NODE(problem.INITIAL - STATE)$;
while do
  $neighbour \leftarrow a\ minimum - valued\ successor\ of\ current$;
  if $neighbor.VALUE \leq current.VALUE\ then\ return\ current.STATE$ **then**
    $current \leftarrow neighbour$;
  end
end

3. *Guided Local Search*– Guided local search moves out of a local minimum by reimbursing particular features of the solution it considers should not be present in a near-optimal solution. It defines a modified objective method, connected to these features with a set of penalty terms. The usual local search method is then invoked to boost the objective function that is being augmented (Kilby et al. (2002)). The local search and penalty term update process can be repeated as much as required.

   The guided local search monitors penalties imposed by a penalty vector p. p_i is the amount of times i have been penalized so far. Assuming $O(S)$ is the original objective function for the problem, the guided local search defines an augmented objective function (Kilby et al. (2002)):

$$O'(S) = O(S) + \lambda \sum_{i \in N} f_i(S) p_i c_i \tag{3.22}$$

   where λ is penalty factor and need local search algorithm that minimizes it. Therefore the user must provide $Local\ Search(S, p)$ procedure which performs a local search starting with solution S and returns a new solution. The improvement is made in relation to the augmented objective O'.

4. *Simulated Annealing*– The simulated annealing algorithm is a method of optimization that imitates the slow cooling of metals, defined by a linear reduction in the atomic movement that reduces the number of lattice defects until a lowest energy state is reached (Aleksendrić and null Carlone (2015)). Similarly, the simulated annealing algorithm produces a new potential solution (or neighbor of the current state) to the problem considered by altering the current state, according to a predefined criterion, at each virtual annealing temperature; The acceptance of the new state is then dependent on the Metropolis criterion being satisfied, and this process is elucidated until convergence is achieved. During the annealing process, each new solution x_j was accepted with a temperature-dependent probability P_T given by

(Aleksendrić and null Carlone (2015)):

$$P_T = \begin{cases} 1 \quad if\ f(x_j) \leq f(x_i), \\ e^{\frac{f(x_j)-f(x_i)}{kT}} \quad if\ f(x_j) \geq f(x_i), \end{cases} \tag{3.23}$$

Where T is the current temperature, k is the Boltzmann constant, and $f(x_i)$ and $f(x_j)$ are the fitness scores of the worst vertex x_i and the best simplex vertex, respectively. The temperature for annealing varied within a range of $[T_{in}, T_{fin}]$, following a predefined cooling rate c and a predefined cooling scheme.

5. *Tabu Search*– Tabu search is a local search algorithm which limits the feasible neighborhood by excluded neighbours. Tonga Island Aborigines used the word tabu (or taboo) to denote objects that can not be accessed because they are sacred (Edelkamp and Schrödl (2012)). Those states are contained in a data structure called a tabu list when searching tabu. They help to prevent being stuck in an optimal locale.

   If all neighbours are tabu, a move that worsens the importance of the objective function to which an standard, deepest decent method will be stuck is embraced. A refinement is the aspiration criterion: The tabu constraint is ignored if there is a step in the tabu list that improves all previous solutions (Edelkamp and Schrödl (2012)).

Algorithm 2: Tabu Search Algorithm (Edelkamp and Schrödl (2012))

Input: State Space min. problem
Output: State with low evaluation
$Tabu \leftarrow [s]$;
$best \leftarrow s$;
$u \leftarrow s$;
while *Terminate* **do**
s $\leftarrow select(Succ(u)/Tabu)$;
if $f(v) < f(u)$ **then**
best $\leftarrow u$;
$Tabu \leftarrow refine(Tabu)$;
$Terminate \leftarrow Update(Terminate)$;
$v \leftarrow u$ **Return** $best$**;**

6. *Objective Tabu Search*– Objective Tabu search algorithm is a simple method of descent, aimed at minimizing a $f(x)$. Such a method only moves to those neighboring solutions that improve the current objective function value and end when no improving solutions are found. The final x obtained by a descent method is considered a local optimum, because it is at least as good as or better than all neighborhood solutions (Glover and Martí (2003)).

   The inevitable shortcoming of a descent approach is that in most situations such a local optimum won't be a global optimum, i.e. it won't normally reduce $f(x)$ above all $x \in X$. Tabu search allows moves that disintegrate the current target function value and chooses moves from a modified $N * (x)$ neighbourhood. The general composition of $N * (x)$ is responsible for the short and long term memory structures. The adjusted neighbourhood, in other words, is the product of establishing a selective overview of the states identified during the search.

The main difference between Tabu search and Objective Tabu search algorithm is that the objective tabu search uses tabu algorithm on the solution's objective value to prevent local minima (Google-Developers (2020b)).

Chapter 4

IoT-based Conceptual Model

In this chapter, a conceptual model is proposed to address the issues in the current practices and infrastructure.
A conceptual model can be defined as a simplified representation of a system used to describe its main physical features and principal processes (Helmig (1997); Tatomir et al. (2018)). I propose a conceptual model of a smart and sustainable solid waste management system based on IoT, in what follows. The model offers a Norwegian municipality a blueprint of a future system design that can be easily integrated into the existing infrastructure and practices of the municipality. It illustrates all the factors needed to develop a smart and sustainable IoT-based waste management system. Several stakeholders for instance, municipality, service providers, waste truck drivers and citizens, are involved in this model. The data transfer technology such as LoRaWAN are proposed to use for connecting the stakeholders with the database. In addition to that the truck drivers are facilitated with the display screens having GPS technology and GIS information of waste bin mounted in the municipality as shown in **Figure. 4.1** (Nasar et al. (2020a)). As for the residents, they are

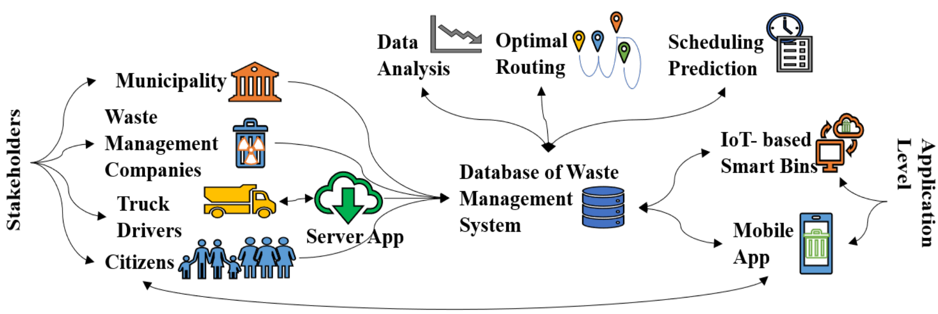

Figure 4.1: A conceptual model of a smart and sustainable SWMS (Nasar et al. (2020a))

linked to the smart waste bin application and can communicate with it through their smart phones. The service provider companies get direct access to the database unit in such a

way that it is profitable for their business. All these stakeholders communicate through the same platform which makes communication smarter and efficient.
The major challenge in current practice is for the truck drivers to get the job done without having optimal solutions. After applying the proposed IoT-based SWM system, this problem can be solved by actively using the sensor capabilities combined with the use of KPIs and optimization algorithms to achieve a reduced cost, distance, and time. An obvious consequence of implementation of the conceptual model will be a decrease in CO_2 and other gases emissions in the atmosphere.

4.1 IoT-based smart sensor bins

Sensor-based bins are subject to several problems in current practices, due to multiple service providers using different systems for data transmission and data handling etc. Another problem faced is the poor battery life. **Figure. 4.2** illustrates how IoT-based smart sensor bins can be designed to overcome current issues. The proposed solutions connect ultrasonic sensors, Infrared sensors, solar batteries and RFID with IoT controls for capturing and transmission of data. The machine learning techniques can be used in the IoT-cloud to predict waste bin fill-up volume in future. Optimization algorithms can be used to find the best routes for the truck drivers by taking into account total waste management.

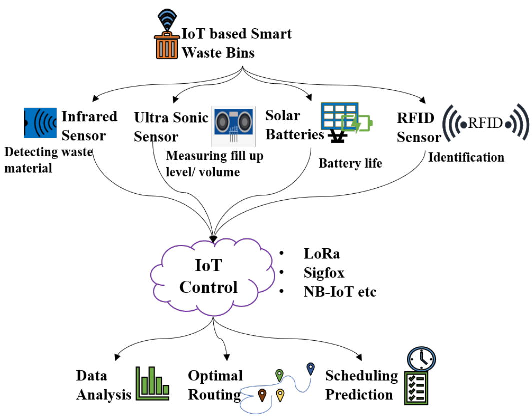

Figure 4.2: Sensor-based smart bins (Nasar et al. (2020a))

The cost of waste management can be defined for N number of bins as (Nasar et al. (2020a)):

$$W_{total} = \sum_{i=1}^{N} W_i^c + \sum_{i=1}^{N} W_i^t + \sum_{i=1}^{N} W_i^P + \sum_{i=1}^{N} W_i^d + \sum_{i=1}^{N} W_i \tag{4.1}$$

where W_i^c is the cost for waste collection, W_i^P is the processing cost, W_i^t is the transportation cost and W_i^d is the disposal cost for k number of unused or produced waste material after processing and W_i is the constant cost that depends on other constraints such as accident, maintenance of waste collection center, transfer station and trucks. The profit gain by N number of sources, can be calculated as:

$$W_{management}(profit) = \sum_{i=1}^{p} R_i - W_i \tag{4.2}$$

where R_i is achievable cost by recycling materials, sales of compost products and electricity sales. Generally, the objective of a smart SWMS is to develop methods that will increase the overall profit $W_{management}(profit)$ associated with the system by reducing cost of collection and transportation $\sum_{i=1}^{N} W_i^c$ and $\sum_{i=1}^{N} W_i^t$. The waste collection and transportation problem for a waste management system is solved in the next chapters. Multi-Objective Traveling Salesman Problem (MOO-TSP), Vehicle Routing Problem (VRP) and Capacitated Vehicle Routing Problem (CVRP) are proposed and implemented for this purpose. The objectives for defined problem is to reduce cost, traveling time, traveling distance and fuel consumption. It achieves the sustainable development goals SDG 11 and SDG 12 related to the waste management system.
In the proposed IoT-based smart sensor bin model, ultrasonic sensors are embedded to sense the waste volume present in the waste bins. While infrared sensors are proposed to sense the waste material type and RFID identifies the location of waste bins. These sensors will help to achieve correct sorting and correspondingly increase the service provider's revenue. As IoT-based devices are facing battery's life as a major barrier for their widespread, the solar battery are proposed as an alternative solution. Developments within these types of batteries provide suitable energy in a very sustainable way for all device activities. Furthermore, developing low-power consuming hardware and scheduling the sleep mode for the proposed waste management system is extremely necessary. As in several devices of electronics, the sleep mode is embedded to allow energy savings when data is not measured, processed, or sent by a sensor-based bin.

4.2 Smart Waste Bin Application

In the proposed model, the application level is divided into two parts. One part constitutes IoT-based smart waste bins, and the second part is smart phone application. To make the IoT-based SWMS user friendly, a smart waste bin application is proposed to interact and connect customers with the service providers.

4.2.1 Features

Customer End

In the investigated municipality, the service providers offer a mobile app with limited-possibility smartphone app for consumers. Features of an improved application, **Figure. 4.3**, can be:

- *Waste volume status*– The app will alert the customers about the amount of waste volume which will help the customer determine whether to go out and dump the garbage or not.

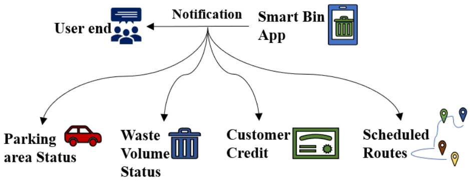

Figure 4.3: User end of smart waste bin application (Nasar et al. (2020a))

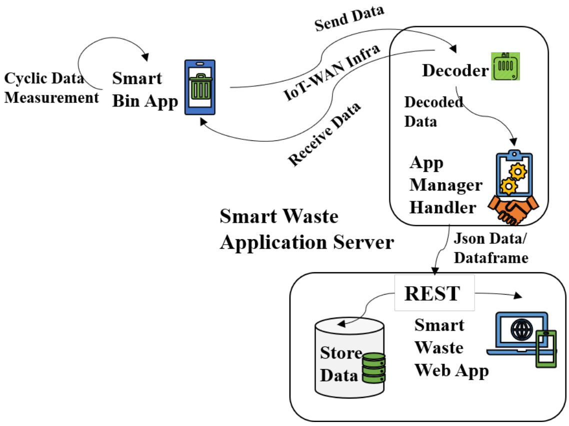

Figure 4.4: Smart waste bin application server (Nasar et al. (2020a))

- *Scheduled route*– The app will inform waste trucks about the expected trips, so the residents can place their waste bins outside.

- *Parking area status*– A vast area is dedicated to waste trucks specifically for collecting waste in current infrastructure. Instead of this practice, customers can be notified about the schedule of the waste trucks in the prototype app, thus orienting the customer as to when certain areas can be used for regular parking.

- *Customer credit*– There are different waste bins for various kinds of waste given to consumers in the current infrastructure. There is a need to treat these different types of waste differently. Food waste, for example, needs to be drained more often than other kinds of waste. Similarly, the household waste is not deemed to be recycled material and should therefore typically be sent to landfill sites. Paper, plastic and other types of waste are usually sent to different recycling plants for recycling. The conceptual model incorporates the idea of giving away customer credits in either the context of bonus points or other appreciating messages to inspire customers to behave properly relevant to waste sorting.

Smart Application Server

A smart waste management framework can be developed based on the data transfer technologies (Kamm et al. (2020)).The framework shown in **Figure. 4.4** can be developed using various Python libraries. Implementation can be subdivided into three parts:

1. A smart bin app based on sensors that detect waste material and senses the amount of waste filled up in the bins. The data analysis can be performed through the data collected,The data analysis can be performed through the data collected, as shown in **Figure. 4.5**. The amount of waste before and after emptying the waste bins is shown in this Figure.Sensor data are subject to data processing from two types of waste, i.e. paper and household wastes.

2. The second aspect is data synchronization between the smart device based on the sensor, a decoder, and an application manager via an IoT-WAN infrastructure suggested to create the device.

3. The final component is a database for smart waste applications.

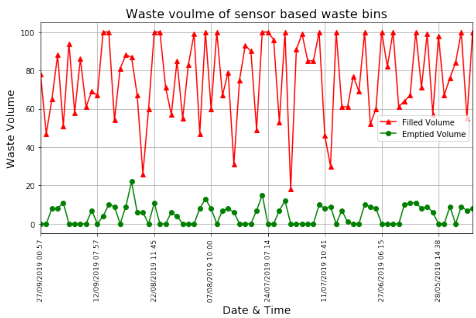

Figure 4.5: Measurement of waste volume in sensor-based bins (Nasar et al. (2020a))

Chapter 5

Optimization models

Selective waste collection and transportation are major expenditures of a city's waste management system. Various scenarios for route planning are taken into consideration to improve time and cost utility. This thesis provides an auxiliary management system for optimal waste collection. In addition to that the provided data is analysed for scheduling future waste collection trips. The proposed solution is considering the challenges such as road conditions, traffic, fuel consumption and toxic gases emissions etc.

In a situation like the investigated municipality, smart decisions rely on the specifics of the landscape and require geographical information to help differentiate between one place and another, and to make appropriate decisions for that location (Del Borghi and Gallo (2009)). Recent advances in ICTs have opened up enormous opportunities for data analysis of communication in spatial and temporal manner. Information representing the real world application can be stored and processed for later presentation in a simplified form to fit suitable needs. In the solid waste management system (SWMS), the geographical information of the city is visualized through Google Maps application.

The Google Maps application own Geo-analytical tools and can preform network analysis which enables traffic and driving queries. Google Maps include rich, multi-layered maps that are proved simple to integrate with our data and data from third parties. It also provides several features such as static maps, dynamic maps, street view, routes, directions, distance matrix, road, time zone, places details and so on, that makes it a relevant and practical tool in a system development (null Ppc Land (February 15, 2020)).

Data obtained from standard underground waste bins and sensor-based underground waste bins of the investigated municipality, is used to build the waste generation model as shown in **Figure. 5.1**. In general, an optimized waste collection and transportation scheme efficiently lowers waste collection and transportation costs and helps to decrease transportation trip's route length.

5.1 Multi-Objective Optimization Traveling Salesman Problem (MOO-TSP)

The following are significant considerations relating to the investigated case of waste collection with the help of multi-objective travelling salesman problem (MOO-TSP):

- *Number of Trucks*– The route is calculated in MOO-TSP by one truck at a time for selective waste collection, as shown in **Table. 5.1**.
- *Starting and Stopping Point*– The drivers have priori knowledge of the start point and end point (generally depot site) besides the number of stop points/nodes.
- *Selective Waste type*– In the case under investigation, different types of sorted waste collection bins are located at each residential area, for instance food waste bins, household waste bins, paper and cardboard bins, plastic bins, glass and metal waste bins. In this scenario dedicated trucks are available for each specific waste collection.

The mathematical representation of MOO-TSP is:

$$min \begin{cases} f_1 = \sum_{i,j=1} i \neq j^N d_{ij} c_{ij} \\ f_2 = \sum_{i,j=1} i \neq j^N t_{ij} c_{ij} \end{cases} \tag{5.1}$$

where

$$\begin{cases} c_{i,j,i \neq j} = 1, \; if \; b_{i,j} \geq \gamma \\ c_{i,j,i \neq j} = 0, \; elsewhere \end{cases} \tag{5.2}$$

Where d_{ij} is the distance between nodes $i \; and \; j$, and c_{ij} is the collection cost. If the nodes

Table 5.1: Traveling time and distance covered by a vehicle with MOO-TSP

Traveling Time	2.58 hours
Traveling Distance	136.47 km
Route for bins b_N	$0- > 3- > 1- > 9- > 5- > 2- > 4- > 7- > 6- > 8- > 0$

does not belong to the optimal route between i^{th} node and j^{th} node then the $c_{ij} = 0$. The optimisation model represents the best shortest route to collect waste with minimal travel time, travel distance and driving cost as shown in **Figure. 5.2**. The following steps describes the MOO-TSP method uses in this case:

1. Import the required PYTHON libraries for MOO-TSP. For instance, googlemaps, os, pandas, or tools and so on.
2. Obtain the API keys for Google maps platform. Google APIs offers various services such as maps, places, street, route, traffic, geographical locations etc (Google-Developers (2020a)).

Figure 5.1: Waste bins locations with unique IDs and waste volume(Nasar et al. (2020b))

3. Pin several locations. In this investigated case, the location of sensor-based waste bins and standard underground waste bins in the municipality is pinned on the map as shown in **Figure. 5.1**. Each waste bin location has hover data with its unique ID and waste volume.

4. To calculate route length between different nodes/bins, the google distance matrix API is used. It provides several measures such as distance, time (Google-Developers (2020b)).

5. In this optimization model, Greedy descent algorithm is used by route solver to find the optimal path with minimum distance and minimum time.

6. The calculated path for pinned locations is visualized on Google Maps as shown in **Figure. 5.1 & 5.2**.

The APIs are set of programming tools that enables communication between different programs or operating systems (OS), and help the developers to build their programs. In this case, several APIs are used for various purposes such as Google Distance Matrix API, Google Map API and so on (Google-Developers (2020a)).
The route is configured according to a waste volume threshold. The threshold γ is set according to existing practices, i.e. when the amount of waste meets or exceeds the specified threshold γ. The γ will be determined by the amount of waste in the bin over the total lid openings number. The services providers assign the waste collection task to the truck drivers accordingly. The optimization model achieves the following keys performance indicators (KPIs) targeted at SDGs (Nasar et al. (2020b)):

- Reduction in fuel consumption.
- Reduction of CO_2 emissions and other gases in environment.
- Reduction in unnecessary road traffic.

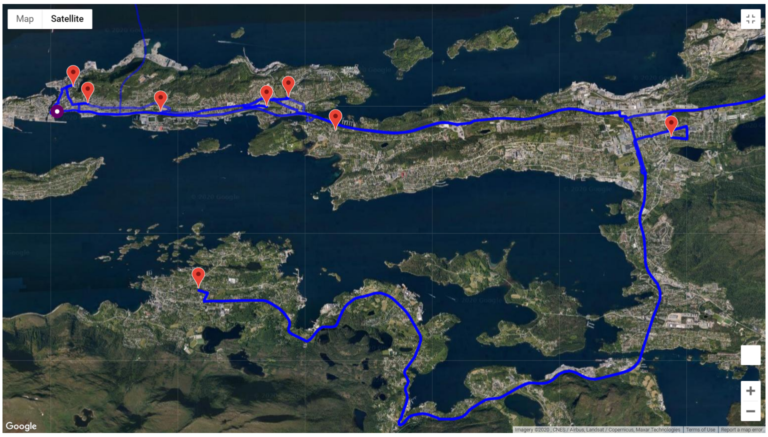

Figure 5.2: Optimized shortest route length with estimated distance and time via multi-objective TSP (Nasar et al. (2020b))

- Improved cost and time effectiveness.
- Minimization of route length.
- Reduction in the trips for truck drivers due to optimal planning solutions.

5.2 Vehicle Routing Problem(VRP)/multiple-TSP

Besides MOO-TSP, the waste collection and transportation problem is addressed via vehicle routing problem which is also known as mTSP. In such cases, several number of vehicles are taken into consideration before solving routing problem. The following steps are performed to solve VRP:

1. Develop the problem solution in the same manner as MOO-TSP such as import libraries, data and location.
2. There are more than one vehicle available for waste collection.
3. Meta-heuristic algorithms specifically greedy descent algorithm, is used for routes calculation.
4. The routes can be calculated for both minimum time and minimum distance with the help of google distance matrix API.

Let $G = (V, E)$ where $V = v_1, v_2, ..., v_N$ is a set of nodes representing cities with the depot location at node v_1 and E is the set of edges. With every edge (i, j) $i \neq j$ is associated with a non-negative distance matrix $C = c_{ij}$. In some cases, c_{ij} can be interpreted as traveling time or traveling cost. In addition, assume that there are N available number of vehicles based at the depot. The mathematical representation of VRP (Dugdhe et al. (2016)):

Figure 5.3: Optimized shortest routes with minimum distance through vehicle routing problem (VRP-distance)

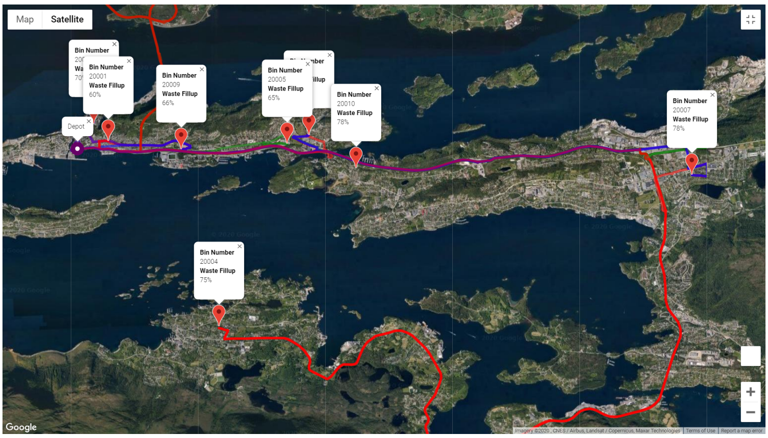

Figure 5.4: Optimized shortest routes with minimum time through vehicle routing problem (VRP-time)

Let x_{ij} be an integer variable which may take value $\{0, 1\}, \forall \{i.j\} \in E\{\{0, j\} : j \in V\}$ and value $\{0, 1, 2\}, \forall \{0, j\} \in E, j \in V$. Note that $x_{0j} = 2$ when a route including the single city j is selected in the solution. The VRP can be formulated as the following integer program:

$$Min \sum_{i \neq j} x_{ij} d_{ij} \tag{5.3}$$

$$Min \sum_{i \neq j} x_{ij} t_{ij} \tag{5.4}$$

Subject to:

$$\sum_j x_{ij} = 1, \forall i \in V, \tag{5.5}$$

$$\sum_i x_{ij} = 1, \forall i \in V, \tag{5.6}$$

$$\sum_i x_{ij} \geq |S| - v(S), S : S \subseteq V1, |S| \geq 2, \tag{5.7}$$

$$x_{ij} \in 0, 1, \forall i, j \in E; i \neq j \tag{5.8}$$

In the above equations (5.9), (5.10), (5.11) and (5.12) define a modified assignment problem i.e. assignments on the main diagonal are prohibited. Constraints in equation (5.13) are sub-tour elimination constraints: $v(S)$ is an appropriate lower bound on the number of vehicles required to visit all nodes of S in the optimal solution.

Table 5.2: Estimated traveling time covered by vehicles v_N

Constraints	Vehicle 0	Vehicle 1	Vehicle 2
Traveling Time (in Hours)	1.12	1.11	1.108
Routes	$0- > 9- > 3- > 0$	$0- > 2- > 8- > 1- > 4- > 7- > 0$	$0- > 6- > 5- > 0$

Table 5.3: Estimated traveling distance covered by vehicles v_N

Constraints	Vehicle 0	Vehicle 1	Vehicle 2
Traveling Distance (in km)	61.46	43.45	60.64
Routes	$0- > 5- > 0$	$0- > 7- > 0$	$0- > 2- > 8- > 4- > 1- > 6- > 3- > 9- > 0$

Table. 5.2 & 5.3 describes the obtained routes for each vehicle with constraints such as minimum time and minimum distance. To generate the routes, Google Distance Matrix API is used. This API has matrix element limitations for certain accesses. Different colors mentioning routes for different vehicles, as shown in **Figure 5.3 & 5.4**.

5.3 Capacitated Vehicle Routing Problem (CVRP)

To solve waste collection problem, there are certain constraints that needs to be taken into consideration. CVRP solution build on the following steps:

- Add the libraries, map and locations of bins on map.
- In addition to the route calculation for vehicles. Consider the capacity of each vehicle for waste collection.
- Take demand of each bin into account.

- The route will be calculated according to constraints with minimum time and minimum distance.

Let $G = (V, E), d, q \; and \; Q$ define a CVRP instance having nodes v_0 as the depot and the remaining nodes in N as customers.

$$Minimize \sum_{e=(u,v)\in E} d(e)x_e \tag{5.9}$$

Subject to:

$$\sum_{e\in\sigma(\{v\})} x_e = 2, \forall u \in N\{0\}, \tag{5.10}$$

$$\sum_{e\in\sigma(\{0\})} x_e \geq 2k^* \tag{5.11}$$

$$\sum_{e\in\sigma(S)} x_e \geq 2k(S), \forall S \in N\{0\}, \tag{5.12}$$

$$x_e \leq 1, \forall e \in E\sigma(\{0\}) \tag{5.13}$$

$$\sum_{l=1}^{P} q_l^e \lambda_l - x_e = 0, \forall e \in E, \tag{5.14}$$

$$x_e \in \{0, 1, 2\}, \forall e \in E, \tag{5.15}$$

$$\lambda_l \geq 0, \forall l \in \{1, ..., p\} \tag{5.16}$$

where x_e represents the number of times that edge e is traversed by a vehicle and its value is assumed 2 if e is adjacent to the depot, corresponding to a route with a single customer. λ_l usually associated with possible routes. Each λ_l parameter is associated with one of all the possible $q - routes$ satisfying the capacity constraint. While a $q - route$ is the distance between depot and the node with maximum demand value Q and back to the depot.

Table 5.4: Estimated traveling distance covered by vehicles v_N with capacity Q_k where $k = i$

Constraints	**Vehicle 0**	**Vehicle 1**	**Vehicle 2**
Capacity of Vehicles (in tons)	15	15	15
Traveling Distance (in km)	44.43	56.39	64.2
Routes	$0- > 7- > 2- > 0$	$0- > 3- > 9- > 1- > 4- > 0$	$0- > 6- > 5- > 8- > 0$
Waste Load (in tons)	$0- > 9- > 15- > 15$	$0- > 4- > 5- > 7- > 12- > 12$	$0- > 4- > 7- > 15- > 15$

Data driven smart waste collection is categorized by highly adaptive routes, considering the demand and filling level of each waste bin. The above tables illustrate the obtained routes for each waste truck depend on different constraints. Additionally the visualization of waste on map helps the stakeholders to detect the current and emerging problems in the city, that will help in decision making and future developments. It can clearly conclude from the above calculated routes that each optimization technique is beneficial under

Figure 5.5: Optimized shortest routes with minimum time through capacitated vehicle routing problem (CVRP-time)

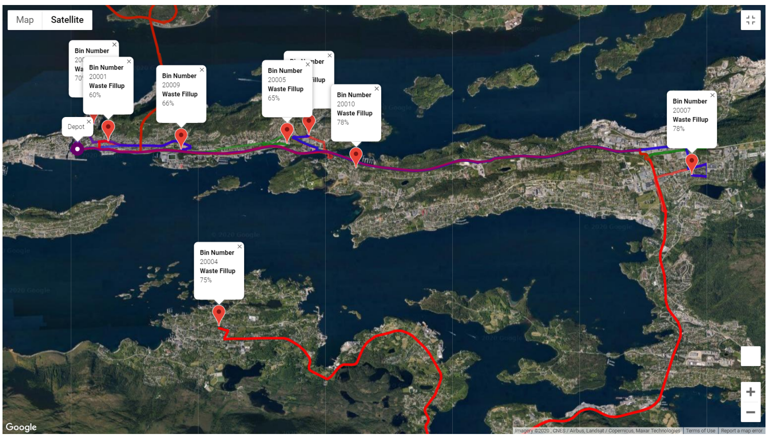

Figure 5.6: Optimized shortest routes with minimum distance through capacitated vehicle routing problem (CVRP-distance)

Table 5.5: Estimate traveling time covered by vehicles v_N having capacityQ_k where $k = i$

Constraints	**Vehicle 0**	**Vehicle 1**	**Vehicle 2**
Capacity of Vehicles (in tons)	15	15	15
Traveling Distance (in Hours)	0.884	1.20	1.17
Routes	$0->7->2->0$	$0->3->9->1->4->0$	$0->6->5->8->0$
Waste Load (in tons)	$0->9->15->15$	$0->4->5->7->12->12$	$0->4->7->15->15$

described circumstances such as in case of multi-objective problem for selective waste collection, MOO-TSP will be the best choose among others. In case of waste collection and

Table 5.6: Estimated traveling distance covered by vehicles v_N having capacity Q_k where $k \neq i$

Constraints	**Vehicle 0**	**Vehicle 1**	**Vehicle 2**
Capacity of Vehicles (in tons)	10	20	15
Traveling Distance (in km)	63.56	49.94	55.9
Routes	$0->6->5->0$	$0->4->7->2->0$	$0->3->9->1->8->0$
Waste Load (in tons)	$0->4->7->7$	$0->5->14->20->20$	$0->4->5->7->15->15$

Table 5.7: Estimated traveling time covered by vehicles v_N having capacity Q_k where $k \neq i$

Constraints	**Vehicle 0**	**Vehicle 1**	**Vehicle 2**
Capacity of Vehicles (in tons)	10	20	15
Traveling Distance (in Hours)	1.16	1.02	1.17
Routes	$0->3->9->1->0$	$0->2->4->7->0$	$0->6->5->8->0$
Waste Load (in tons)	$0->4->5->7->7$	$0->6->11->20->20$	$0->4->7->15->15$

scheduling trips for various truck drivers, the best option is VRP and in case of waste collection on demand and limited vehicle capacity, CVRP will outperform others.

Chapter 6

Discussion & Conclusion

6.1 Discussion

Based on the data about waste volume, advanced optimization methods and further services can be offered. Additionally, new business opportunities and markets can be created. Most promising emerging opportunities are the following:

- Advent route optimization, and highly adaptive and flexible route.
- Waste collection on demand.
- Setting a threshold for prioritizing emptying waste bins. Each emptying cycle per waste bin depends on filling behaviour
- Emptying food waste bins more frequently than other waste bins to avoid odor and unhygienic environment.
- Creation of waste maps with waste bins collection, waste volume in each bin and route information for waste collection.
- Smart waste bin placement management.
- Change existing pricing and business models of waste collection services.
- Adapt an IoT-based smart and sustainable waste management.
- Connect and inter-linked all the stakeholders on single platform

These mentioned points help to detect the problem regions of a municipality regarding the solid waste management system (SWMS). The maps with waste bins location and waste volume reduce the problem of overfilled waste bins. One of the major issue in the current practices is overlooked or delayed trips to the waste bins. The proposed conceptual model of IoT-based smart and sustainable SWMS promises to tackle this problem with the help of sensors data.

It will be helpful for future waste bin placement management. In areas where the demand is more than supply, for example, the waste bins are filling up frequently, then the smart and sustainable SWMS provides the solutions by mounting IoT-based smart waste bins. The volume and capacity of a container can vary accordingly. The filling behaviour of bins detected from sensor data will help in future installments of smart bins.
The process of waste collection and transportation has been the same for decades. The truck drivers adapt the traditional way to collect waste from different locations regardless of the optimal way. These practices are time inefficient and cost ineffective. The proposed solutions overcome this problem by giving optimal solutions with minimum time and minimum distance.
The optimal data driven solutions proposed in this thesis along with the conceptual model of IoT-based SWMS leads towards:

- Reduction in the number of employees for waste collection services.
- Reduction in traveling distance and traveling time.
- Reduction in overall workload and working hours with the decreased number of unnecessary trips.
- Reduction in fuel consumption.
- Reduction in CO_2 and other gases emissions.
- Smart and sustainable municipality with IoT enabled waste bins.
- Reduction in unnecessary traffic on roads. It will increase the lifetime of vehicle tyres and improve the road conditions.
- Increase in accountability in waste generation and improved communication between municipalities.

Hence, the proposed solutions achieve the sustainable development goals (SDGs) for a waste management system provides by U4SSC. The KPIs achieved by the solutions are:

- SDGs 11.6.1 stated as: “Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities” (SGDs (2020)).
- Strongly supports SDGs 12.4, stated as: “By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment” (SGDs (2020)).
- Supports SDGs 12.5 stated as: “By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse”

Nowadays, the Norwegian municipalities are self-responsive for their waste management or assign third-party service providers. In this thesis, the domestic waste bins are investigated and an IoT-based conceptual model is proposed to improve the current practices and infrastructure. The environmental company responsible for providing services regarding a waste management system including waste collection and transportation, has several types of waste bins as shown in the above chapters. The optimization solutions are based on the data collected from the currently available sensor waste bins and underground waste bins. The proposed solutions are cost effective and time efficient. These solutions will help the existing practices and infrastructure for future placement of waste bins according to the demand of regions and inhabitants.

6.2 Conclusion

For past few years the core processes of waste collection and transportation trends have been remained unchanged. One of the major issues is the absence of an optimal route for waste collection and transportation. In addition to the absence of smart solutions, the over filled bins or overlooked trips for waste collection is another major factor to address for a smart and sustainable solid waste management system (SWMS).
In this thesis, the methods based on IoT technologies are proposed not only to improve the waste management system but also to give a profitable business model to the service providers. Several optimization techniques are proposed for various scenarios. The solution of a particular situation depends on the demand for waste collection. These data driven techniques can easily be adopted by current practices and can incorporate with future systems.
In this thesis, I contribute to the ongoing discussion about smart and sustainable SWMS for households in the smart sustainable cities (SSC) by:

1. A real world case study and implementation of sensors bins in a challenging smart sustainable city application field.
2. Sharing my experience from about a year of project involvement and summarizing the main findings.
3. Giving an overview of the current practices and infrastructure.
4. Proposing the solutions for the problems faced by current practices and infrastructure.
5. Evaluating the results from sensor's data.
6. Calculating the optimal routes for different number of waste trucks.
7. Sharing my ideas for improving the waste management process in order to establish data driven collection and transportation processes.

The proposed solutions for route optimization and conceptual model for SWMS are not limited to the waste sector only but it can also contribute to other IoT application fields with same challenges and hurdles. The optimization algorithms proposed in this thesis,

Table 6.1: Comparison of estimated traveling time (in Hours) between current practices and the proposed data-driven optimal solutions

Route	Waste type	Waste bins b_N	Curr. sol.	TSP	VRP		CVRP	
					trucks	time	trucks	time
1	Residual	b_1, b_2, b_3	2.06	0.4036	v_1	0.254	v_1	0.254
					v_2	0.133	v_2	0.133
2	Paper	b_1, b_2, b_3, b_4	2.50	1.299	v_1	0.329	v_1	0.329
					v_2	1.02	v_2	1.02
3	Paper	b_1, b_2, b_3, b_4, b_5	3.00	2.166	v_1	1.098	v_1	1.098
					v_2	1.112	v_2	1.112
4	Residual	b_1, b_2, b_3, b_4, b_5	3.00	2.166	v_1	1.098	v_1	1.098
					v_2	1.112	v_2	1.112
5	Paper	b_1, b_2	1.50	0.312	Null		Null	

can be used in many major applications such as crew scheduling, mission planning and so on.
Regarding the waste management, we need to change our attitude. Each single piece of plastic or each sheet of paper, has a certain importance. It is not appropriate that waste materials pollute oceans and environments, with drastic environmental consequences. Hence it is important to increase the performance of waste management systems. Major companies and brands must use alternative sustainable solutions rather than using plastic bags. We ,as individuals, have a responsibility towards our ecosystem and environment. Therefore, each one of us must think before producing any litter.
In the **Table. 6.1**, the traveling time is estimated and comparison is made between current practices and developed data-driven solutions. The results clearly show that the optimal developed solutions are cost effective and time efficient. In the given table, the data is taken from the routes assigned for waste collection task from certain bins in current practices and compared them with the estimated time obtained from the proposed optimization algorithms. Route 5 has two assigned bins, therefore it is preferable to calculate route with MOO-TSP rather than allocating more than one vehicle for such a short route.

6.3 Future Recommendations

The waste management processes including collection, sorting, recycling and transportation, need to be improved to attain sustainable development goals (SDGs) of smart sustainable cities (SSC) . In this thesis, the main focus was waste collection and transportation processes. I investigated the local municipality and proposed a conceptual model to improve the core processes of waste management with the implementation of IoT technologies. Furthermore, this study provides solutions for optimal and effective waste collection and transportation by proposing different optimization algorithms for certain circumstances.
Future opportunities are offering promising services such as predictive analysis and advanced waste sorting. These services can be achieved with the help of IoT based commu-

nication within the system. The correct waste sorting can be achieved either by cameras installation in the bins or using infrared sensors to detect the waste materials. The predictive analysis can be done by ultrasonic sensor to detect the waste volume and from that data by studying the behaviour of each waste bin. The study of inhabitants behaviour can also help to improve a solid waste management system (SWMS). Several variables and information such as age of citizens, living conditions, weather information, population can effect the overall waste production. All these variables can be considered for future developments.

In this thesis, the proposed optimization algorithms for route planning are multi-objective traveling salesman problem (MOO-TSP), conventional vehicle routing problem (VRP) and capacitated vehicle routing problem (CVRP). The solution can be modified by adding a time window constraint in VRP (VRPTW).

In here, the optimization techniques are used for routing and vehicle allocation. These algorithms can be used for various applications such as print scheduling, satellite systems, mission planning and so on. Other than that in this research work, the focus was on a domestic waste management system. This data-driven SWMS can easily be adopted by other service providers for waste collection and treatment tasks such as industrial waste collection, commercial waste collection or waste collection from public bins.

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Appendix

- **Case I:** Pertaining to the development of smart and sustainable waste management system, an IoT-based conceptual model is proposed and a research paper based on the proposed conceptual model is written, title: ”A Conceptual Model Of An IOT-Based Smart And Sustainable Solid Waste Management System: A Case Study Of A Norwegian Municipality” (Nasar et al. (2020a)). In this paper, IoT-based conceptual model is proposed that connects all the stakeholders in the development and deployment of smart sustainable city (SSC) technologies.

- **Case II :** For waste collection and transportation, a multi-objective TSP approach is proposed to find optimal shortest routes with minimum distance and time. It also uses the collected waste bin's data to predict the waste volume in each waste bin for future scheduling of waste trucks and drivers. Another research paper based on the proposed approaches is written, named as: ”An optimized IoT-based Waste Collection and Transportation: A Case Study of a Norwegian Municipality”. The benefits of implementing this proposed system are illustrated along with comparison of existing practices and proposed solutions. The Papers regarding these cases are attached in here.

- **Case III:** The waste collection and transportation problem on a large scale, is generally addressed as multiple traveling salesman problem (mTSP) or vehicle routing problem (VRP). To solve the route length problem with multiple constraints and objectives, I proposed the solution to sovle the VRP and CVRP with greedy descent algorithm. For visualization of calculated routes with different numbers of vehicles, google maps API and google distance matrix API is used. I am planning to write a research paper based on these approaches.

A CONCEPTUAL MODEL OF AN IOT-BASED SMART AND SUSTAINABLE SOLID WASTE MANAGEMENT SYSTEM: A CASE STUDY OF A NORWEGIAN MUNICIPALITY

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KEYWORDS

Conceptual Model, Internet Of Things, Smart And Sustainable, Infrared Sensors, Ultrasonic Sensors, RFID Sensors, Iots Based Smart Bins, Smart Bin App, Data Transfer Technologies, LoRaWAN

ABSTRACT

The core processes of waste management have been changed during the last few decades. Through advanced technologies, sensors, cameras, actuators, IoT controls, data driven and data transfer technologies, the old and insufficient processes for waste management can be replaced. In this paper, we propose a conceptual model for an IoT-based smart and sustainable waste management system for a Norwegian municipality. The model illustrates all the aspects needed to develop a smart IoT-based waste management system. A Norwegian municipality constituted our case study. Our conceptual model proposed here, provides a design solution with data analysis in such a way that it can easily be adopted by the current infrastructure and practices of the municipality. Finally, features of a prototype system are suggested.

I. INTRODUCTION

With the advent of recent advancements of smart devices, the abstraction of connecting everyday objects via the existing networks has become highly favorable. The Internet of things (IoTs) is an arrangement of web related items that can accumulate and exchange data. A result of the evolution of conventional networks that link billions of connected devices together defines a world where almost anything can connect and interact in a smarter fashion than before (Silva, et al. 2018). Technological advancements in ubiquitous computing (UC), wireless sensor networks (WSN), and machine-to-machine (M2M) communication have further strengthened the notion of IoT (Vaisali, et al. 2017). Moreover, linked devices share their information and access authorized information of other devices to support contextual decision making. As a result of these developments, new business areas and opportunities have originated, summarized into various smart city and smart factory concepts. Due to the dramatic urbanization all over the world, the continuous developments into smart cities have become the main concern in the past few decades. Information and communication technology (ICT) have made cities efficient in several aspects. However, incorporating only ICT does not fully interpret the smart city concept. In general terms, a smart city is an urban environment that utilizes ICT and other related technologies to improve performance efficiency of regular city operations and quality of service provided to urban citizens (Kamm, et al., 2020). IoTs link various areas/operations of a smart city into holistic entities. In Figure 1, the concept of an IoT enabled smart and sustainable city is illustrated. In a smart and sustainable city, all the aspects of a society are connected through shared IoT clouds. This enables the use of the new opportunities offered by IoT platform, thereby empowering us to set a sustainable footprint to the world. Smart waste management is one fundamental concern in smart and sustainable city development (ITU 2019). According to Periathamby et al. (2014) the global population will increase into 9 billion in 2050. In addition to that, the increased level of urbanization will lead to a massive pressure on the current infrastructures and practices of municipalities. This led us towards investigating good practice of solid waste handling. Current practices for a waste management system includes waste collection, waste sorting, waste recycling and its transportation as in Figure 4. They can often be improved by reengineering. A vital concept in this circumstance is Key performance indicators (KPIs) for solid waste, categorized by the EU report agenda (ITU 2019). This is a conceptual framework that achieved the KPIs described in Figure 2.

Our paper is structured as follows: The related literature for smart and sustainable solid waste management systems based on IoTs technologies are discussed in section II. The conceptual models are described in detail in section III. Current practices and relative techniques to develop a smart and sustainable solid waste management system are proposed. In the discussion section, we also provide future recommendations.

II. LITERATURE REVIEW

A solid waste material hierarchy, Figure 3, can be described as follows: The material should be prevented as much as possible and if it can’t then it goes for reuse.

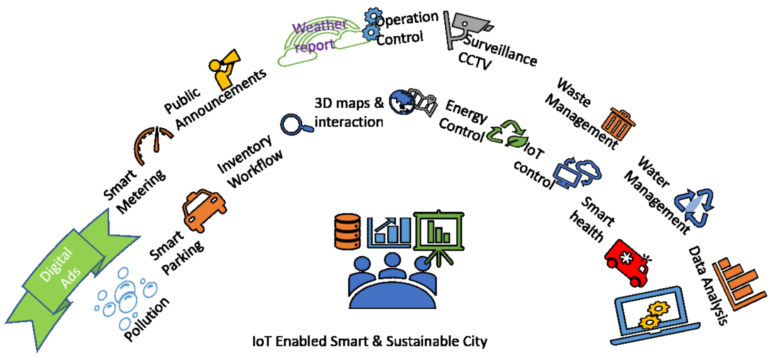

Figure 1: A Conceptual Model of an IoT Enabled Smart And Sustainable City

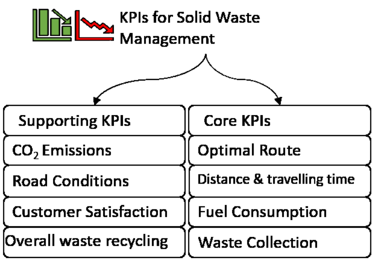

Figure 2: Smart And Sustainable Solid Waste Management KPIs

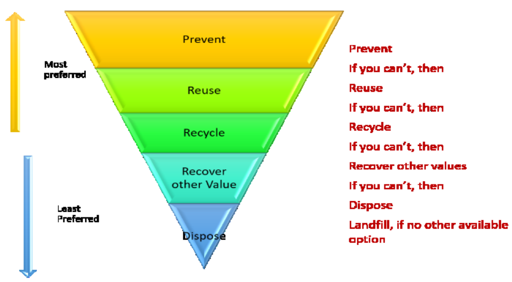

Figure 3: Solid Waste Material Hierarchy

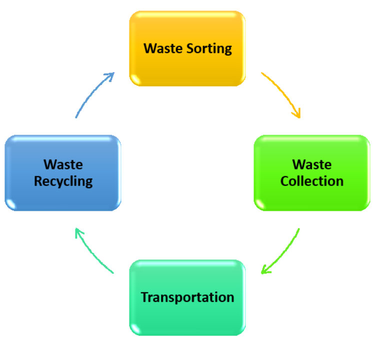

Figure 4: Smart And Sustainable Solid Waste Management System

If reuse isn't possible, then it goes for recycling. When recycling is not an option, a possibility might be to recover other values. If that isn't possible disposing is the last option.

The disposal and reuse procedure associated with each waste material is different. Additionally, there are several solid waste management projects executed worldwide in rural and urban areas. The solutions proposed in these projects are based on different techniques and data transfer technologies (Kamm, et al. 2020).

One important issue in waste management is transportation. The transportation of waste includes collection from waste bins and the transportation to various disposal sites as illustrated in Figure 4. For waste collection and transportation several methods have been proposed in literature. For example, in an article by Mingaleva et al. (2019) waste management in green and smart cities are discussed. Further on, current practices and further actions towards sustainable cities are described. In Patel et al. (2019) dry and wet dustbins are segregated, and different sensors and Wifi module for waste collection are used for their proposed model. Dugdhe et al. (2016) propose a method for waste collection scheduling for truck drivers, using mathematics to calculate the shortest route between filled-up bins and bins producing harmful gases.

With all the proposed IoT techniques described in literature, we are now able to solve many obstacles associated with waste management systems. Still there are many issues that need to be solved pertaining to reliability, scaling, bandwidth, security and power consumption.

III. CONCEPTUAL MODEL

A conceptual model can be defined as a simplified representation of a system used to describe its main physical features and principal processes (Helmig 1997; Tatomir et al. 2018). In what follows, we propose a conceptual model of an IoT-based smart and sustainable solid waste management system. The model provides a

Norwegian municipality with a blueprint of a potential system design that can easily be adopted into the municipality's current infrastructure and practices. We assume that the model might also be relevant for others as an initial template for building smarter waste management systems.

Current practices

The current practices and infrastructure of the Norwegian municipality's solid waste management system relates to different types of bins (for example, standard volume waste bins, underground waste bins and sensor based underground waste bins) for all types of waste (household waste, paper, plastic, glass, metal and food waste), mounted and scattered around the municipality. In Nasar et al. (2020) current practices for the Norwegian municipality under study are described.

Both 2G and 3G communication techniques are used for data transfer and data analysis (Nasar et al. 2020). Experience indicates that battery life of sensors devices is a major problem that should be resolved. Additionally, the product portfolio of service providers in the municipality differ from each other. Pertaining to the ultrasonic sensors used to sense the fill-up volume of waste in the bins, most of them communicate through GSM technology.

As regards data transmission via GSM, this also faces some challenges in relation to high power consumption and dependency of the network provider. In our proposed conceptual model, all these facts such as data transfer technologies, sensors, planning to future development etc are considered to enable the construction of a smart and sustainable solid waste management system based on IoT technologies.

Towards an IoT-based smart and sustainable solid waste management system

Our conceptual model is presented in Figure 5. Several stakeholders or actors, for example management companies, truck drivers and citizens, are in this improved system, connected to a database so that they can make choices and corresponding actions as regards the functioning of the waste management system. Additionally, truck drivers are equipped with a display screen with GPS and GIS information for waste collection from the bins scattered in the city.

As regards the citizens, they are connected to and can interact with the smart waste bin application via their mobile phones. The waste management companies get direct access to the database in the same manner. That the stakeholders communicate through the same platform makes communication smarter by being easier and more efficient.

A challenge in current practice is that the waste truck drivers follow a traditional way for waste collection whereby optimization has not been an issue. After deploying the proposed conceptual model focusing on IoT use, this problem can be solved by making active use of the possibilities provided by sensors combined with the use of KPIs and optimization algorithms to achieve reduced cost, distance and time. An evident outcome of an implementation of the conceptual model will be reduced CO_2 emission in the atmosphere as shown in Figure 2.

Sensor-based bins

In Figure 6, our proposal for how an IoT-based smart waste bin system can be designed, is illustrated.

In current practices, sensors-based bins are subject to many problems, due to different service providers using different platforms for data transfer and data handling etc. Another experienced problem is low battery life. The proposed IoT-based smart waste bin solution attach ultrasonic sensors, RFID sensors, Infrared sensors, and solar batteries with the cloud for data capturing and data transmission process. In the IoT-cloud, machine learning techniques are used to predict the fill-up volume of the waste bin. Optimization algorithms are used to find the truck drivers' optimal routes by taking total waste cost management into consideration.

The waste management cost for *N* number of bins can be described as:

$$W_{total} = \sum_{i=1}^{N} W_i{}^c + \sum_{i=1}^{N} W_i{}^t + \sum_{i=1}^{N} W_i{}^p + \sum_{i=1}^{N} W_i{}^d \qquad (1)$$

where W_i^c is the collection cost, W_i^t is the transportation cost, W_i^p is the processing cost, W_i^d is the disposal cost for k number of unused or produced waste material after processing and W_i is the constant cost that depends on other parameters such as accident, maintenance of collection center, transfer station and trucks.

The profit gain by the *N* number of sources is:

$$W_{management\_cost}(profit) = \sum_{i=1}^{p} R_i - W_i \qquad (2)$$

Where R_i is achieved by the recyclable materials, sales of compost products and electricity sales.

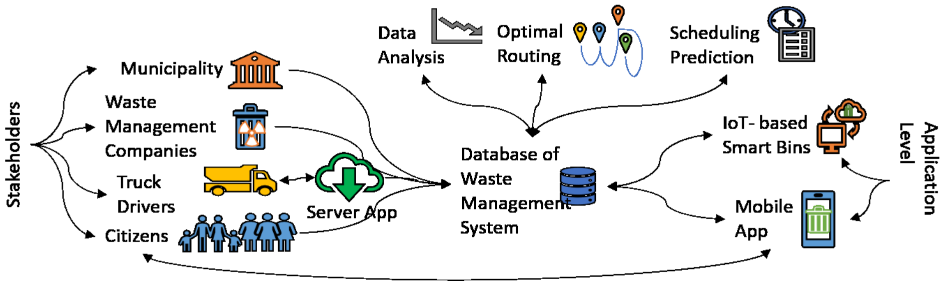

Figure 5: A Conceptual Model of a Smart and Sustainable Solid Waste Management System

In general, the objective of a waste management system is to develop mechanisms that will increase the overall profit $W_{management\_cost}(profit)$ associated with the system by reducing the $\sum_{i=1}^{N} W_i^c$, $\sum_{i=1}^{N} W_i^t$ and increase $W_{management\_cost}(profit)$.

A transportation problem for a waste management system in such cases is referred as a combinatorial optimization problem. The main objective for such problems is to reduce cost, distance, travelling time and fuel consumption. Besides that, to build a prediction model for smart waste collection, we must consider both road and weather conditions as these will impact on fuel consumption.

In our proposed conceptual model, ultrasonic sensors are embedded to sense the present waste volume in the waste bins. Infrared sensors are implemented to sense the type of waste material. These will be helpful to achieve correct waste sorting and correspondingly to increase the waste management company's revenue. Implementation of RFID sensors will be used to identify where bins are placed. As the performance and lifetime of sensors depends on batteries, we suggest the use of solar batteries. Whilst using solar batteries have the potential of solving the experienced problems associated with present battery life. Developments within these types of batteries provide enough energy for all system actions in a very sustainable manner. Further on, it is very important to produce low power consuming hardware and to schedule the sleep mode for the proposed waste management system. The sleep mode, as in several electronics' devices, are embedded to enable energy savings when a sensor-based bin is not measuring, processing or sending data.

In order to provide independent telecommunication for enabling smart and sustainable city initiatives, an IoT network will be installed. The term IoT-WAN (also known as Low Power Wide Area Network-LPWAN) contains a variety of technologies such as LoRa, Sigfox or NB-IoT (Kamm, et al. 2020).

Features of a Smart Waste Bin Application

User End

In the proposed conceptual model, the application level is divided into two parts. One part constitutes IoT-based smart waste bins, and the other one contains a smart waste bin mobile application. In current practice, the waste management company offers a mobile app for customers with limited possibilities. Features of an improved application, Figure 8, can be:

- *Waste volume status* – The app will notify about the volume of waste in the customer's bin which will help the customer to decide whether to go out for throwing the trash or not.
- *Scheduled route* – The app will notify about the scheduled trips of waste trucks, so the citizens can put their waste bins outside.
- *Parking area status* – In current infrastructure, a vast area is dedicated specifically for waste trucks to collect waste. Instead of this practice, in the prototype app customers are notified about the waste trucks' schedule, thereby orienting the customer of when certain areas can be used for regular parking.
- *Customer credit* – In the present infrastructure there are different waste bins provided to the customers for different types of waste. These different types of waste are to be treated differently. For example, food waste needs to be emptied more frequently than other waste types. Similarly, the household waste is not considered as being recycling material and therefore are usually to be sent to disposal sites. Paper, plastic and other waste types are commonly sent for recycling in various recycling plants. To motivate customers to act properly pertaining to sorting waste, our prototype embeds the idea of giving away customer credits in the form of bonus points or some appreciating messages.

Smart App Server

Based on the data transfer technologies, a smart waste management application can be built (Kamm, et al. 2020). Various Python libraries can be used to build the platform shown in Figure 9. The implementation can be divided into three parts:

1. A smart bin App based on sensors which will detect waste material and sense the fill up volume of bins. Through the obtained data, the data analysis can be done as shown in Figure 7.

In this Figure, the fill-up volume before and after emptying the waste bins is shown. Sensor data from two types of waste, i.e., paper and household waste, are subject for data analysis.

2. The second part is data connectivity between the sensor based smart app, a decoder and an application manager handler through an IoT-WAN infrastructure which is suggested to build the app.
3. The last part is a smart waste application server.

IV. DISCUSSIONS & FUTURE RECOMMENDATIONS

In this paper a conceptual model is proposed as a blueprint for a smart and sustainable waste management system based on IoT technologies. We investigated a Norwegian municipality as a case study and based on our knowledge of current practice and the needs and wishes of the municipality we propose a design solution.

In the future it is our hope that this conceptual model can be implemented by the municipality using IoT technologies, sensors, cameras, actuators and Python for software development.

By implementing some of our suggestions we hope the municipality will end up with an IoT-based waste management system providing optimal routes and schedules for truck drivers via prediction models. For this different machine learning and artificial intelligence techniques can be used. To solve optimization problems, we can use techniques such as multiple travelling salesman problem (MTSP), constraint vehicle routing problem (CVRP) and multi objective optimization (MOO). These are all issues and possibilities to be investigated in future work.

In Nasar et al. (2020), the waste collection and transportation problem is addressed. The multi-objective traveling salesman problem (MOP-TSP) is used to find the optimal shortest possible route with multiple constraints such as minimum traveling time and distance as shown in Figure 10. The obtained results are compared with current practices and it is concluded that the proposed method is 34% cost and time saving. The solid waste KPIs i.e. stated in Figure 2 have been achieved with this proposed solution.

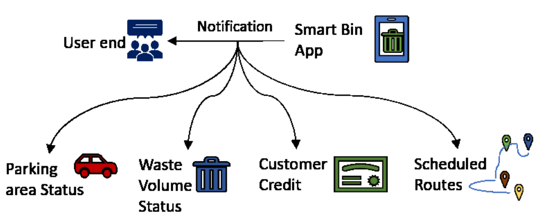

Figure 6: Smart Waste Bin Application at User end

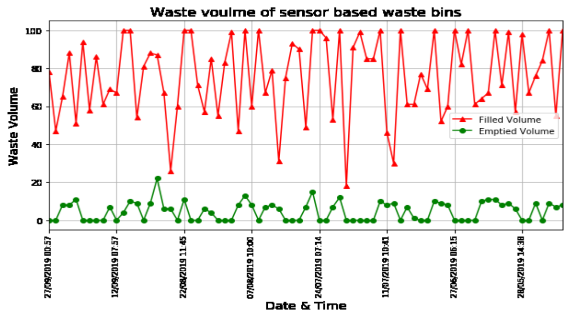

Figure 7: Sensor Measurement Of Waste Volume In Waste Bins

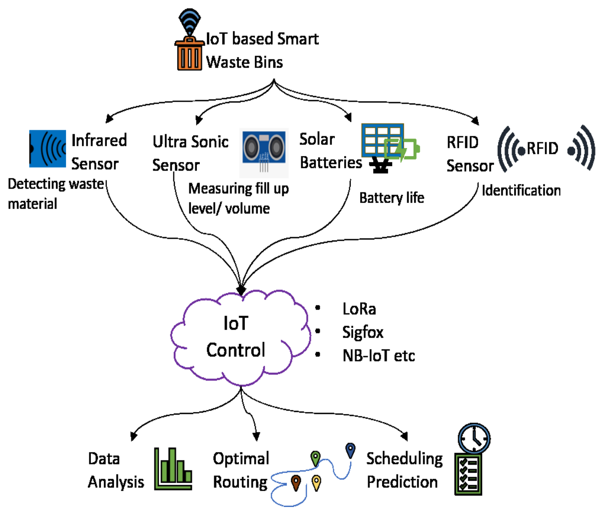

Figure 8: IoT-Based Smart Waste Bins

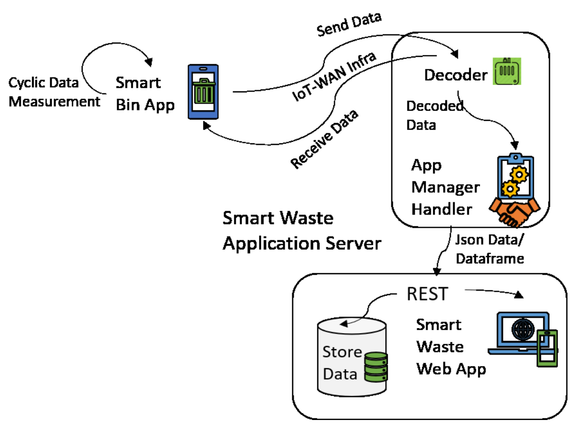

Figure 9: Smart Waste Bin Application Server

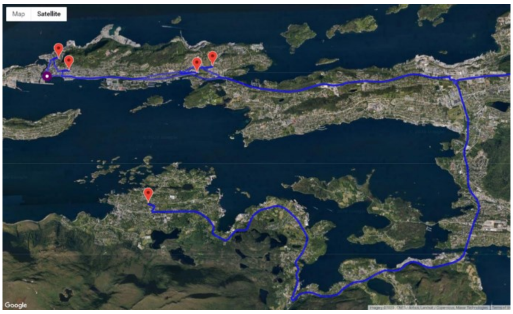

Figure 10: MOP-TSP optimal route finding with minimum distance and minimum time (Nasar et al. 2020)

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An Optimized IoT-based Waste Collection and Transportation Solution: A Case Study of a Norwegian Municipality

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Abstract. Smart and sustainable solid waste management systems (SWMS) are of major interest in the development of smart sustainable cities (SSC). Selective waste collection and transportation are known to be major expenditures of city waste management systems. In this paper, we investigate the waste management system for domestic waste in a Norwegian municipality as a case study. Different scenarios for route planning are considered to improve cost and time usage. The study provides an auxiliary management system for multi-objective TSP using google maps and operation research (OR) tools for optimal domestic waste collection. Additionally, a prediction model for scheduling future waste collection trips is provided, whereby challenges such as road conditions, road traffic, CO_2 and other gases emissions, and fuel consumption are taken into account. The proposed prediction model considers the hazards associated with food waste bins that need to be emptied more frequently than other waste types such as plastic and paper. Both of the proposed models signify consistency and correctness.

Keywords: Cost and Time Effective · Domestic Waste · IoT Technologies · Multi-objective Optimization · Route Length · Smart and Sustainable Solutions · Smart Waste Bins · Solid Waste Management · Smart Sustainable City · Traveling Salesman Problem

1 Introduction

The smart city paradigm encompasses important factors that can affect the society in terms of smart economy, smart traffic, smart health, smart energy, a smart municipality and so on. These factors are interlinked with ICT technologies and the use of Internet of things' (IoTs) applications for the development of a smart city. A smart sustainable city (SSC) can be defined as [11]:

> *"An innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets*

the needs of present and future generations with respect to the economic, social, environmental, as well as cultural aspects."

Pertaining to urbanization and climate change, waste management is an important focus of many cities and municipalities [1]. There are ongoing initiatives taken by governments and public authorities around the world to manage waste collection and its disposal. With the growth of ICT technologies and infrastructure facilities in economically developing countries, the implementation of smart and sustainable solid waste management system (SWMS) has become a key objective. Internet of Things (IoT) technologies enable new services and reshapes existing technologies in smart sustainable cities. IoT represents an internet evolution known as the next generation of the internet (i.e., the Fourth Industrial Revolution) [2]. Equipping waste bins with IoT-based sensors provides a smarter future for waste management.
Generally, solid waste refers to the solid material in a flow pattern that is discarded as useless or unwanted by society. It includes organic and inorganic waste materials which have lost their value to the first user in categories of domestic waste, industrial waste, commercial and institutional waste. In turn, solid waste management (SWM) involves waste sorting, collection, recycling and transportation.
There are different key indicators proposed for SSC and the SWM key performance indicators (KPIs) organised in the environmental category by the United for Smart Sustainable Cities (U4SSC), EU report [11]. In our research, a set of core and supporting SWM KPIs was used to find the optimal way for waste collection from the waste bins. The intelligent way of waste collection links with complex tasks such as route planning and planning for transportation networks. In this paper we focus on the optimal transportation problem where the solution for domestic waste collection relates to achieve the minimal route length along with reduced fuel consumption, and minimal associated costs and work time [12]. Correspondingly, smart waste management also reduces the emissions of CO_2 and other gases in the environment.
The paper is structured as follows; Section 2 presents the literature review in the area of smart sustainable solid waste management systems for smart cities. Section 3 describes main features and scenarios. Section 4 describes the methods used to implement the developed smart, cost and time effective, and sustainable waste management system. Section 5 concludes the paper and section 6 proposes the future recommendations.

2 Literature Review

Solid waste management system (SWMS) includes waste collection, sorting, recycling and transportation. The area of route planning and optimizing logistics purposes has contributed to the development of hundreds of intelligent transportation systems. Even so, there are still many projects going on, all around the world, to provide effective and efficient systems for waste collection and management. The waste collection and transportation problems are also considered as combinatrial optimization problem [8, 12, 13]. Different techniques in literature are used to solve waste collection and transportation problem. For instance, a dynamic decision model (DSS) which is integrated in a GIS- based decision support system is proposed by Anghinolfi et al.[6]. In [7] five routes in different areas of Ipoh city of Malaysia are optimized to reduce the length of the routes collectively in terms of time required to complete the tasks. GIS tools and a combinatorial optimization technique are used to minimize collection time, operational and transportation costs whilst enhancing the current solid waste collection practices [8].

In [9], the optimization of vehicle routes and the planning for municipal solid waste collection in Eastern Finland is described. The solutions are generated by a developed guided variable neighbourhood thresholding meta-heuristic that is adapted to solve real-life waste collection problems. In [10] a dynamic routing algorithm is proposed for a situation whereby a truck is overloaded or damaged, needs a replacement. The solution also incorporates a system model which assumes two types of trucks for waste collection, a low capacity truck and a high capacity truck. By incorporating high capacity trucks, the researchers achieved a reduction in waste collection operational costs because of reduced need for trips to waste bins.

In [5] an advanced DSS for efficient waste collection in smart cities is proposed. The proposed system integrates a model for real-time data sharing among truck drivers for waste collection and adaptive route optimization. Furthermore, the proposed system can handle inadequate waste collection in problematic areas and provide evidence to the authorities.

[12] proposes an optimal transportation solution of classified garbage that improves the sustainability of the present practices and considers a city of China as a case study. In [13], it proposes an optimization model for municipal solid waste (MSW) collection and transportation through heuristic solutions. The proposed heuristic solutions minimize the route length which efficiently reduces waste collection and transportation cost.

The mentioned publications have inspired and directed our research development of a visualization tool providing insight into optimal route lengths and plans for waste collection trips. An optimization model is embedded into the tool to achieve the shortest possible route for collecting waste in minimum time and cost.

3 Main Features and Scenarios

Generally, system architecture for waste management has two main targets [12]. The first target is to provide software as a service (SaaS) for service provider companies. These companies own their own waste trucks, hire the truck drivers, give contracts to other companies for performing different tasks and pass waste for recycling or recovering other profitable values from waste [12]. The second target is to develop a system focusing on cooperative communication among all the stakeholders involved in the chain of development of a smart sustainable city. A list of possible stakeholders are presented below:

1. *City administration* must understand the broad picture of waste management such as generating reports and ensuring overprice control etc.
2. *District administrations* are interested in controlling the waste collection process and checking the quality of services to resolve disputes and problems effectively.
3. *Waste management companies* need a system for organizing and optimizing their business processes without the need for large investments in developing, deploying and supporting such a system.
4. *Waste truck drivers* need optimal solutions for smart navigation to fulfill their tasks. Some major needs are automatic insight into route lengths, road traffic, and the ability to report problems to operators in the office, instead of wasting time in thinking how to solve the problem themselves.
5. *Managers of disposal sites and recycling plants* can publish their needs or possibilities for obtaining certain amounts of waste for recycling.
6. *Traffic police* can get reports on unpleasant incidents that have caused hazards in waste collection processes.
7. *Citizens* are interested in and can experience better services at lower costs through an improved waste collection system.

All stakeholders are generally interdependent in smart and sustainable municipality using IoT technologies and it is possible to develop plenty of system usage scenarios to fulfill each stakeholder's need. In what follows, we present our insight into the development of a time and cost effective optimal SWM system addressing current practices and infrastructure for reduction in route length, fuel consumption, CO_2 and other gases emissions. A prediction model is embedded into the system to enable the planning of trips for waste trucks drivers based on prediction of the level of waste volume in bins. With this prediction model in place, future trips for selective waste collection can be planned in an improved manner compared to current practices.

3.1 Challenges and Risks

Waste collection and transportation are well-known challenges in many cities or municipalities. In the case we studied, the challenges and risks for the municipality to deploy a smart and sustainable SWMS were subject for investigation. Following challenges were collected and taken into consideration when developing the prediction model.

1. *Narrow and steep roads* in the city center make the task of collecting waste sometimes impossible for waste collection trucks.
2. *Busy roads* are one of the major concerns in the current infrastructure. At present, there is no optimal template for truck drivers to pursue whilst planning trips for waste collection. Present practices are cost and time inefficient.

Fig. 1: Challenges and risks in the city (a) Waste bins located aside from the roads, (b) Open Waste bins

Fig. 2: Types of waste bins (top-Standard underground waste bins, left bottom- Sensor-based underground bins, right bottom- normal bins)

3. *Non-environment friendly* and non-optimal ways of waste collection cause delays which can create an uncomfortable and unsanitary environment in the neighborhood.
4. *Location of Waste bins* in the municipality is also an issue. Many bins are allocated relatively far away from the road. It is quite challenging and time-consuming for truck drivers to collect waste from such locations as shown in Figure. 1-a.
5. *Open Bins* is a problem becoming rare with the growth of urbanization, but still present in some areas thereby causing unpleasant odor and sight for inhabitants as shown in Figure. 1-b.

At the initial stage of our research, the proposed solution for addressing challenges in current practices and infrastructure focused on the city center where there are narrow and steepy roads with normal size waste bins. Various types of waste bins for selective waste collection are scattered around the city as shown in Figure. 2. Due to extreme weather or road conditions present practices are time consuming and cost inefficient for trucks with waste collection done in a non-optimal manner. The service providers also have to spend a lot of money on feasible trucks able to function in such challenging locations. The smart and sustainable SWMS we propose, considers current practices and infrastructure of the municipality where waste truck drivers among others report on their inability to collect waste in rush hours. Evidently traffic and conjugation on roads increase fuel consumption and CO_2 emissions in the environment and is both cost and time consuming

4 Waste Collection Models

In a case like this, smart decisions depend on details of the surroundings and require geographical information to help distinguishing one place from another and to make appropriate decisions for that location [14]. Recent developments in ICT have opened-up vast potentials in communication and in, spatial and temporal data analysis. It is possible to store and process data representing the real world for later presentation in simplified form for suitable needs. In the waste generation model, geographical information of the city is viewed through google maps. The google maps app has its own Geo-analytical tools and can perform network analysis. It enables traffic and driving queries [15]. Google maps provides rich, multi-layered maps that are proved easy to combine with our data and third-party data. It also provides various features such as maps, street view, routes, directions, distance matrix, roads, time zone, places details and so on [15], making it a relevant tool in systems development.

4.1 Optimization Model

For the development of the waste generation model, data collected from standard underground and sensor-based underground waste bins was utilized. In general, an optimized waste collection and transportation scheme effectively reduces the cost for waste collection and transportation and tends to minimize the route length of each trip for transportation. Studies related to these problems are generally divided into three categories with respect to the number of disposal sites [14].

- Single disposal site, single route
- Single disposal site, multiple routes
- Multiple disposal sites, multiple routes

Table 1: Traveling time and distance covered by vehicle

Traveling Time	2.58 hours
Traveling Distance	84.8 Miles
Route for Vehicle	0−>3−>1−>9−>5−>2−>4−>7−>6−>8−>0

The following are important aspects of waste collection associated with our case:

- Number of trucks: There is one vehicle available at a time for selective waste collection and its optimized route is shown in Table. 1.

Fig. 3: Optimized shortest route length with estimated cost, distance and time via multi-objective TSP

- *Starting and Stopping points*: The starting and ending points data along with the number of stopping points is known to the drivers. A starting point indicates the truck's starting location and the ending point is normally the recycling site or the landfills site.
- *Selective Waste type*: In the investigated case, different types of sorted selective waste collection bins are placed at each residential area. For each selective waste collection, there are dedicated trucks in this Norwegian municipality shown in Figure. 2. Usually two disposal sites are used to dispose waste collected from selective waste bins. One disposal site for recycling of waste such as paper, cardboard, plastic, glass and metal and another disposal site for residual and food waste.

The waste collection and transportation problem can be solved by the traveling salesman problem (TSP) [14]. Generally, TSP is known as a NP-hard problem and there is no polynomial time algorithm for obtaining its exact solution [14]. TSP can be defined as:

> A list of cities N and the distances between each pair of cities is given. The traveling salesman has to find the shortest possible route to visit each city and return to the origin city.

TSP can be classified as single-objective optimization problem (SOP) such as calculating optimal routes with minimal length, and as multi-objective optimization problem (MOO) such as calculating optimal routes with minimum cost, time, distance and so on [16]. The problem can be represented graphically as [16]:

$$G = (V, E) \tag{1}$$

where $V = v_1, v_2...., v_N$ is a set of N nodes and E is a set of edges. While the distance d_{ij} and time t_{ij} are associated with each edge $(v_i, v_j) \in E$ respectively as in Figure. 5. In the investigated case, we are classifying TSP as MOO which can be represented as [18]:

$$TSP_{MOO} = \begin{cases} min\ F(x) = f_1(x), f_2(x), ..., f_m(x) \quad \text{s.t.} \quad x \in S \end{cases} \tag{2}$$

where $F(x)$ is the $vector_{objective}$; $m \geq 2$ is the number of $functions_{objective}$; $f_1(x), f_2(x), ..., f_m(x)$ is the decision variable vector where n is the of cities/waste bins; x is a permutation of $1, 2, ..., n$ that minimizes $F(x)$. S is feasible solution space. The set $O = F(S)$ corresponds to the feasible solution in the objective space, and $y = y_1, y_2, y_3, .., y_m$, where $y_i = f_i(x)$ is a solution. For the TSP under consideration, m = 2 where $f_1(x) = travelingdistance$ and $f_2(x) = travelingtime$.
An OR-tool solves the optimization problems by computing the cost of transportation by distance matrix between two nodes (x_i, y_i), (x_j, y_j) is calculated using Manhattan distance which sum up the absolute distance of x *and* y coordinates respectively in Table. 1 & Figure. 3. This can be mathematically obtained as [20]:

$$C = |x_i - x_j| + |y_i - y_j| \quad where \quad i \neq j \tag{3}$$

The mathematical representation of the stated problem is as follow:

$$min \begin{cases} f_1 = \sum_{i,j=1,i\neq j}^{N} d_{ij} c_{ij} \\ f_2 = \sum_{i,j=1,i\neq j}^{N} t_{ij} c_{ij} \end{cases} \tag{4}$$

where

$$\begin{cases} c_{i,j,i\neq j} = 1, & \text{if } bi, j \geq \gamma \\ c_{i,j,i\neq j} = 0, & \text{elsewhere} \end{cases} \tag{5}$$

In here,d_{ij} is the distance between nodes i *and* j, c_{ij} is the collection decision. If $c_{ij} = 0$, then the nodes do not belong to the optimal route, the truck does not visit the between the i_{th} bin and j_{th} bin. The optimization model shows the optimal shortest route for waste collection with minimum driving time, driving distance, driving cost in Figure. 3 & 4. The locations of waste bins are pinned in a map to visualize the route for selective waste collection. The route is established according to a threshold of waste volume. The threshold γ is set according to current practices, i.e., if the waste volume reaches or exceeds the set threshold. The γ is calculated by the waste volume in the bin over the total number of opening of lid. The truck driver schedules a trip for waste collection accordingly. The optimization model achieves the following aimed solid waste key performance indicators (KPIs) [11]:

1. Reduction in fuel combustion.
2. Reduction of the CO_2 emissions in environment.
3. Reduction in unnecessary road traffic.
4. Improved cost and time effectiveness.
5. Minimization of route length.
6. Reduction in the trips for drivers due to optimal planning solutions.

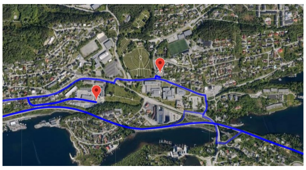

Fig. 4: Satellite view with optimal routes by TSP

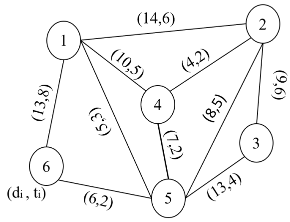

Fig. 5: MOO-TSP representation with edges- traveling distance and time, and nodes b_N

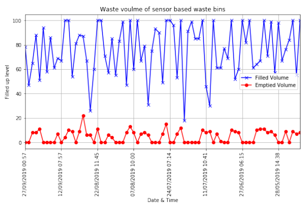

Fig. 6: Waste Volume gather through sensors

High Threshold Fillup Date

#	Garbage Bin ID	Next Fill up Date
0	7001	2020-01-25
1	7003	2020-01-26
2	7010	2020-01-26
3	7013	2020-01-25
4	7018	2020-01-25
5	7020	2020-01-29
6	7023	2020-01-25
7	7026	2020-01-26
8	7031	2020-01-28
9	7034	2020-01-25
10	7038	2020-01-28
11	7044	2020-01-29
12	7045	2020-01-28
13	7046	2020-01-28
14	7050	2020-01-27

Fig. 7: Prediction model for trips scheduling

4.2 Prediction Model

According to the current practices of the investigated municipality, the total volume of waste collected in 2019 from domestic sensor-based bins is 930.40 m^3. The sensors tracked waste volume of each bin to update the database. One of the major problems in current practices is that trips scheduled for waste collection are often overlooked or delayed. This causes an unsanitary environment. The proposed optimal SWMS solves the delaying problem by using a prediction model. In our case, the prediction model is scheduling trips for waste collection truck drivers as illustrated in Figure. 4. The prediction coefficient (γ) predicts waste volume for each bin. In the prediction model dummy variables are used to predict time *(t)* for the next trip and driving cost of each trip as shown in Figure. 7 & 6.

$$\gamma = waste\ volume_{threshold}$$

$$\nabla\ volume = \gamma * t$$

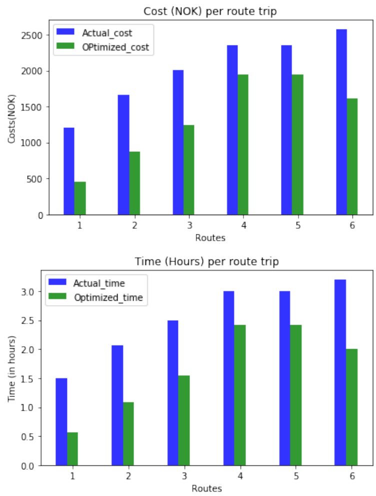

Fig. 8: Comparison between Proposed system and current system

5 Discussion and Conclusion

Smart and sustainable solid waste management systems are main concerns for smart sustainable municipality development initiatives. This paper present findings from the investigation of current infrastructure and practices of waste collection from waste bins and its transportation in a municipality, and provides a solution to achieve smarter ways for waste collection. The objective of achieving solid waste KPIs is fulfilled to some extent an optimized multi-objective TSP algorithm used to find the shortest route length in minimal time for each trip. In the developed data driven solution, the historic data is used for implementing an optimization model and a prediction model. The solution can easily integrate real-time data to predict and plan trips for truck drivers with minimal cost, distance and time.

The time (in hours) and cost (in Norwegian kroner) comparison between current and a data-driven practice is shown in Table. 2 and in Figure. 8. The bar graphs based on Table. 2 clearly show that the smart and sustainable SWMS is cost and time effective. In the table, we use six different routes to calculate the driving time, driving cost and driving distance between current practices and the developed data-driven system. The 33.4 % saving cost shows that the data-driven system is more profitable than the existing one. In these routes, the truck drivers are subject to selective waste collection from different bins $b_1, b_2, ..., b_N$ and the routes are calculated by MOO-TSP. The developed system is based on

Table 2: Time and cost comparison between current practices and the developed data-driven solution

Route	Waste type	Waste bins b_N	Current practices		Developed practices		Cost Saving %
			Time (hours)	Cost(NOK)	Time(hours)	Cost(NOK)	
1	Paper	b_1, b_2	1.50	1207.0	0.57	459.0	62.0
2	Residual	b_1, b_2, b_3	2.06	1661.0	1.09	877.0	47.0
3	Paper	b_1, b_2, b_3, b_4	2.50	2013.0	1.55	1248.0	38.0
4	Paper	b_1, b_2, b_3, b_4, b_5	3.00	2348.0	2.42	1984.0	17.0
5	Residual	b_1, b_2, b_3, b_4, b_5	3.00	2348.0	2.42	1984.0	17.0
6	Plastic	b_1, b_3, b_5, b_6	3.20	2576.0	2.00	1610.0	37.5
Total			15.27	12153.0	10.05	8090.0	33.4

data retrieved from current practices and infrastructure which is practical and helpful for future developments.

6 Future Recommendations

In this research, the focus is to contribute insights into building an optimal solution for the sensors and for the standard underground waste bins scattered around a Norwegian municipality. A next step towards smart and sustainable SWMS development process can be to integrate the developed optimized solution into a generic waste management system. This can then easily integrate future developments such as multiple disposal sites and multiple routes such as MOO-mTSP.

The tasks regarding developing a waste management system usually include waste collection, sorting, recycling and transportation. This paper focuses on MOO waste collection and transportation by finding the shortest path with minimal cost and time usage. It can be extended for smart sorting and recycling with the help of IoT technologies such as cameras, actuators and wireless networks. For instance, the sensors can be modified for smart sorting to sense and classify the waste material. The waste management system can also be modified by studying and taking into account the behavior of inhabitants as regards how their age and general living conditions for example influence the waste production, sorting and management.

A Current practices and Infrastructure

The current solid waste management practices and infrastructure for domestic waste have three different types of waste bins for selective waste collection as shown in Figure. 2. The sensor-based waste collection bins notify the volume of waste in bins, if it is filled or empty to schedule the trip for waste collection truck drivers as shown in Figure. 6. Senor-based waste bins transmit data in real-time through wireless networks to the BioEnable waste management system. 2G and

3G telecommunication modules available through WCDMZ and GSM networks for data transfer. One of the main problem in current SWM practices is lack of optimal solutions which affects the SSC goals for SWMS.

Acknowledgment

This work is supported by the project Smart Circular City. We thank Espen L. Mikkelborg for his extraordinary support in this research process.

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