Efficient, sustainable and secure use of smart city resources

Cyber Security
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The rapid advancement and increased use of technology has introduced the concept of smart cities, driving cities around the world towards developing a wide variety of smart systems, solutions and services. While these smart components provide improvements to various city operations, from increased resource efficiency and sustainability to general quality of life enhancements, they also introduce many challenges that must be dealt with in order to ensure future success.

The purpose of this thesis is to determine the necessary measures both current and future smart cities should take in order to use their resources in an efficient, sustainable and secure manner. This was primarily achieved through extensive theoretical research, using a wide variety of information sources, from various scientific publications to different web-based resources. In addition, a simulated model of a smart waste management system was designed in this thesis in order to aid the development of the Salo smart city project.

Resource efficiency and sustainability are integral to successful smart city implementations, as they ensure that smart cities can continue to prosper and develop more and more advanced solutions and services in the future. Consequently, the importance of solutions such as smart energy, smart waste management and smart mobility will only continue to increase in the future. Moreover, smart cities must be prepared to deal with various challenges presented by the use of advanced technologies and smart systems - from security, privacy and service availability to people- and ethics-related challenges.

In the final parts of the thesis, the aforementioned topics were discussed from the perspective of the Salo smart city project. The use of different security measures and cheaper smart solutions, such as the smart waste recycling centre designed in the thesis, were given as recommendations to guide Salo towards a more resource efficient, sustainable and secure future.

Keywords: smart city, resource efficiency, sustainability, security, waste management, Arduino, Salo

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Acronyms

AI artificial intelligence. 7, 13–15, 17, 22, 28, 29, 34, 62, 82

ANN Artificial Neural Network. 14

BLE Bluetooth Low Energy. 10, 11

CITS Copenhagen Intelligent Traffic Solutions. 37, 47

CNN Convolutional Neural Network. 14, 15, 28, 29, 38

DBN Deep Belief Network. 14, 15

DDoS Distributed Denial of Service. 50

DoS Denial of Service. 49, 50, 72, 81

EC European Commission. 5, 8, 16

GDPR General Data Protection Regulation. 41, 46, 47, 61, 81

IDS Intrusion Detection System. 53

IoT Internet of Things. 7–10, 12, 13, 15, 17, 22, 23, 25, 28, 50, 52, 58, 72, 82

LoRaWAN Long Range Wide Area Network. 10, 28, 69, 70, 80

LTE Long-Term Evolution. 10–12, 69, 80

MitM Man-in-the-Middle. 43–45, 49, 52, 81

ML machine learning. 13–15, 22, 29, 53, 54, 56

RL reinforcement learning. 14

UN United Nations. 16

VPN Virtual Private Network. 46, 72

1 Introduction

The concept of smart cities has become increasingly popular in recent times, which has led to a high number of research and development initiatives in the field of smart cities and technologies. With these initiatives, integral smart city techniques, such as smart sensors and automated data-driven decision-making capabilities, have increased significantly, thus accelerating the growth of smart cities in general. Moreover, the understanding of what smart cities should consist of has become an extremely important topic of discussion.

With the growth of the smart city concept and the increasing success of different smart city projects and initiatives around the world, citizens' demands for various smart solutions and services have also experienced significant growth in recent years. As a result, even smaller cities are now looking to increase their appeal and general comfortability through the development and implementation of different smart city initiatives. Successful implementations in other, larger or more established, cities around the world play a key role in this development, as they can provide inspiration and guidance to the development of smaller smart city projects.

In order to ensure the future success of different smart city projects and solutions, smart cities must find ways to develop their resource efficiency and sustainability. These measures can range from, for instance, automated energy consumption monitoring and optimised waste collection routes to the reduction of emissions and accidents with the help of smart vehicles. These solutions will aid smart cities in using their resources in the most effective ways in order to ensure sustainable and citizen friendly operations and services, both now and in the future.

Despite its benefits, the smart city concept also introduces a wide variety of challenges. With the high amount of data collected and used by different smart systems, efficient and secure utilisation of that data, as well as the preservation of the citizens' privacy, becomes extremely important. In addition, due to being highly reliant on technology, smart cities must find ways to protect their critical systems from different cyber attacks and other threats that could jeopardise the cities' operations. Furthermore, as the citizens themselves are one of the key components of any city, smart cities also suffer from people- and ethics-related challenges.

This thesis is written in collaboration with the University of Turku, the city of Salo and the Salo smart city project. The different concepts surrounding the topics discussed above will be inspected from a wide variety of perspectives – from their general key characteristics to how they can be applied to the Salo smart city project.

1.1 Research questions

The main objective of this thesis is to determine what is required for a city to develop into a resource efficient, sustainable and secure smart city that utilises advanced technologies for improving the lives of its citizens. This process involves determining the technologies and smart solutions that are the most important for accomplishing this goal, as well as applying these methods to the development of the Salo smart city project.

As different smart city developments are still at fairly early stages, the possibilities for further advancements and developments in the field are endless. Consequently, gaining an understanding of the future of smart cities is one of the main objectives of the thesis, and therefore, the future will be heavily emphasised in the research on the different concepts surrounding the topic of resource efficient, sustainable and secure smart cities.

Based on the objectives presented above, the thesis aims to find answers to the following research questions:

1. Which characteristics make a city “smart”, which technologies are required for achieving these characteristics, and how are smart city projects carried out in different cities around the world?
2. What measures can be taken to increase the resource optimisation and sustainability of different smart city projects and solutions?
3. What are the most prominent challenges that threaten the resource efficiency, sustainability, security and general success of smart cities, and what measures should be taken to deal with these challenges?
4. What are the key objectives and requirements of the Salo smart city project, and how can the city of Salo utilise the measures and solutions discovered in questions 2 and 3 to increase their resource efficiency, sustainability and general appeal?
5. Which smart solutions can be used to address the considerations identified in question 4, as well as increase the resource efficiency and sustainability of the Salo smart city project in general?

1.2 Thesis structure

Chapter 2 covers basic smart city concepts, the knowledge of which is required for understanding many of the topics discussed later in the thesis. These basic concepts include general smart city components and characteristics, as well as the key technologies behind different smart systems and solutions. Additionally, various successful smart city projects and their different smart solutions are highlighted.

Chapter 3 contains detailed discussion about the central approaches to smart city resource optimisation and sustainability improvements – smart energy, smart waste management and smart mobility. These approaches are inspected from a wide variety of perspectives, from the required technologies and achieved benefits to examples of their successful implementations in the smart cities presented in chapter 2.

In chapter 4, the most prominent challenges of smart city initiatives are discussed from the perspective of smart city resource efficiency, sustainability and security. Additionally, the chapter provides discussion and recommendations on the different measures that smart cities can implement in order to mitigate and solve these challenges.

Chapter 5 provides an overview of the general structure and objectives of the Salo smart city project. The chapter also discusses the city's current issues and limitations, as well as recommends different measures for increasing the effectiveness and general success of the city of Salo and its smart city project.

Chapter 6 explains the process of designing a simulated model of a smart waste recycling system for the smart city of Salo. Moreover, the simulated testing results are presented, and the possible limitations and future applications of the system are discussed.

The thesis is concluded in chapter 7. The chapter also summarizes the answers found to the research questions determined in section 1.1 and discusses the potential approaches for future research and other work on the subject.

2 Smart city

Smart cities have experienced significant growth in recent years. Firstly, the advancements made in different fields of technology have enabled the development of smarter services and city infrastructure. Secondly, with the successful development and implementation of different smart city projects around the world, citizens' desires and requirements for better and smarter services have continued to increase. These factors have led to the emergence and increased implementation of the general idea behind smart cities – the use of various technologies for providing a better living environment to the cities' inhabitants.

In this chapter, the smart city concept is discussed from different perspectives in order to gain an understanding on what a smart city is and how various smart services can be developed, as well as how various smart city approaches are applied in different cities around the world.

In section 2.1, the general characteristics of smart cities are discussed, and an overall description of what cities need to accomplish in order to be considered "smart" is presented. Additionally, the different technologies behind smart city developments are discussed in section 2.2. Finally, in section 2.3, different successful smart city approaches around the world are discussed in order to form an overview of the suitability and benefits of different smart city concepts and solutions in practice.

2.1 What makes a city "smart"?

The meaning of a "smart" city is not completely clear, as there are many different areas and factors to consider. Cities consist of a wide variety of solutions, services and citizens, all of which set different requirements on what the city should be capable of. When different, often very complex, technologies are added into this equation, the number of things to consider grows exponentially. Furthermore, smart city projects of different sizes are developed all over the world, meaning that the conditions between different smart cities can vary a lot. As a result, a general understanding of what makes a city "smart" is incredibly important.

In this section, the meaning of a "smart" city is examined from a wide variety of sources in order to gain a comprehensive view of what a smart city is comprised of. Moreover, the most common smart city characteristics are identified and combined into a unified description of the most important areas to consider in the development of future smart city solutions and initiatives. This description is then be used in the rest of the thesis, when discussing different smart cities and their key components, solutions and services.

The smart city definition of the European Commission (EC) [1] states that *"A smart city is a place where traditional networks and services are made more efficient with the use of digital and telecommunication technologies for the benefit of its inhabitants and business."* In addition, efficient use of resources and reduced emissions are considered important in this smart city definition. Moreover, the key initiatives for successful smart cities proposed by the EC include improved lighting and heating of buildings, smart waste disposal and smart transport. As a result, optimised and sustainable use of resources can be considered as the key component of the smart city concept, especially in the case of many European cities.

Deloitte [2] on the other hand, present a framework that divides smart cities into six components: environment, economy, security, mobility, living and education. The framework also presents the main objectives and motivations behind smart city projects and initiatives – better quality of life for both citizens and visitors, economic competitiveness and sustainability. Based on these discussions, smart city initiatives consider all key areas of a successful city, from the city's infrastructure and resources to its citizens.

Mohanty et al. [3] state that in a smart city, technology is used to provide better public services to the citizens, as well as optimise the use of resources in the city. According to their definition, smart cities consist of smart infrastructure, smart buildings, smart technology, smart energy, smart transportation, smart healthcare, smart education, smart governance and smart citizens. They also present the core requirements for the attributes of smart cities – sustainability, quality of life, urbanisation and general smartness. Moreover, they consider the environment, economy, society and governance as the key areas that different smart city initiatives should focus on. As shown by this definition, smart cities can be considered as a combination of a wide variety of areas. As a result, in order to understand the concept of smart cities, a good understanding of many different technologies and smart city application areas is required.

According to Musa [4], people, processes, and technology are the three key elements of smart cities. Musa also describes smart cities as cities that engage their citizens, connect their infrastructure with electronical measures, and manage their assets in a secure manner by connecting a wide variety of technological solutions. In short, the overall goal of these approaches is to utilise technology for providing more efficient and versatile services to the citizens. Finally, Musa defines society, infrastructure, mobility, strategic planning and a healthy city-citizen relationship as the key areas of focus in smart city projects.

Sikora-Fernandez and Stawasz [5] simply define smart cities as cities that are managed *"in a modern way, using the latest technical means offered by advanced technologies."* They also present that the advancements made in smart cities should be good for the environment, as well as save resources, while also achieving the excepted efficiency and performance. In addition, based on these approaches, a city can be considered smart if it follows the general attributes of intelligence, such as solving problems, adapting to changing circumstances, preventing the most significant threats and predicting the consequences of various actions. Due to emphasising security alongside resource optimisation, this definition is particularly important to consider for future smart city developments.

Another approach to defining smart cities is presented in a white paper [6] published by the State of Green. The paper explains that in smart cities, technology is not directly seen as a solution, but instead, an enabler for sustainability and the citizens' well-being. The paper also presents that in order to achieve this objective, smart cities utilise commonly accepted technical solutions for increasing the liveability, sustainability and prosperity of the city.

The definitions discussed in this section show that the definition of smart cities is not completely unified, as the different definitions can vary quite a lot based on the perspective of the person or organisation that is discussing the topic. However, there are various features and characteristics that appear in many smart city definitions, and therefore, can be considered as the most important features that need to be taken into account in both current and future smart city projects and developments.

Based on the discussions in this section, a city can be considered "smart" if it achieves significant developments in a large majority of the following areas: resource efficiency, sustainability, security, eco-friendliness, smart infrastructure, smart buildings, smart energy, smart transportation, smart healthcare, smart education, smart governance and smart economy. In addition, above all, the city should improve the citizens' quality of life and provide them with better opportunities for living their lives the way they desire. Furthermore, all of these smart city qualities are enabled and enhanced with various advanced technologies. These technologies are discussed further in section 2.2.

2.2 Key smart city technologies

In order to deliver smart services to their citizens, smart cities utilise various technologies that provide the technical capabilities for carrying out these services. As a result, different technologies are the key enablers of nearly every smart city initiative. In order to understand how smart cities operate, we must first have a good understanding of these technologies as a whole, as well as have the knowledge of how the technologies can specifically be used for various smart city developments.

The most notable technologies used in smart cities include sensors, Internet of Things (IoT), communication technologies, big data and artificial intelligence (AI). In this section, the overall structure, characteristics and suitability of these technologies is evaluated, particularly based on the smart city definitions and objectives discussed in section 2.1.

2.2.1 Sensors

Sensors can be considered as the backbone of smart cities, particularly due to their ability to monitor and collect real-time data about various key areas of different cities [7]. Generally speaking, a sensor is a device that measures information of physical events, converts that information into an electrical signal, and returns the information in digital form, [8] so that it can be used by various systems and other technologies.

Smart sensors take the concept of information measuring further, as they also have the ability to process data and make decisions locally [8], which allows them to operate independently, without constant supervision. From the smart city perspective, these smart sensors are the most important, since, thanks to their local decision-making capabilities, they can be deployed in a wide variety of situations and trusted to perform their tasks reliably.

Sensor networks allow smart sensors to be utilised to their full potential. In these networks, smart sensors are connected with either wired or wireless connections, and the data from each sensor is captured and transferred, as well as routed around the entire network [9]. As a result, all of the data collected by the different smart sensors can be utilised extremely efficiently, thus improving the performance of the smart city, its solutions and technologies.

Sensor networks can vary a lot based on the types of sensors they consist of – for instance, homogenous sensor networks consist of sensors of similar types, whereas heterogenous sensor networks include various types of sensors [9]. In terms of smart cities, various types of sensors are utilised for collecting information – more traditional sensors are used to measure information about physical properties of cities, such as traffic, temperature or lighting, whereas wearable sensors provide information about the citizens' actions [10]. Through the use of these sensors, smart cities can provide a wide variety of services to its citizens. Different smart city solutions require different types of information, so the versatility of sensors, and sensor networks, makes them a key component of any smart city project.

2.2.2 IoT

IoT is another key technology behind smart cities. IoT plays a key role in utilising the data collected by smart sensors and other technologies, which in turn, helps with producing various services across the smart city [11]. Consequently, by utilising both smart sensors and IoT, cities can make significant advancements towards smarter solutions and services for their citizens.

IoT can be a difficult concept to define, as it consists of a large number of different devices and technologies. However, an overview of the general characteristics of IoT can be identified. For instance, the EC defines IoT as *"a network of billions of interconnected devices or systems ('things') that can be remotely controlled over the Internet"* [12]. These interconnected IoT devices include a wide variety of devices, such as smart home voice assistants, smart appliances, wearables, smart lights, energy consumption monitors and various security systems.

IoT devices collect and exchange data that is used for improving and developing services to smart environments [12]. In addition, the overall objective and purpose of IoT can be described as enabling *"things to be connected anytime, anyplace, with anything and anyone ideally using any path/network and any service"* [13]. This widespread connectivity provided by IoT is particularly important in smart cities, as all areas and services of the city must function in unison, so that the cities can continue to operate as intended.

Another benefit of IoT is that it provides a low cost and accessible connection between the physical and digital worlds [14]. This is particularly important in smart cities, as physical parts of the cities are controlled by different digital technologies – by providing a connection between the two worlds, IoT can help smart cities with providing suitable, efficient and versatile solutions for their citizens. The low costs and accessibility ensure that all citizens can benefit from the solutions, which further helps smart cities with achieving their goals of improving the citizens' quality of life with various smart solutions and services.

In general, the primary use of IoT in smart cities revolves around the development and implementation of an efficient communication infrastructure, which increases the simplicity and cost efficiency of the cities' public services, as well as provides a better connection between the different services deployed in the cities. Most notably, this IoT-based infrastructure integrates new and improved technologies to existing communication solutions, allowing for further developments in smart city IoT, both in terms of new devices and IoT-based services. [11] As a result, different communication solutions, which are discussed further in subsection 2.2.3, are integral in the effective development and implementation of various advanced smart city IoT solutions.

Based on the above discussions, IoT is an integral component of the technological developments behind successful smart city developments. As a result, further development and implementation of various IoT technologies and solutions will shape the future of smart city developments all around the world.

2.2.3 Communication

Communication solutions play a key role in smart cities, as they connect different smart city components, both machines and humans, with each other, providing a platform for the components to interact with each other [15]. This assures that all of the components can be used efficiently together to accomplish the goals of the smart city project. The role of communication in connecting smart city sensors and IoT technologies is particularly apparent – in fact, it can be considered as the main objective behind the development of smart city communication solutions [16]. Furthermore, as discussed in subsections 2.2.1 and 2.2.2, sensors and IoT combine to form the foundation of smart city projects, which is why the ability to effectively connect these two technologies with suitable communication solutions is a key part of different smart city developments.

Communication networks can be configured and organised in various ways. The different layouts, also known as topologies, determine how the network elements are connected to each other. Star, mesh, and point-to-point topologies are some of the most common approaches in communication networks. In a star topology, all network elements are connected to a central hub. This approach allows the network to function, even if some of the elements become faulty or unavailable. On the contrary, mesh topology involves connecting each network element with each other, which allows for more effective communication. Finally, in a point-to-point topology, two network elements are connected to each other, making it a simple and easily achievable option for communication networks.

Due to the varying communication and data requirements of different smart city components, many different communication solutions are required [15]. The most common communication technologies used in smart cities include Wi-Fi, Bluetooth, ZigBee, Long Range Wide Area Network (LoRaWAN), Long-Term Evolution (LTE) and 5G. Many of these technologies vary a lot based on their communication range and topology, as well as the purposes they are used for.

Bluetooth, Zigbee and Wi-Fi are used for short-range communication. Out of these technologies, the range of Wi-Fi is the longest at around 100 meters, whereas Bluetooth only supports communication up to 100 meters, and ZigBee networks only reach a range of 10 to 20 meters. LoRaWAN and LTE networks on the other hand, support more long-range communication, with ranges of 2 to 5 kilometres and 30 kilometres, respectively. [17]

In terms of network arrangements, star topology is the most common in smart city communication solutions, as Wi-Fi, LoRaWAN and LTE are all based on star topology. However, other topologies are also used – Bluetooth and LTE advanced are based on point-to-point connections, and the Mesh topology is used in ZigBee networking. [17] Due to the differences between these networks, smart city communication technologies are extremely versatile, and therefore, are able to support a wide variety of smart solutions in different areas.

ZigBee and LoRaWAN technologies are power efficient [17], making them especially suitable for IoT devices, which can often suffer from low energy and resource constraints. As a result, these technologies are extremely useful for various smart city solutions. ZigBee communication is most commonly utilised in smart buildings, smart grids and smart water management [18], whereas LoRaWAN helps with smart homes, smart healthcare and smart transportation [17], for instance.

Similar to ZigBee, Bluetooth is also suitable for smart buildings, smart grids and smart water management [18]. Compared to many other technologies, Bluetooth is also cheaper and easier to use, but due to its shorter communication range [17], its implementation can be quite limited. However, as a result of its cost efficiency and simplicity, Bluetooth is a great option for areas where larger communication ranges are not required. Moreover, the Bluetooth Low Energy (BLE) technology brings significant reductions to Bluetooth's power consumption [19], making it much more power efficient compared to traditional Bluetooth technologies. Furthermore, BLE supports multiple topologies and a higher number of different solution areas [19], which increases the potential of Bluetooth communication in short-range smart city applications.

Another fairly short-range communication technology, Wi-Fi, is used in a wide variety of smart city systems and solutions [18]. Perhaps the most notable difference between Wi-Fi and many other communication technologies, such as ZigBee and Bluetooth, is that Wi-Fi supports higher data rates [18], making it a more effective solution for various situations. In addition, despite its traditional deficiencies in the area of power consumption, the advancement of Wi-Fi has enabled the development of more power efficient Wi-Fi solutions as well. For instance, in various Wi-Fi technology -utilising smart city applications, such as smart water networks and unmanned aerial vehicles, a low level of power consumption has been reached [18]. Consequently, the power efficiency, as well as the general performance, of Wi-Fi can be expected to experience more and more improvements in the future.

In addition to the benefits discussed above, Wi-Fi's versatility also makes it a suitable communication solution for various smart city implementations. Most notably, Wi-Fi technologies can be used to effectively transfer data to the internet, allowing the information to be used anywhere, at any time. As a result, the short range of Wi-Fi is not an issue, as long as a Wi-Fi enabled device is close to the deployed smart system, so that the information can be transferred as efficiently as possible. Moreover, as Wi-Fi technologies are incredibly common, Wi-Fi based solutions are accessible to all types of smart cities, systems and solutions.

The main benefits of LTE and LTE Advanced technologies are related to increased communication efficiency. For instance, LTE allows for more efficient information transmission and reduces latencies, while LTE Advanced provides higher data rates compared to other communication technologies [17]. However, due to their higher costs [17], the use of LTE technologies in smart cities should be carefully considered before wider implementation. From the perspective of resource optimisation and sustainability, LTE technologies should only be used if their benefits in other areas of resource management and sustainability outweigh the disadvantages caused by the lack of cost efficiency.

5G is the next evolution of wireless mobile communication. Therefore, the possible improvements 5G can provide to various smart city solutions must also be considered. Most importantly, 5G can provide the necessary base for expanding and developing smart cities in the future, as well as provide increased cost efficiency compared to other wireless technologies [20], such as LTE and LTE Advanced.

The high speeds and increasing number of connections provided by 5G allow cities to provide smart services to new locations, which cannot be reached with previous communication technologies, thus accelerating the general growth of smart cities [20]. This helps with starting smart city initiatives in completely new areas, as well as provides additional development opportunities to existing smart city projects – faster and better connections enable more effective communication, which means that smart cities can utilise their existing solutions and technologies, such as sensing and IoT devices, more effectively than before. Moreover, due to the increased cost efficiency, 5G opens up possibilities for more efficient use of smart city resources, both now and in the future.

All in all, many different communication technologies can be used for enabling different smart solutions in smart cities. These technologies have varying advantages and disadvantages, meaning that there is not a universal technology fit for all situations. Instead, the most suitable communication technology depends on the smart systems' characteristics and general objectives.

2.2.4 Big data

As discussed in the previous subsections, smart city technologies collect and utilise large amounts of data about different components of the city. As a result, the concept of big data in smart cities has become increasingly important. Based on a definition by Joshi [21], big data is simply data that *"is large enough such that it cannot be processed on a single machine"*. In smart cities, everything from the overall infrastructure to different smart services is connected with each other, resulting in a large amount of diverse data that requires extensive and thorough analysis in order to be utilised most effectively. This data clearly cannot be processed on a single machine, thus fulfilling Joshi's definition of big data. Therefore, proper understanding of how big data impacts smart cities is crucial to any future smart city developments.

A major motivation behind big data in smart cities is to achieve more sophisticated, extensive and real-time understanding and control of smart city components [22]. As a result of the increased understanding, smart cities can prioritise the development of the most important components and solutions, and not waste resources on less important solutions, which allows the cities to develop much more efficiently. Moreover, the extensive and real-time control of smart city components further increases the cities' efficiency and general success.

Big data can often be used together with IoT to improve the performance of smart cities. In fact, there is a close connection between smart cities, IoT and big data, as one will not function properly without the others [3]. Various IoT solutions are implemented all across the cities, providing various types of data that helps with the successful development of big data, and at the same time, big data technologies enhance the development of IoT by providing more effective data processing capabilities to different IoT systems [23]. Moreover, IoT big data, which can be slightly different compared to conventional big data, will become increasingly common in the future [23]. As a result, the connection between IoT and big data in smart cities will become even more relevant in the coming years.

Due to the various features and benefits of big data discussed above, effective utilisation of big data plays a key role in successful smart city initiatives and developments. As a result, the ability to effectively and accurately analyse and process big data is an integral part of smart cities, both now and in the future.

2.2.5 AI

AI is an important part of smart cities, particularly due to its ability to efficiently analyse, process and utilise data in ways that is not possible with other technologies. More specifically, AI will play a key role in structuring the vast amounts of data and improving the decision-making in smart cities of the future [24]. As a result, the understanding of AI and the added efficiency it provides to various smart city solutions is extremely important.

One of the founding fathers of AI, Professor John McCarthy [25], defines AI as *"the science and engineering of making intelligent machines, especially intelligent computer programs"*. Moreover, according to the Britannica encyclopaedia [26], AI stands for *"the ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings"*, and various AI systems often have many human-like intellectual characteristics. It is precisely this intelligence and human-like decision-making ability that makes AI a promising technology for different smart city developments.

Many different technologies fall under the umbrella of AI. For instance, machine learning (ML) is a subfield of AI, and deep learning (DL) is considered a subfield of ML. Furthermore, these concepts can be divided further into many different types of techniques. These techniques have fairly different, and in many ways, more advanced, features compared to more traditional AI solutions.

ML involves algorithms that are able to autonomously learn and improve from the training data they receive, allowing them to become “intelligent” without requiring specific programmed instructions for every situation and action. Consequently, the intelligence of ML systems closely resembles human intelligence, as humans also learn many things by themselves, through different experiences. As a result, ML-based systems can be applied to many traditional operative city tasks to increase the efficiency and reliability of smart cities and their operations.

ML is typically further divided into three areas: supervised, unsupervised and reinforcement learning (RL). Supervised learning is based on accurate and specific training data, containing many examples of situations the algorithm is being trained to be used in. Unsupervised learning on the other hand, is able to make use of less accurate training data by finding different patterns in unorganised data. By utilising both technologies, smart cities can develop effective ML-based solutions that are suitable for a wide variety of scenarios.

Finally, RL does not require much training data, as it learns directly from the consequences of different actions – RL algorithms receive “rewards” from favourable actions, whereas unfavourable actions result in “punishments” [27]. Over time, based on these rewards and punishments, RL algorithms learn the most optimal way of completing specific tasks. This type of learning is most similar to the learning of humans, meaning that RL-based systems are often most suitable for the aforementioned operative tasks, where they can replace, or work alongside, humans to achieve the best results.

DL also involves various elements of supervised and unsupervised learning, as well as RL. In addition, neural networks, such as Artificial Neural Networks (ANNs), Deep Belief Networks (DBNs) and Convolutional Neural Networks (CNNs), play a key role in enabling these learning processes in various DL solutions.

ANNs are considered as the starting point of DL research, whereas the introduction and development of DBNs has provided various improvements to the analysis of unlabelled data. Furthermore, CNNs achieve further efficiency, particularly due to their layer-based training approach and minimal pre-processing requirements. [28] Due to this efficiency, CNNs are particularly suitable for smart systems and solutions.

DL brings added efficiency to data analysis by solving some of the key issues plaguing various AI and ML solutions. For instance, DL is better for analysing raw data, as well as discovering complex structures from large-scale datasets. The latter of these features in particular makes DL a suitable solution for a wide variety of areas, from scientific developments to business and governmental issues. [29] As a result, DL is an extremely versatile technology compared to many of its predecessors.

DL is also extremely useful for big data analytics. DL techniques, such as DBNs and CNNs, are able to process data more efficiently than other techniques, which provides drastic improvements in performance, even in simpler systems [30]. In addition, as discussed earlier, DL is an extremely versatile technique for analysing different types of data, which makes it even more suitable for big data analytics. As a result of these DL features, not only does big data analytics become more effective, but it also becomes more accessible. Therefore, by utilising DL, a smart city can fully benefit from all of the data gathered by different technologies deployed across the city.

Personalisation is another significant area of development enhanced by various AI technologies. A good example of AI in smart city personalisation is presented in [31], where Chin et. al discuss how ML techniques can be used in combination with IoT and big data in smart cities to provide personalised services to citizens. The main idea behind these personalisation approaches is to utilise ML for analysing citizen behaviour in order to gain information the system can use to adapt different smart services in such a way that they match the citizens' needs and expectations much better than before [31].

With personalisation solutions similar to the approach discussed above, smart cities can achieve significant quality of life and resource efficiency improvements – personalisation means that citizens will receive the services and opportunities they require in their daily activities, while only using the optimal amount of resources that are specifically required for those tasks. These benefits combined with the general adaptability and big data analysis capabilities discussed earlier showcase the suitability and potential of AI in both current and future smart city developments.

2.3 Smart cities around the world

Various smart city projects are carried out all around the world. The analysis of these cities showcases the potential and general key objectives of smart city projects, as well as provides valuable information on how future cities can work towards smarter, more resource efficient and sustainable solutions in different areas.

Some of the most successful smart cities around the world include London, Barcelona, Copenhagen, New York, Dubai and Singapore. Moreover, many Finnish cities have adopted various smart solutions. The aforementioned smart cities are chosen for further analysis in this section due to their successful and innovative solutions, particularly in the areas of resource optimisation and sustainability.

London is one of the major cities in Europe, and such is the case in the area of smart cities as well. In fact, the central motivation behind the Smarter London Together project, launched in 2018, is to transform London into the smartest city in the world in the near future [32]. Moreover, London's smart city initiatives are mainly focused on the development of smart and effective solutions for transportation, the environment, equal healthcare, housing, culture and economic development [32]. The London smart city project has also already seen a great level of success – in 2019, London achieved its goal, as it was identified as the smartest city in the world, particularly due to its advancements in mobility, governance, technology and urban planning [33]. Moreover, with further technological advancements, the London smart city project will only continue to develop in the future.

Barcelona has often been considered as one of the leading smart cities in the world, and its smart city initiatives have received recognition from both the EC and the United Nations (UN) [34]. The 22@Barcelona innovation district, which aims to provide *"modern spaces for the strategic concentration of intensive knowledge-based activities,"* is a key part of Barcelona's smart city project [35]. Key strategic areas covered by this initiative include media, information and communication technologies, medical technologies, design and energy [35]. In addition, the strategy emphasises various waste management and environmentally friendly transportation solutions [35].

Copenhagen is another good example of a thriving European smart city, as it has become one of Europe's fastest growing cities in recent times [36]. Due to being a Nordic city, and therefore sharing many similarities with Finnish cities, including Salo, Copenhagen is one of the most important cities to inspect for the purpose of this thesis.

In the Copenhagen smart city project, environmental development is considered particularly important – most notably, the city is focused on providing improved mobility and accessibility to its citizens through effective public transport and cycling opportunities [36], thus making the city more environmentally friendly, while also providing the citizens with effective and suitable solutions for improving their daily lives. In addition, future goals of Copenhagen include increasing the city's capacity by 100,000 additional citizens [36] and becoming carbon neutral [37] by the year 2025.

Outside of Europe, New York and Dubai are among the world's leading smart cities. In New York's smart city program, smart city projects are required to be sustainable, modern, accountable, reliable and thriving [38]. The private sector is also heavily involved in developing smarter and more innovative solutions for New York [38], which opens up further possibilities for effective smart city development. Moreover, Dubai has made significant progress towards becoming a successful smart city. The purpose of the Smart Dubai 2021 strategy is to *"embrace the future and emerge as a world-leading city by 2021"* by prioritising seamless, efficient, safe and personalised smart solutions [39]. The main areas of focus in the Dubai smart city strategy are smart living, smart economy, smart people, smart mobility, smart environment and smart governance [39].

The characteristics of the New York and Dubai smart city projects discussed above showcase many notable components of smart city development in general. Despite being larger cities located in different areas of the world, the approaches of New York and Dubai share many similarities with smart city projects in both bigger and smaller European countries and cities as well. As a result, regardless of their size and location, all current and aspiring smart cities can draw inspiration from other successful smart city projects and apply that knowledge to make further improvements to their own smart solutions and services in the future.

Singapore takes the smart city initiative even further by aiming to become a smart nation that utilises technology to provide meaningful and fulfilled living to its citizens. In order to carry out their smart nation initiative, Singapore focuses on building a suitable *"Digital Economy, Digital Government and Digital Society"* that provide the base for the development of various smart services across the nation. Some key areas include smart transport, health and finance, as well as sustainable and secure smart homes. [40]

In order to carry out the smart nation strategy discussed above, Singapore utilise a wide variety of smart technologies, such as sensors, big data, AI and IoT, [40] discussed in section 2.2. Therefore, Singapore is a great example of how different advanced technologies can be used for developing traditional cities and their components towards a more resource efficient, sustainable and secure future.

In Finland, many cities have started developing various smart city initiatives. For instance, in Helsinki, the Kalasatama district aims to provide smart services that save an hour of the citizens' time each day, and the Jätkäsaari area is focused on smart mobility solutions, alongside many other smart services. Moreover, many other Finnish cities, such as Espoo, Tampere, Turku and Jyväskylä, have started numerous smart city initiatives. [41] Finally, the city of Lahti, which focuses on smart environment, mobility and infrastructure solutions, as well as creating a sustainable society with a circular economy, has been chosen as the European Green Capital for 2021, particularly due to its environmentally friendly initiatives [42]. In addition to these projects, the city of Salo has recently started its development towards a smart city. This project is examined more closely in chapter 5.

What we can learn from the examples discussed in this chapter is that smart city projects can be successful in many different circumstances – regardless of the region, size and objectives of the city in question. While there are some approaches and objectives, such as smarter energy usage, more environmentally friendly transportation and increased sustainability in general, that appear in the strategies of most of these smart cities, the exact approach to implementing various smart solutions and services can still vary quite a lot between different cities. Consequently, the key to a successful smart city project is to understand the objectives and characteristics, as well as the limitations, of the city, so that the exact requirements of different smart solutions and services in specific areas can be identified.

3 Resource optimisation and sustainability in smart cities

Resource optimisation and sustainability play a key role in the success of smart cities. In fact, lower resource consumption can be considered as one of the major metrics of technical progress in smart cities [43], and the pursuit of sustainability through smart solutions has increased the interest towards different smart city projects and initiatives [44]. Moreover, since resource efficiency and sustainability were identified as some of the key smart city characteristics in section 2.1, the importance of resource optimisation and sustainability in all smart city projects is extremely apparent, and therefore, these topics are covered extensively in this thesis.

Resource optimisation involves designing systems and services that can achieve the best results with as few resources as possible, thus making the most out of any available resources. Furthermore, sustainability is focused on making sure that current operations do not jeopardise any future opportunities. In the case of smart cities, optimal use of resources allows smart cities to reliably provide all the necessary services to their citizens, while sustainability ensures that different smart city initiatives and services can be carried out in the future as well. These two qualities are very closely connected, and therefore, are equally important to the success of different smart city projects, solutions and services around the world.

In this thesis, smart energy, smart waste management, and smart mobility are chosen as the main focus areas regarding smart city resource optimisation and sustainability. These areas are heavily emphasised in the successful smart city projects discussed in section 2.3, making them the most important areas to discuss. All of these areas include a wide variety of benefits that can significantly improve resource optimisation and sustainability in both current and future smart city projects.

Smart energy, its characteristics and benefits to smart cities are discussed in section 3.1. The different areas of smart waste management on the other hand, are covered in section 3.2. Finally, in section 3.3, various smart mobility and transportation solutions are examined.

3.1 Smart energy

Energy production and consumption are key components of any city, as practically all city services and areas require energy in some fashion. Smart energy takes this concept further by allowing smart cities to produce and utilise energy more cheaply and effectively, as well as provide their citizens with more optimised and resource efficient energy solutions for various purposes. As a result, smart energy not only helps with more sustainable energy generation, but it also enables other smart resource optimisation and sustainability solutions.

Generally speaking, any type of energy that is enhanced with different information and communication technologies can be considered as smart energy. Moreover, smart energy consists of three major areas: efficient energy distribution, generation of low-carbon energy and energy consumption optimisation. [3] By efficiently carrying out these areas with the help of various technologies, smart cities can achieve a wide variety of smart and sustainable energy solutions for both their citizens and the cities themselves.

Smart energy is achieved with a wide variety of techniques, such as smart grids and technologies, as well as smart and energy efficient building and lighting solutions. The aforementioned techniques, as well as their suitability and implementation from the perspective of smart city resource optimisation and sustainability, are discussed in subsections 3.1.1 – 3.1.4.

3.1.1 Smart grid

The smart grid can be considered as the foundation of successful smart energy solutions. Smart grids support the development and implementation of high-quality and sustainable energy systems, which are also extremely secure and cost efficient to operate. Moreover, with the help of smart grids, smart cities can effectively utilise many different types of energy sources in combination with each other. [3] This allows the cities to provide energy more reliably – even if a specific energy source is unavailable, the lacking energy can be received from another source, which allows the cities to continue all operations without downtime. Due to these benefits, proper understanding of smart grids is an integral part of efficient energy management in smart cities.

In general, the main purpose of a smart grid is to enable two-way delivery of both energy and information [45]. This enables the use of various data and technology -driven energy management solutions, resulting in smarter and more efficient smart city energy management. For instance, smart grids utilise advanced technologies and communication solutions to gather and analyse real-time information about current energy levels and energy requirements across the city, which allows the city to rapidly balance its energy supplies based on the energy usage of each different area in the city [45]. As a result, smart grids and the technologies they utilise allow smart cities to optimise their energy usage by ensuring that each area has the energy it requires, while making sure that any area does not have an abundance of energy it does not need. Smart technologies in energy management and resource optimisation are discussed further in subsection 3.1.2.

Another key feature of smart grids is that they can potentially allow consumers to generate their own energy, and send the excess energy back to the grid [46], which provides additional possibilities for using renewable energy sources. For instance, consumers could generate energy with solar panels, and the rest of the energy can be transferred to the smart grid and used in other areas. With the increase of renewable energy, more and more sustainable energy solutions can be implemented in different areas of the city. As a result, smart grids play a key role in sustainable smart cities, both now and in the future.

Renewable energy and smart grids are at the centre of New York's energy strategy. In fact, by the year 2030, the city aims to provide 70% of their electricity from renewable energy sources. The main objective of New York's renewable energy strategy is to develop a renewable smart grid that allows the city to distribute renewable energy to different areas, as well as ensure that the citizens will receive the maximal benefits from various renewable energy solutions across the city. [47]

New York also utilises smart grids for various other energy solution improvements, with the development and implementation of advanced smart grid technologies as the key area of focus. The purpose of these technologies is to support the development of distributed energy systems that generate power in diverse ways. In addition, the technologies should help with making sure that the city's buildings are *"flexible and responsive under changing conditions."* [47] These factors are key to successful smart city energy solutions, as the conditions and energy requirements in smart cities are changing constantly. By implementing an approach similar to new York's smart grid strategy, smart cities can use various technologies for providing the citizens with smarter and more effective energy management solutions.

3.1.2 Technological solutions for smarter energy management

As discussed previously, different technologies enhance the energy management processes and measures around smart cities, making the cities more and more energy efficient. Not only do the technologies help with improving existing solutions, but they also provide opportunities for the development of entirely new solutions. Due to this high variety of possible solutions, extensive knowledge of the different technologies and smart energy areas is a necessity for successful smart energy developments.

Generally speaking, smart energy is based on extensive cooperation between the different stages of the energy management process, such as the generation, distribution and use of energy across the smart city. Various technologies, such as sensors, IoT devices and smart algorithms, ensure that this cooperation is carried out as effectively as possible. Sensors gather data from power transformers and transmission lines, whereas IoT devices collect information about how energy is utilised in different parts of the city. This information can then be analysed with automated, particularly ML-based, algorithms to enable real-time learning and decision-making regarding the smart energy systems in the city. [48] With this approach, a smart city can determine what types of energy solutions are required, thus improving the energy efficiency and quality of life in the city.

The effectiveness of smart energy solutions can also be enhanced with various communication technologies. For instance, Zigbee networks can be used to improve the monitoring and optimising of building power consumption [49], and cellular networks powered by renewable energy can be integrated into smart grids, resulting in reduced costs and more efficient smart grid solutions [50]. Moreover, in [51], Li et al. present a 5G-enabled system for improving the energy efficiency and resource allocation of various IoT systems.

5G networks also provide many other benefits to smart energy. 5G is believed to *"unleash the next wave of Smart Grid features and efficiency,"* which will provide significant financial benefits and savings in the coming years. By using 5G to connect various devices into the smart grid, the energy consumption and requirements of these devices can be monitored more accurately, which will allow smart cities to plan their energy infrastructure much more effectively than before. In addition, 5G connections will increase the reliability of smart grids by reducing and preventing power outages and downtime. [20] As a result, 5G will play a key role in many future smart energy solutions.

In recent years, Finnish cities have made significant progress towards technology-based smart energy solutions, particularly with the help of the Smart Energy Finland Program. The program focuses on supporting the development of various smart energy innovations by providing funding of around a hundred million euros to various companies developing smart energy solutions. The motivation behind this funding is to enable the development of smart systems for more efficient energy consumption management in the future. These smart systems are primarily expected to utilise key technical developments, such as digitalisation, IoT and AI, to improve energy management in different areas across Finland. [52]

Technology-based smart energy initiatives like the Smart Energy Finland Program, as well as many others around the world, are at the forefront of resource efficiency and sustainability advancements in different smart cities. These advancements range from energy efficient buildings to smart lighting, which are covered in the next two subsections, respectively.

3.1.3 Smart energy in smart buildings and homes

Due to the high energy consumption and general lacking energy efficiency of buildings and homes, smarter and more effective energy management solutions are required for optimising the use of resources in this area. Different smart technologies, such as IoT and DL, play a key role in this transition towards smart energy management, as they can be used for real-time monitoring and analysis of the buildings' energy consumption. [53] The information gathered with these approaches allows a smart city to determine the necessary smart energy solutions for different buildings, improving the energy efficiency and overall quality of smart buildings and smart homes across the city.

In recent times, Denmark has been heavily focused on the development of energy efficient smart buildings. One of the key areas of focus has been centred around remote monitoring of the energy consumption of various key building services, such as heating, ventilation and cooling. [6] This remote monitoring improves the efficiency of the energy management process, as any issues and energy inefficiencies in buildings can be detected on short notice, allowing the city to quickly initiate the necessary measures for improving the energy efficiency of those buildings, regardless of their location. As a result, with the development of remote energy consumption monitoring, the energy management of smart buildings and homes will become more and more accessible and efficient in the future.

In addition to energy consumption monitoring, Denmark has also implemented smart solutions for building heating and cooling. For instance, district energy systems, consisting of large thermal heating and cooling storages and heat pumps, are a key area of the used smart energy strategies and approaches. This type of system is utilised in the Greater Copenhagen project, delivering smart heating and optimised energy usage solutions to buildings across the Greater Copenhagen area. [6]

Since the aforementioned Greater Copenhagen area comprises of around 4.4 million people across both Eastern Denmark and Southern Sweden [54], the district energy system described above is a key contributor in providing many European cities with smarter and more energy efficient solutions. Furthermore, due to the success of Greater Copenhagen energy system, similar approaches will likely become more and more common in other cities and countries as well, which will increase the overall energy efficiency of smart cities all around the world.

Energy efficient buildings are also a key area of New York's smart energy initiatives. Most importantly, New York aims to develop carbon neutral buildings, as well as introduce new technologies that provide smarter and more energy efficient solutions for building heating and cooling. The implementation of these solutions is believed to lead to *"higher performing"* and *"healthier"* buildings, as well as a more effective transition towards carbon neutrality. [47]

By adopting similar approaches to the Denmark and New York smart energy strategies, different smart cities can increase the energy efficiency of their buildings, resulting in more sustainable, efficient and citizen friendly infrastructure. Moreover, combining smart and energy efficient buildings with other smart energy solutions, such as smart grids and smart lighting, allows for further advancements in energy efficiency and sustainability.

3.1.4 Smart lighting

Smart lighting is another key component of smart energy solutions. Most importantly, smart lighting provides significant energy savings, while also making cities safer and more comfortable for their citizens. As a result, smart lighting helps smart cities with their goals of optimising the use of resources and improving the citizens' quality of life in different areas.

The ability to adapt to different situations and conditions is a key feature of smart lighting solutions in urban environments. In order to achieve this adaptability, smart lighting systems utilise a network of sensors that monitor citizens' movements in real time, and adjust the lighting based on the gathered information. In addition to monitoring the movements, the sensors provide real-time information about the systems' usage and energy consumption. [55] This allows smart cities to identify which areas require the most extensive lighting solutions, as well as recognise the areas where the energy consumption of lighting solutions exceed the desirable amount. The city can utilise this information to prioritise improving the quality and resource efficiency of lighting solutions in specific areas, where proper lighting is most important and the energy consumption of lighting solutions is a particularly large concern.

In addition to energy savings, safety and comfortability, smart lighting also provides various other benefits to smart cities, particularly due to recent wireless technology developments. Firstly, smart lighting solutions result in extremely significant cost savings in different smart cities around the world, and with the increased cost efficiency of 5G connectivity compared to other wireless technologies, the cost savings are now even more significant. Secondly, by connecting smart lighting systems to the cities' broadband networks, the systems are also capable of monitoring the cities' air quality, [20] for instance.

In the United Kingdom, the South Kesteven district, located in Lincolnshire, utilises smart LED street lighting and IoT to monitor the air quality in the district [56]. Based on the success of this initiative, air quality monitoring with smart lighting will likely be more widely implemented in, for instance, the London smart city project, as well as many other smart cities around the world.

Copenhagen has also implemented smart lighting solutions by installing around 20,000 smart streetlamps in order to make progress towards their carbon neutrality goal. The lamps include a communication module, which allows them to be automatically controlled and adjusted based on different situations and the citizens' movements. This approach particularly supports cycling opportunities in the city, which will greatly contribute to both resource efficiency and the citizens' quality of life, especially since around half of Copenhagen's citizens commute by bicycle. [57]

Based on the above discussions, smart lighting is not only suitable for smarter energy usage, but it also provides opportunities for safer and more effective mobility around the city, which further increases the resource efficiency and sustainability of smart cities. Smart, resource efficient and sustainable mobility solutions are discussed further in section 3.3.

3.2 Smart waste management

Smart waste management is one of the key processes for optimising the use of resources and increasing sustainability in smart cities. It allows cities to, for instance, recycle and reuse waste to turn the waste into additional resources much more efficiently than before. Moreover, smarter waste sorting and collection solutions allow smart cities to manage waste more effectively, while ensuring that only the required amount of resources is used for each waste management solution. As a result, the understanding and improvement of different waste management processes is integral to the success of both current and future smart city initiatives.

Waste management generally consists of the following areas: waste deposit, waste collection, waste delivery and waste processing. In smart cities, these procedures are performed with the help of different technologies, which allows the cities to, for instance, monitor waste chains, control emissions and recycle waste more effectively. [58] In addition to the aforementioned areas, waste prevention is also an important part of waste management – in fact, with effective waste prevention, the other stages of waste management are not even always fully required. As a result, in order to ensure resource efficient and sustainable waste management processes in smart cities, many different factors need to be considered.

In addition to improving existing waste management practices, various technologies can also introduce new solutions for smarter and more sustainable waste management in the future. In this section, smart city waste management processes are evaluated from many different perspectives. The key measures of preventing and reducing the amount of waste in smart cities are discussed in subsection 3.2.1. Additionally, subsection 3.2.2 covers the overall process of managing waste, from waste collection to sorting and recycling. Finally, in subsection 3.2.3, various smart waste management solutions from different smart cities around the world are presented.

3.2.1 Waste prevention

Excessive generation of waste can mainly be prevented by minimising the amount of material used in the manufacturing of various products and services, as well as making sure that all products are utilised as efficiently as possible [59]. This approach shares many similarities with general smart city resource optimisation practices, which shows the benefits of waste prevention in ensuring the efficient use of smart city resources.

Smart city technologies can provide additional effectiveness to the waste prevention approaches discussed above by collecting and analysing information about the use of different products and services, identifying which of them are the most waste efficient, and which areas still require more work. With this information, cities can prioritise the manufacturing of those products and services that do not generate a lot of waste, as well as develop the less waste efficient areas towards becoming more efficient in the future. If waste generation can be reduced with these measures, the required effort in e.g. waste collection and processing will also be much lower, resulting in significant resource savings and resource optimisation opportunities in smart cities.

Waste prevention is an integral part of London’s waste management program. In addition to minimising the amount of municipal waste in the city, London’s waste prevention initiative focuses on reusing and recycling their waste with the goal of turning the waste into additional energy. With this approach, London aims to increase recycling rates and resource efficiency, as well as ensure that it has the required capabilities for managing all the waste generated across the city. [60]

Barcelona has also made significant progress towards more effective waste prevention. For instance, in their waste prevention plan from 2012 to 2020, Barcelona emphasised the reuse, recycling and general prevention of waste [61]. In addition, the Barcelona zero waste strategy, initiated in 2016, supports the city's waste prevention efforts, particularly by focusing on getting the citizens more involved in the waste management process [62].

The above discussions on the waste prevention approaches of London and Barcelona highlight the suitability and potential of waste prevention in smart cities. Successful smart waste prevention solutions have already been implemented, and as the technologies and knowledge of the subject keep developing, various waste prevention techniques will become more and more useful in the future. Moreover, the high number of smart technologies that can be used to accelerate and improve the process of waste prevention will lead to even better results.

3.2.2 Smart waste collection, sorting and recycling

Despite the benefits of waste prevention, the generation of waste cannot generally be avoided entirely, which means that smart cities also require many other waste management measures. Most importantly, different waste management solutions, such as waste collection and sorting, can be integrated into general city development plans [59], allowing cities to focus on waste management at all times. For instance, waste collection practices and suitable placement of recycling stations can be considered during the entire development process of smart architecture and services in different areas, so that each city area will immediately include the waste management solutions that are required for that specific area.

The approach described above will provide significant resource efficiency and sustainability improvements to smart cities, as the waste management process across the entire city can be optimised right away. Consequently, the city will not spend too many resources on waste management, while still keeping the city as clean and comfortable as possible. Based on this discussion, the city and its governance play a key role in the development of smart, resource efficient and sustainable waste collection, sorting and recycling solutions.

In addition to the public sector and the city itself, many other parties, such as private waste service providers, waste treatment companies and citizens [59], also play a key role in waste management. In smart cities, the service providers and companies utilise different technologies, such as sensors, IoT and AI, to provide smart waste management solutions according to the cities' needs and requirements. Moreover, citizens' participation in waste management can be increased with smart services that make recycling as seamless as possible.

In order to develop the solutions described in this section, the use of smart sensors for waste data collection is extremely important. Not only does the sensor data help with developing more efficient waste management services by detecting the amount of waste across smart cities, but it can also provide various financial benefits. The sensors can, for instance, measure the waste levels in waste bins to provide information that can be used to optimise the waste collection process, making it both more automated and cost effective [63]. This concept is taken further in one of the suburbs of Copenhagen, Albertslund, where the performance of multiple different sensors is compared in order to achieve the most effective solutions for cost effective waste collection [6].

Based on the above discussions, smart waste management approaches commonly involve utilising the aforementioned waste data collected by smart sensors for smarter and more automated decision-making. Moreover, after being collected by different sensors, the waste data is transferred for further analysis with the different communication technologies, such as Wi-Fi, Zigbee and LoRaWAN, discussed in subsection 2.2.3. This analysis provides further information about, for instance, the volume of different waste types generated in a specific area, as well as the average time between waste collections, allowing smart cities to optimise the waste management process by implementing additional waste bins and modifying waste collection times and routes.

Many other smart technologies and solutions can also be used to improve waste collection. For instance, if done correctly, smart waste detection can provide significant benefits and optimisation opportunities to waste collection. In smart cities, waste can be detected with various DL-based methods, such as CNNs [53]. These networks are, for instance, trained with city and street images, so that they are able to detect unrecycled waste and evaluate street cleanliness in different parts of the cities they are implemented in [53].

The aforementioned ability is integral to smart waste management, as it allows smart cities to detect areas where littering is most common, and prioritise waste collection, street cleaning and additional waste bins in those areas. By combining the DL-based information of unrecycled waste with the sensor data from waste bins, smart cities can form an overview of their waste situations, resulting in effective and optimised waste collection solutions.

Waste sorting is another important area of waste management where smart cities can utilise technology to make significant advancements and improvements. Smarter and more automated waste sorting is particularly necessary due to the challenges and lack of hygiene related to manual waste sorting processes [63]. Moreover, compared to conventional waste sorting solutions, automated waste sorting is much more effective, making it an extremely resource efficient solution for waste management – if waste sorting can be done effectively with less resources, the leftover resources can be invested into developing various other city areas.

Smart cities can primarily utilise AI-based solutions for waste sorting, allowing them to increase the efficiency of the process, as well as approach waste sorting in a new and improved fashion. For instance, ML-based waste sorting systems, which are trained with a large number of waste examples, can adapt to situations beyond preprogramed rules, allowing them to exceed the performance of both manual waste sorters and previous waste sorting systems [63]. Moreover, various systems utilising DL algorithms are able to sort waste with over 90% accuracy, and most notably, CNN-based systems can reach an accuracy of over 99% [64]. These solutions are likely to keep improving in the future as a result of the general improvement of AI-based technologies, and therefore, will be an integral part of the future of smart waste management.

3.2.3 Smart waste management solutions around the world

Several successful waste management initiatives have been implemented in different smart cities around the world. These initiatives showcase the benefits and potential of smart city waste management, as well as provide insight on the different ways smart cities can enhance their resource efficiency and sustainability through effective and smart waste management.

Barcelona has made significant developments in different areas of waste management. For instance, the city is efficiently turning their waste into resources by separating recoverable waste, such as paper, plastic and glass from all other waste, and then burning the unrecoverable waste in furnaces in order to generate additional energy [35].

As a result of the approach described above, Barcelona is able to optimise the creation of resources from its waste. Recoverable waste can either be reused directly or used as raw material for producing energy or other products. Furthermore, the city also benefits from the unrecoverable waste, which cannot directly be utilised in the aforementioned ways, by using it to enhance the city's energy generation. Since waste can likely never be prevented entirely, this extensive and versatile waste-based energy source is very sustainable, and therefore, it will remain as a significant component of Barcelona's energy and waste management strategies for years to come.

Barcelona has also deployed a smart and automated system for waste collection in the city. The system consists of a large number of waste drop-off points across the 22@Barcelona district. The drop-off points are connected with an underground pipe network that transports the waste to their collection area. The waste is also compressed in this area in order to increase the required time between waste collection, which reduces traffic and noise pollution in the city. Furthermore, the system is enabled by a communication network that is used for controlling the system and measuring the fill level of waste containers in order to optimise waste collection times and routes. [35] With these measures, Barcelona ensures that it only uses the minimal amount of resources required for its waste collection, while still maintaining cleanliness and general comfortability around the city.

The Singapore waste conveyance system is one of the best examples of a smart waste collection system, particularly due to its ability to automate the waste collection process. The system is based on an underground pipe network that collects and transports household waste to a container where it is later collected by waste trucks. A major benefit of this automation is that it reduces the need for manual labour in the city's waste management endeavours. [65] As a result, Singapore can achieve a more efficient and sustainable use of its resources, as the resources of manual work can be allocated to other areas, where automated solutions are not available.

London's smart waste monitoring solution is mostly based on three smart techniques – data analytics, smart waste bins and waste collection optimisation. Data regarding different waste types, as well as waste generation times and locations, is analysed in order to enhance waste management solutions in areas where waste generation causes the most issues. In addition, sensors installed in smart waste bins monitor the bins' fill levels, providing data on when the bins need to be collected. All of this data is then used in combination with GPS-based vehicle location tracking in order to optimise waste collection times and routes in different areas of the city. [66] As a result, London is able to manage their waste effectively, while also enhancing their resource efficiency by making sure that any unnecessary resources are not consumed during the different stages of the city's waste management process.

Smart waste management practices have also been implemented in Finland, particularly in the Kalasatama area, which is one of the neighbourhoods of Finland's capital, Helsinki. The smart waste collection system of Kalasatama takes a similar approach to the automated waste collection system of Barcelona discussed above – waste is automatically transported through an underground pipe network, reducing the need for waste collection vehicles in the area. Moreover, Kalasatama has deployed various smart waste bins, which contain sensors that monitor the bins' fill levels in real time, as well as notify when the bins are close to filling up, and therefore, should be emptied as soon as possible. [67]

Finnish smart waste management solutions are also implemented in other parts of the Helsinki Metropolitan Area – a pipeline-based waste collection system, located in Jätkäsaari, aims to utilise technology *"on an unprecedented scale"* in order to provide a new and innovative approach to waste recycling. Similar to the Barcelona, Singapore and Kalasatama automated waste collection systems discussed earlier, the Jätkäsaari waste collection system is based on an underground pipe network, which is used to quickly transfer waste to the collection station, where it is collected by the city's waste collection trucks and transported onwards for recycling. This system provides significant benefits to the Jätkäsaari area, particularly in the form of comfort and reduced traffic near the citizens' houses, as well as the general increase of simplicity and safety in the Jätkäsaari waste management processes. [68]

The previous examples of the Kalasatama and Jätkäsaari waste management solutions are particularly encouraging in terms of the objectives of the Salo smart city project, as they show that different smart waste management solutions can be implemented in smaller Finnish locations as well. By adopting similar approaches to the Kalasatama and Jätkäsaari waste management solutions, the general efficiency of waste management in Salo, as well as across Finland as a whole, can be significantly improved in the future.

All in all, the different waste management solutions discussed in this subsection show that waste management is a key component of some of the most developed smart city strategies and projects in the world. As a result, smart waste management should be considered in every smart city project, especially since it will only continue to improve due to the constant technological advancements made in various key areas. With the right approach, smart cities can utilise different smart waste management technologies and solutions to further improve their resource efficiency, sustainability and quality of life for years to come.

3.3 Smart mobility

Smart mobility plays a key role in resource efficient and sustainable smart cities due to its capabilities of reducing and preventing many of the issues plaguing mobility in today's cities. For instance, traffic congestions and delays can cost a lot of time and money, as well as cause many stressful situations to citizens, but by utilising various smart mobility solutions, smart cities can provide faster, cheaper and more comfortable transportation opportunities to their citizens [69]. In addition, smart mobility solutions provide significant improvements to energy efficiency. As a result, the understanding of the different areas of smart mobility is crucial to the successful development of both current and future smart city projects.

Smart and sustainable mobility consists of many different areas. Smart mobility solutions should improve the cities' public transportation by making it more affordable and resource efficient, as well as provide the citizens with a wide variety of mobility options, including improved cycling and walking opportunities. Moreover, similar to smart waste management, the planning, development and implementation of smart mobility solutions should be included in the entire city development process, from start to finish. [70] With these approaches, different smart cities can improve their mobility and transportation strategies and solutions, thus increasing their resource efficiency and general comfortability.

In the European Union (EU) smart mobility strategy, sustainable, smart and resilient mobility solutions are defined as the key areas of focus. In addition, the use and further implementation of new technologies is at the core of smart mobility improvements across Europe. [71] These focus areas and objectives of the strategy closely resemble the overall structure and aspirations of smart city projects in general, which showcases the potential and importance of smart mobility in smart city resource optimisation and sustainability.

Smart mobility is developed and implemented with a wide variety of solutions. Most notably, electric and smart vehicles, as well as various traffic reduction measures, ensure resource efficient and sustainable mobility in smart cities. These factors are discussed in more detail in subsections 3.3.1 and 3.3.2, respectively. In addition, the future of smart mobility, which is discussed further in subsection 3.3.3, is extremely promising, with many different strategies focused on future smart mobility developments.

3.3.1 Vehicles

Vehicles are a key component of mobility in nearly every city. However, the increasing use of vehicles can cause various issues, particularly in the form of increased noise pollution, worse air quality and reduced walkability in the city. In addition, the resource consumption of vehicles is extremely significant, both in terms of energy and costs. By incorporating electrical and smarter vehicles into their mobility strategy, smart cities can reduce emissions and achieve more cost effective and citizen friendly mobility solutions.

Electric vehicles make use of renewable and cheaper energy sources, making them a suitable and resource efficient solution for effective mobility and emission reduction in smart cities. The benefits of electrical vehicles can be realised in both personal and public transport – not only can citizens charge their own electric vehicles during the night in order to make use of the cheaper prices of off-peak energy, but electric buses also improve the energy efficiency of public transport. Copenhagen is at the forefront of electric public transport in particular – the city has tested the use of electric buses extensively, and it intends to transition all of its bus transportation towards more electric solutions within the next 10 years. [6]

As discussed in section 3.1, the use of renewable energy is an integral part of the resource optimisation and sustainability of smart cities. As a result, due to their ability to use renewable energy, electric vehicles will play a key role in future smart mobility and resource optimisation solutions and initiatives. If done correctly, further developments of both electric vehicles and renewable energy solutions will continue to increase the benefits of smart mobility over the coming years.

Car sharing solutions will also provide significant resource savings. Car sharing reduces the number of vehicles in the city, thus also reducing the energy consumed by different vehicles. Moreover, with less vehicles, other modes of transport, such as public transport, walking and cycling, become easier and more appealing. By combining this with the smart lighting solutions discussed in subsection 3.1.4, smart cities can achieve further benefits to their resource efficiency, as well as offer additional mobility options to their citizens, thus becoming more citizen friendly in general. In addition, the increase of alternative mobility methods includes many financial benefits – for instance, in Copenhagen, the use of bicycles instead of cars can save approximately one euro per one travelled kilometre [72]. As a result, smart car sharing solutions play a key role in smart, resource efficient and sustainable mobility.

Smart solutions and technologies can be used for further car sharing and general mobility improvements. A smart car sharing system can collect information about how cars are used around the city – most notably, how does a certain area, weather condition or specific event influence the use of cars in the city. Not only can this information be used to optimise car sharing services, but it also helps with the implementation of electric vehicles, as the number of charging stations can be decided based on the aforementioned information. Furthermore, this approach also enables more effective implementation of electric car sharing. [72] By combining the benefits of electric vehicles and car sharing, smart cities can develop more and more resource efficient and sustainable solutions for smart mobility.

Smart and autonomous vehicles are another key component of smart, resource efficient and sustainable mobility. These vehicles are primarily enabled by smart sensors that monitor the vehicles' surroundings, providing information about other vehicles, pedestrians and potential obstacles, allowing the vehicles to mostly function on their own, with very minimal or no manual input at all. In addition, smart and autonomous vehicles utilise AI for performing automated sensor data analysis and human-like decision-making. Finally, these vehicles are equipped with smart communication technologies, which allows them to communicate with their environment, as well as other smart vehicles, resulting in smarter and more connected vehicles and mobility in the city.

Smart and autonomous vehicles also provide a wide range of benefits to smart cities. Firstly, they improve the general safety of mobility by eliminating the errors of human drivers, thus decreasing the number of traffic accidents. This also provides financial benefits, as the required resources for dealing with traffic accidents are reduced, and those resources can be allocated to other important areas. Secondly, autonomous vehicles can achieve significantly lower fuel consumption compared to traditional vehicles [73], and as smart vehicles are developed further, the resource efficiency of these vehicles will continue to improve as a result of the wider implementation of electric solutions. Finally, by combining smart vehicles with smart traffic management systems, further benefits can be achieved in various areas of smart city mobility and transportation [20].

Singapore has implemented various autonomous vehicles in their smart nation initiative. For instance, public road testing of self-driving vehicles was initiated in July 2015, and in the Nanyang Technological University, a driverless shuttle bus drives around the campus, *"connecting student halls with the main academic areas, ferrying up to 300 passengers a day."*

In addition, autonomous vehicle technologies, such as GPSs and smart sensors, are used to develop smarter electric buses capable of autonomously detecting road signs, traffic lights, pedestrians and other vehicles. The general goal of these autonomous vehicle solutions is to make mobility and car sharing more accessible, as well as reduce accidents and traffic congestions in the city. [74]

Finland has also experimented with various mobility solutions revolving around smart and autonomous vehicles. In Helsinki, the first fully electric bus was implemented in 2017, and by the year 2025, one third of the buses in the Helsinki metropolitan area are expected to be electric. Helsinki also aims to improve its public transport with the addition of autonomous robot buses in the near future. Additionally, the development and increasing implementation of 5G networks is also projected to provide various improvements to Finland's smart mobility solutions. [75]

Finland's contribution to the development of smart and autonomous vehicles is also showcased by the Prystine project. In this project, 58 partners across Europe, including the University of Turku, worked towards improving the safety and reliability of autonomous vehicles in both urban and rural areas in European cities. In short, the main focus of the project was to develop a new fail-operational radar- and sensor fusion -based smart vehicle system that ensures the safety of autonomous vehicles, even in the case of different failures. The project was based on extensive collaboration between the partners, with each partner responsible for their own area of expertise – for instance, the University of Turku focused on improving the decision-making and security of heavy-duty vehicles and their control systems, whereas the research conducted in Italy prioritised regular cars. [76] As a result, the project was extremely helpful in developing Europe's smart and autonomous vehicle technologies as a whole.

Based on the above discussions, the Prystine project highlights the enormous potential and importance of autonomous vehicles in improving various smart mobility solutions. Moreover, increased and developed collaboration between different countries and organisations will lead to further improvements on the research, development and implementation of smart and autonomous vehicle -based mobility solutions in the future. By combining the findings and developments achieved in the Prystine project with the other smart solutions discussed in this subsection, significant improvements to the resource efficiency, sustainability and security of smart mobility can be achieved in the coming years.

3.3.2 Traffic management

In addition to implementing smart vehicles, smart cities can also utilise various larger-scale solutions for managing their traffic. For instance, traffic reduction prevents traffic congestions and car idling, thus reducing emissions and energy consumption, as well as improving the air quality and general comfortability. Moreover, with better traffic management, smart cities can ensure more efficient mobility for its citizens, which will greatly contribute to both resource savings and added comfortability in different areas of the city.

Smart mobility systems, often enabled by various DL techniques, play a key role in mobility and traffic prediction in smart cities. For instance, sensor-collected data about traffic, vehicle speeds and the number of vehicles on a specific road can be processed and analysed with DL in order to predict future city traffic. This information will then help with the planning of more efficient mobility solutions in the future. In addition, DL-based analysis and prediction of human mobility, based on location data collected by GPS and Wi-Fi technologies, allows smart cities to, for example, predict citizens' mobility and average travel time, as well as their potential demands for personal transportation services, such as taxies. [10]

The prediction of citizen demands for mobility services can also include other modes of transport, such as car- and bike-sharing services, as well as public transportation, in specific areas. This analysis helps smart cities optimise the amount of resources spent on specific mobility solutions, as well as maximise the revenue generated by different mobility services. Moreover, by utilising DL alongside GPS- or sensor-based techniques, smart cities can predict the most popular modes of transportation in specific areas. [77] As a result, cities will be able to provide their citizens with more personalised, resource efficient and sustainable transportation opportunities, thus improving their quality of life and overall well-being.

In addition to the solutions discussed above, DL also allows for more effective prediction, and prevention, of traffic accidents in smart cities. Different smart mobility systems can predict the areas where accidents are most common, as well as evaluate the severity of potential accidents in different areas. Based on this information, additional safety measures and the encouragement of potential alternative routes can be prioritised in the most accident-prone areas. [77] Not only will this help with increasing safety, but it will also naturally reduce the amount of healthcare required for treating various injuries caused by traffic accidents, thus allowing those resources to be allocated into other areas of healthcare. Moreover, by prioritising additional measures in only specific areas where they are most useful, further resource savings can be achieved.

Big data is another key technology in smart city traffic reduction, as shown by the Copenhagen Intelligent Traffic Solutions (CITS) project. Wi-Fi access points, that are capable of anonymously recognising the location of any Wi-Fi enabled devices, are spread across the city, allowing for real-time monitoring of the traffic and the citizens' mobility in different parts of the city. This large amount of data is then analysed in order to recognise specific patterns in Copenhagen's traffic and mobility, which allows the city to make more effective plans and predictions regarding future traffic management processes, such as smart traffic lights. [72]

Copenhagen has also focused on other areas of smart traffic management, particularly with their data-driven traffic management and air quality improvement initiative. The project is focused on improving the city's air quality through reducing the pollution caused by traffic congestions. This approach is based on the development of traffic signals that guide mobility based on its air quality impacts. By collecting and analysing data about the traffic and pollution caused by different mobility routes and solutions around the city, Copenhagen aims to make further progress towards more environmentally friendly traffic management. [6] These types of approaches are particularly suitable for smart cities, as they combine resource efficiency with comfortable and healthy living conditions, thus achieving many of the overall objectives of smart cities in general.

The potential accidents and pollution caused by traffic can also be reduced with other measures, as showcased by Dubai's smart mobility strategy. Reducing the need for mobility prevents traffic congestions, thus making the transportation infrastructure much easier and cheaper to maintain. In order to achieve this goal, Dubai encourages videoconferences and remote online meetings, so that their citizens do not congest the roads with constant commuting between meeting locations. In addition to the resource savings achieved by the reduced traffic congestions, this approach also saves the citizens' most valuable resource, time, allowing them to cut out any unnecessary transportation. [78] As a result, Dubai's citizens can spend more time on doing things they enjoy, resulting in a happier and more citizen friendly environment in general.

The traffic reduction strategy of Dubai has a lot of potential to make a significant impact on the future of smart mobility in many other areas as well. Remote and flexible working hours are becoming increasingly common, and with the further development of various communication and networking technologies and online services, the efficiency and simplicity of virtual meetings and other tasks will continue to increase. As a result, the reduction of traffic through videoconferencing and online meeting opportunities will improve the resource efficiency of mobility in future smart cities.

Smart city traffic management can also be enhanced through the implementation of smart parking. The main purpose of smart parking is to ensure that citizens always have the knowledge of the free parking spaces in different areas of the city, which reduces traffic congestions and improves the overall efficiency of mobility around the city. This parking space detection can be enabled by a wide variety of technologies, such as various smart sensors and DL-based techniques.

The implementation of cost-effective sensors, often enabled by 5G communication, allows smart cities to receive real-time information of empty parking spaces. As a result, the citizens can immediately find an open space, instead of congesting the streets by driving around looking for empty parking spaces. The increased parking efficiency provided by this approach also increases the cities' revenue, as paid parking spots will be utilised more effectively. Finally, the introduction of simpler and more effective parking will make the cities' commercial areas more appealing and easier to travel to, providing further financial benefits to the cities. [20] For instance, if the citizens of smart cities know that they will not have to worry about finding an open parking space, they will be more encouraged to visit the various stores and services located in the city centres, thus boosting the local businesses, and the city economy in general.

Since the parking space -monitoring sensors are often connected to the cities' street lamps [20], sensor-enabled smart parking can be combined with various smart lighting solutions, resulting in significant smart mobility improvements. In addition, by combining two smart solutions in the same infrastructure, smart cities can make significant resource savings in the construction phase of different smart mobility systems, as both solutions can be built simultaneously.

DL techniques, most notably CNNs, provide many improvements to parking space monitoring. The techniques provide smart parking systems with increased adaptability to varying changing conditions, such as lighting or shadows, between different parking areas. These systems are often based on image recognition – the CNNs are trained with images of both free and taken parking spaces, allowing them to analyse the vacancy of a parking spot, regardless of the conditions. [10] Due to this adaptability, DL-based smart parking systems can be used in all smart city areas, which maximises the potential benefits of different smart parking solutions. Furthermore, by combining DL-based approaches with other smart parking developments, smart cities can achieve significant improvements in future smart mobility solutions.

3.3.3 Future developments

Based on the discussions in this section, smart mobility is already an integral component of any successful smart city, providing a wide variety of benefits to resource efficiency, sustainability and comfortability around the city. Moreover, as is the case with most smart city areas, smart mobility is still at its early stages, and with the rapid advancements of different smart technologies, it will only continue develop in the future. The future of smart mobility developments has already been evaluated extensively in order to accommodate the eventual changes and improvements in this area.

In their paper [79], Noy and Givoni present the results of a survey regarding the future of smart and sustainable mobility, highlighting some of the key areas of future smart mobility improvements. Most notably, the areas presented in the paper include the development of autonomous mobility, as well as increased connectivity of both public and private transportation. In addition, even though the reduction of traffic congestion is extremely desirable, it will likely not be fully achieved in the near future [79], which means that other smart mobility measures, such as smart vehicles and traffic prediction, will play a key role in the future of smart mobility as well. With these measures, the negative impacts of traffic congestions can be reduced significantly, resulting in more resource efficient and sustainable mobility solutions for future smart cities.

The EU considers zero-emission transportation as one of the key areas of the future of smart mobility, with the goal of implementing at least 30 million zero-emission cars across Europe by the year 2030. In addition, zero-emission aircraft is expected to be available by the year 2035, and by 2050, most cars around Europe should be emission-free. Moreover, automated mobility is expected to increase significantly in the coming years, and a transportation network, enabled by high speed connectivity, will connect transportation solutions across Europe by the year 2050. [71]

With the approaches discussed in this section, smart cities in Europe, as well as other smart cities around the world, can increase the effectiveness of their transportation opportunities, while also making sure that different mobility solutions do not consume an excessive amount of resources. By combining resource efficient mobility with other resource optimisation solutions, such as smart energy and smart waste management, smart cities can ensure the resource efficiency and sustainability of their operations, both now and in the future.

4 Smart city challenges

Smart city operations are threatened by a wide variety of challenges that cause various issues to different smart systems and solutions. These challenges directly jeopardise the very objectives and benefits of a smart cities, introducing various resource efficiency and sustainability constraints, as well as disrupting the general security and quality of life in the cities. Consequently, the analysis of different smart city challenges is crucial to the successful design and implementation of different smart city solutions and services.

The most significant smart city challenges are related to security and privacy, service availability, people and ethics. In order to gain an understanding of how these challenges can be handled to ensure future smart city success, the main causes, risks and potential solutions of the challenges are discussed and evaluated throughout this chapter, with sections 4.1 – 4.4 covering the aforementioned four challenge areas, respectively.

4.1 Security and privacy

The challenge of security and privacy must be considered in the development of all smart city projects and initiatives. These challenges are primarily caused by the vast amount of data required for enabling and developing different smart solutions and services. If potential cyber attackers are able to access this data, the security and privacy of smart cities and their citizens can be jeopardised through a wide variety of malicious activities. Not only do these security and privacy issues inflict significant harm to the attacks' victims, but they also cause major disruptions to general smart city resource efficiency and sustainability efforts.

Security is commonly modelled with the CIA triad, consisting of Confidentiality, Integrity and Availability. The CIA triad is a widely accepted description of data security and its key components, and as a result, it has become a popular guideline for the development and implementation of various security solutions [80]. Consequently, the CIA triad also plays a key role in evaluating and developing the security and privacy of different smart systems, solutions and services.

Confidentiality is focused on retaining the privacy of sensitive data by protecting it from unauthorised access. Data confidentiality is the foundation of security and privacy in smart cities, as the exposure of sensitive data is the main cause of security and privacy -related challenges across different smart cities around the world. Any unauthorised access to data introduces a high risk of malicious activities, as attackers can use the data for recognising the most suitable and vulnerable targets for various attacks, resulting in significant inconveniences, resource losses and other issues.

Integrity on the other hand, is centred around ensuring the accuracy and reliability of data by preventing unauthorised and undesirable data modifications. Data integrity is particularly important in enabling the security and privacy of personalised smart city services, as the use of inaccurate or modified data would cause personalisation-based smart systems to work in unintended ways, potentially leading to the exposure of the users' personal information, as well as general security issues, especially in the case of personalised smart home systems, for instance.

Finally, as the name suggests, availability means that all necessary data is always available and accessible to authorised users. Availability is particularly important in smart cities, as smart city systems and services require data in order to function in the most optimal ways. In addition, since different smart systems, particularly those that provide personalised services, contain a lot of personal information about the citizens, each person should be able to access and modify their personal data, so that the different personalised services and their features always match the preferences of each individual. Moreover, the ability to access and modify personal information also protects the citizens' privacy, as the citizens can choose to hide some of their personal information, the exposure of which they would consider harmful or dangerous.

The General Data Protection Regulation (GDPR) is a major contributor in the security and privacy of European cities and people, making it an important topic to discuss from the perspective of smart city security and privacy as well. GDPR focuses on the protection of personal data, such as names, locations, health records and banking information, of all individuals within the EU [81]. Personal data is defined in the GDPR as *"any information that relates to an identified or identifiable natural person",* and the responsibility of protecting it applies to all entities that process the data in any way [81]. As a result, in European cities, data and privacy protection applies to a wide variety of organisations and service providers, which makes the smart city security and privacy challenge a fairly complex topic, where many different areas, threats and possible solutions need to be considered.

All in all, based on the above discussions, security and privacy is a significant challenge that must be dealt with in order to ensure the success of different smart city projects, both now and in the future. The collection and potential challenges of sensitive data in smart cities are discussed in subsection 4.1.1. Moreover, the different privacy attacks and their countermeasures are presented in subsections 4.1.2 and 4.1.3, respectively.

4.1.1 Sensitive data in smart cities

Based on the earlier discussions in the thesis, data is a key enabler of different smart city operations, particularly since many smart solutions are based on data analysis and data-driven decision-making. As a result, different smart sensors and systems collect large amounts of data about different smart city areas and citizens. While this data collection is required for carrying out different smart city initiatives, it also introduces various security and privacy issues that must be considered.

The biggest issue with data collection in smart cities is that a large portion of the data collected by different smart systems contains a lot of sensitive information about the cities and their citizens. This sensitive data includes information about the city's infrastructure and services, as well as a wide variety of personal citizen information, such as addresses, social security numbers, employment information, service preferences and location data. All of this sensitive data opens up opportunities for different malicious activities, and therefore, introduces significant security and privacy challenges to smart cities around the world.

With the emergence of big data, the challenges related to sensitive data have grown significantly, and the same trend can be expected to continue in the future. As discussed in subsection 2.2.4, smart city big data consists of a large amount of diverse data about different areas of the city. As a result, more and more data will be exposed and available for attackers to exploit, resulting in further security and privacy challenges in the future.

Sensitive data and the risks related to it are present in all types of smart solutions, including the smart resource efficiency- and sustainability-focused energy, waste management and mobility solutions discussed throughout chapter 3. To suit the overall goals of this thesis, the primary focus is on evaluating the exposure and protection of the sensitive data related to these solutions, as this evaluation will provide the most accurate information on how security and privacy issues can impact the resource efficiency and sustainability of different smart city projects.

4.1.2 Attacks against smart city security and privacy

The security and privacy of smart cities is threatened by a wide variety of malicious attacks that can have devastating consequences to smart cities and their citizens. Spyware, eavesdropping and Man-in-the-Middle (MitM) attacks, as well as data and identity theft, are among the most significant attacks against smart city security and privacy. These attacks allow cyber attackers to carry out different malicious activities, which can be extremely detrimental to the resource efficiency, sustainability and general success of smart cities. As a result, the understanding of these attacks and their dangers is an integral part of both current and future smart city developments.

Malware, a common term for different types of malicious software, sets various challenges to the development of smart cities. In the case of security and privacy, spyware causes the most major issues, particularly due to its effectiveness in sensitive data gathering. In short, spyware can be secretly installed in the targeted device in order to gather information about its users without their knowledge or consent. This secretive nature of spyware is what makes it particularly dangerous, as the attacks can be carried out for a long period of time before they are detected and ultimately dealt with. Consequently, cyber attackers can utilise spyware to gather large amounts of information that can then be used for carrying out many different malicious activities against smart cities and their citizens.

As an example, by installing spyware into the DL-based waste detection systems discussed in subsection 3.2.2, attackers can gain access to the city and street images of a smart city, resulting in a breach of the citizens' privacy, as the attackers can gain access to a large amount of information about different locations in the targeted city. In addition, different smart car software could contain spyware that collects information about the car's usage, from the most typical driving times to general location data. Attackers can then utilise this spyware-collected information to recognise when the car's owner is using the car, and therefore, is not at home, thus determining the most optimal opportunity for committing burglary, for instance.

Based on the wide variety of spyware threats discussed above, spyware is one of the most versatile and major challenges related to smart city security and privacy. Not only does spyware cause general privacy breaches, but it can also lead to other issues and malicious activities, making it an extremely prominent challenge for both current and future smart city projects and solutions.

In addition to spyware, smart city security and privacy is threatened by a wide variety of other attacks. Most notably, as discussed in subsection 2.2.3, smart city solutions and services are enabled by communication, meaning that different smart systems and devices are constantly communicating information about different areas of the smart city. Consequently, attacks against communication, such as eavesdropping and MitM attacks, present major challenges to ensuring security and privacy in different smart cities.

Eavesdropping is a communication attack where attackers exploit vulnerable and insecure networks in order to listen to the communication in the network, allowing them to steal potential sensitive information sent and received by different network-connected devices. These attacks are particularly dangerous in the smart city context due to the high amount of sensitive data discussed in subsection 4.1.1. Eavesdropping attacks are a major threat to data confidentiality, integrity and availability in smart cities, and they can lead to various security and privacy issues, particularly due to the exposure of personal, financial or other types of sensitive information [82].

One of the major challenges related to eavesdropping attacks in smart cities is that, as the cities become more and more connected, the severity of the attacks and their consequences grow significantly [82]. This issue can be very difficult to deal with, as the general goal of smart city initiatives, the development of more connected, versatile and efficient systems and solutions, fight against the security and privacy of smart cities by introducing additional threats and exploitation opportunities for potential attackers. As a result, finding the balance between performance and security is a key component of ensuring resource efficiency, sustainability and security in both current and future smart city projects.

The likelihood and severity of eavesdropping attacks also varies between different types of connections [82], which introduces additional challenges to smart city security and privacy. Smart city infrastructure, solutions and services consist of a wide variety of connections, making the protection against eavesdropping extremely difficult – due to the large number of different connections, the required level of security for each smart city area is not always clear, resulting in additional challenges to optimising the resources used for security enhancements in different smart city areas.

Eavesdropping is often carried out with MitM attacks, where the attacker deceives the message sender by posing as the receiver, allowing them to read or modify the messages sent over the communication network [83]. In addition, due to this deception, MitM attacks often remain undetected for extended periods of time, as the message sender does not know that the messages are received by the attacker. Based on these discussions, MitM attacks are a significant threat to security and privacy, particularly in smart cities, where the attack surface is considerably larger compared to more traditional cities.

An MitM attack can, for instance, be performed on a smart energy consumption monitoring system, providing the attackers with information about potential empty houses based on abnormally low energy consumption values. Moreover, MitM attacks can be used in combination with personal information, such as employment and address information, to carry out a targeted attack against a rich individual, who would be a more appealing target for a burglary, as their home would likely have more valuables for the attackers to steal in order to gain maximal benefits from the attack.

Based on the above examples, MitM attacks pose a major threat to smart city security and privacy, especially since they exploit various key services, such as smart energy and personalisation-based services, which are required for smart city resource optimisation and sustainability improvements. As a result, finding the balance between security and the cities' performance and service requirements is a key challenge with various smart city initiatives and developments.

In addition to the issues discussed above, the general exposure and theft of personal data through the different attacks described in this subsection can lead to a wide variety of personal issues, such as identity theft and other fraudulent activities. By stealing and using the personal data of the citizens of smart cities, cyber attackers can impersonate their victims in order to make fraudulent payments, take loans or create new online accounts in the names of the victims, potentially leading to both financial and reputational damage.

In addition to personal harm, data and identity theft -related malicious activities also have more widespread effects on smart cities and their operations. For instance, if attackers are able to retrieve the citizens' login credentials by breaching the security of a particular smart system, further issues may arise, if the same login credentials are used in other systems as well. Moreover, since identity theft recovery can be a long process, the overall productivity of the victims of these attacks can be jeopardised for an extended period of time, which can lead to general inefficiency and resource losses in their respective smart cities.

4.1.3 Data and privacy protection

Due to the wide variety of security and privacy issues discussed in this section, data and privacy protection must be improved in order to develop more resource efficient and sustainable smart cities in the future. However, the task is not simple, as there are many different factors and measures to consider. In fact, in [10], Chen et al. present that the development of smart city privacy requires a combination of regulatory and technical measures. Consequently, the process of data and privacy protection in smart cities must be considered from a wide variety of perspectives.

As discussed earlier in this section, GDPR plays a key role in regulating the protection of personal information in different smart cities around Europe. Similarly, the Singapore smart nation project focuses on laws and policies that ensure sufficient personal data protection in different digital innovations in the city [40]. These regulations, as well as many others around the world, guide the development and implementation of different privacy and data protection measures in both current and future smart city projects.

When it comes to technical measures, data and privacy can be protected with many different techniques, all of which provide unique approaches and benefits to protecting smart cities and their citizens from the different attacks discussed in the previous subsection 4.1.2. The most notable techniques for smart city data and privacy protection include authentication, authorisation, encryption, pseudonymisation, anonymisation and Virtual Private Networks (VPNs).

Authentication and authorisation are the base of data and privacy protection. In short, authentication focuses on confirming the system users' identities, and authorisation gives authenticated users access to the system's resources. These processes support the intended use of different smart systems and services, while also protecting the confidentiality of the citizens' personal data, as well as preventing different security and privacy attacks in general.

The technical process of data protection is most commonly carried out with different encryption techniques. These techniques convert sensitive data to an unreadable form, that is only usable to authorised parties that have been given access to a decryption key or password. In smart cities, this process results in the protection of the sensitive data discussed in subsection 4.1.1, thus protecting the cities and their citizens from the wide variety of attacks, such as spyware and eavesdropping, discussed in subsection 4.1.2. Consequently, encryption is a central component of confidentiality protection in different smart solutions and services.

Encryption is also heavily utilised in VPNs in order to establish secure and private connections between different devices and networks. Most notably, this allows VPNs to protect the users' data and privacy even in unsecure Wi-Fi connections, resulting in effective and sustainable smart city privacy protection – ensuring the reliability and security of every Wi-Fi connection is too difficult and resource demanding, but with increased implementation of VPNs, many of the security and privacy challenges of smart systems can be mitigated in a more reliable and sustainable manner.

Data pseudonymisation, which is the act of *"processing of personal data in such a manner that the personal data can no longer be attributed to a specific data subject without the use of additional information"* [81], is another promising technique for smart city data and privacy protection. Most notably, pseudonymisation achieves a very important feature of smart city security measures – the balance between performance and security. Pseudonymisation allows the citizens' personal data to be used for providing them with various smart and personalised services, while still maintaining their privacy by hiding the connection between the person and their data from outsiders.

In cases where a solution does not specifically require the citizens' personal data, the data can also be anonymised to increase security. GDPR defines this anonymised data as *"information which does not relate to an identified or identifiable natural person"* or *"personal data rendered anonymous in such a manner that the data subject is not or no longer identifiable"* [81]. Due to these factors, the different data protection principles presented in the GDPR do not even apply to anonymised data [81], meaning that data anonymisation can help with avoiding and mitigating many of the security and privacy challenges discussed in this section.

The data anonymisation approach has already been applied to successful smart city solutions, as showcased by the Copenhagen CITS project discussed in subsection 3.3.2. In this project, the collected location data is anonymised before analysis [72], resulting in secure solutions that preserve the citizens privacy extremely effectively.

The Copenhagen CITS project is also a good example of another important approach to smart city security and privacy protection – privacy by design. In short, this approach is based on implementing privacy directly in the developed solution itself, instead of treating security and privacy as an afterthought or an external factor. In the CITS project, this is accomplished through the aforementioned anonymisation of the collected data prior to its analysis. In order to increase the general security and privacy of different smart cities around the world, a similar approach should, if possible, be applied to various other smart city solutions as well.

All in all, smart city data and privacy protection is integral to dealing with the security and privacy challenges threatening the resource efficiency, sustainability and general success and security of different smart city initiatives. By utilising the measures and techniques discussed in this subsection, smart cities can solve many of the security and privacy challenges caused by sensitive data collection and different security and privacy attacks. As a result, the overall security and sustainability of smart cities will increase significantly, which will greatly contribute towards more advanced and successful smart city initiatives in the future.

4.2 Service availability

In addition to the data availability discussed in section 4.1, ensuring and maintaining general service availability is a significant smart city challenge that must be considered. Service availability is closely related to security and privacy, but it goes beyond the data-related challenges discussed in section 4.1 – service availability refers to the general state of all services across the smart city, and is affected by a wide variety of attacks, which attempt to disrupt or disable different smart systems in order to gain personal benefits or cause harm to different smart cities and their citizens. In addition, general failure and errors of smart systems can jeopardise the availability of many critical smart city services.

Service availability is a major requirement in any successful smart city, since if one or many of its critical services are either completely or partly unavailable, the city will not be able to operate as intended. For instance, if the city's power, transportation or other key systems become unavailable, the caused outages can have devastating consequences to the city and its citizens. Moreover, the unavailability of a particular service can also cause issues with other services. For instance, a disruption in the smart grid could jeopardise the operations of other services due to a lack of power, and inefficient waste management around the city could lead to decreased comfortability and quality of life in the city, resulting in a less desirable and liveable environment for both current and potential future citizens.

In addition to the dangers discussed above, a lack of service availability also introduces significant challenges to smart city resource optimisation and sustainability. If resource optimisation- and sustainability-focused services and solutions, such as smart energy, smart waste management and smart mobility, are not available, smart cities will not only lose resources due to ineffective operations, but they will also lose the potential benefits that the aforementioned solutions could provide. Based on the discussions in chapter 3, these solutions are crucial to the success of different smart city projects, meaning that their consistent availability is extremely important.

For the purpose of this thesis, service availability is primarily inspected from the perspective of the smart solutions discussed in chapter 3, although the different attacks against smart service availability, as well as their countermeasures, are applicable to other smart city areas as well. As a result, this section provides a comprehensive discussion of the risks and preventive measures of various smart city service availability -related issues.

As discussed previously in this thesis, smart cities consist of a wide variety of smart technologies, systems and solutions. While this versatile and complex structure provides smart cities with many opportunities for improving the quality, resource efficiency and sustainability of different services, it also introduces various challenges, due to the high number of different attacks that can be used against different smart systems. Subsection 4.2.1 provides a more detailed discussion of these attacks and their potential dangers.

Due to the importance of service availability, as well as the risks related to suboptimal or completely disabled services, smart cities must find effective ways to deal with different types of threats. Fortunately, this can be achieved through a wide variety of countermeasures, which are discussed in subsection 4.2.2.

4.2.1 Threats

System failure is a significant cause of service availability -related challenges in smart cities, and it can be caused by a wide variety of factors, from faulty hardware to badly coded software. As a result of these failures, the system will function in unintended ways, causing a disruption in the services that are controlled by that particular system.

The challenges of system failure are particularly apparent in smart environments, as nearly every city component is controlled by technology, meaning that the number of any severe system-related issues is exponentially high. For instance, faulty hardware in smart lighting systems can lead to excessive energy consumption or increased traffic accidents. In addition, a software issue can cause a smart and automated waste tube to transport waste in the wrong direction, back to the waste bins, resulting in major disruption in the city. As a result, system failure poses a major threat to general smart city service availability.

In addition to system failure, the breaches of physical security also set various challenges to smart city service availability. For instance, due to their autonomous nature, various smart systems utilised in smart cities are often left to mostly function by themselves, leaving them vulnerable to various acts of vandalism and tampering. In addition, the system failure threat, discussed above, is closely connected to the physical security issue – for instance, if a physical feature, such as a smart vehicle lock component or a waste container closing mechanism, of a smart system experiences failure, gaining physical access to the system and its different components, such as smart sensors and IoT devices, becomes an even easier task for malicious actors.

In the aforementioned scenarios, any sophisticated or highly technical attacks against smart city systems are not required. Instead, malicious actors simply need to gain physical access to the deployed systems, many of which are easily available for the citizens to use, in order to cause harm and disruption to various critical smart city services. As a result, the likelihood of physical security attacks in smart cities is extremely high, making them a notable threat to smart city service availability.

Service availability in smart cities is also threatened by many sophisticated and technical malicious activities. Most notably, different cyber attacks, such as Denial of Service (DoS), ransomware, injection, MitM and zero-day attacks, introduce a wide variety of challenges to maintaining different smart city services. These attacks can target different areas and exploit different vulnerabilities, but they all serve a similar malicious purpose – threaten the availability of critical smart city services.

DoS attacks are based on overwhelming a particular service by flooding it with excessive requests, until the capacity of the targeted device or network is exceeded, and therefore, the target is not able to handle any more requests. As a result, the service becomes unavailable to its intended users, as it cannot process the users' legitimate requests, until all of the disruptive requests of the DoS attackers have been dealt with. Moreover, in Distributed Denial of Service (DDoS) attacks, the requests are sent from many different sources, allowing for larger-scale and more sophisticated attacks, which are increasingly dangerous and difficult to protect against.

As a result of their resource constraints and general lack of focus on security features, the security of IoT devices is often quite lacking, making them a primary target for DoS attacks. Consequently, due to the high number of IoT implementations in different smart city services and components, DoS attacks can target practically any smart city area.

Perhaps the most severe smart city DoS attacks can be performed against the smart power grids of a smart city – by disabling the power grid with a DoS attack, attackers are also able to affect many other smart city services due to the loss of power in the city. In addition, direct DoS attacks against other services, such as smart recycling centres or smart traffic prediction solutions, can also cause various disruptions, accidents and resource losses.

Another major service availability threat, ransomware, is a type of malware that prevents its victims from accessing critical systems and information before a ransom is paid. Most commonly, ransomware attacks encrypt various important files and notify the victims about the attack and the required ransom payment. In addition, ransomware attackers often threaten the victims about the potential consequences, such as permanent data losses or increased payments, of missing or delayed ransom payments. The main idea of these attacks is to cause panic, thus forcing the hand of their victims – the victims feel inclined to comply with the attackers and pay the ransom in order to restore critical services, systems and information that are required for their daily activities.

Smart cities consist of many critical data-driven services, making them appealing targets for ransomware attacks. These attacks pose a significant threat to smart city resource efficiency, particularly because they can inflict multiple types of financial harm. Firstly, the disruption of an important service hurts the overall efficiency of the city, which often results in significant financial losses. Secondly, the potential ransom payment can be expensive, and there is no guarantee of the attackers returning access to the information, even if the ransom is paid. Therefore, the information should be recovered in other ways, which can also be very costly, and sometimes even impossible, if the ransomware attackers have completely deleted the information from the targeted system.

Many cities and organisations have been targeted by widescale and severe ransomware attacks. For instance, in 2017, a ransomware attack against one of London's major universities, the University College London, prevented access to the shared drives of the university, as well as disabled its student management systems [84]. Moreover, in 2019, a large industrial company, Norsk Hydro, was hit with a large-scale ransomware attack that locked many of the company's important files, affecting 35000 employees in 40 countries and resulting in major financial losses of around 71 million dollars [85].

While ransomware attacks are most common in larger cities and companies, where attackers have more opportunities for financial gain through higher potential payment demands, the threat of ransomware attacks is still present in all smart cities, regardless of size, location or other factors. As a result, ransomware attacks and their mitigation have significant impacts on service availability in both current and future smart city projects.

Injection attacks are another major threat to smart city service availability, especially in the case of various data-driven services. In short, injection attacks are mainly based on inputting malicious code into the targeted system with the purpose of disabling or disrupting the system and its features. In the smart city context, some of the most common injection attacks involve the injection of false data into different sensor- and data-based systems, leading to false measurements and analytics, which then results in the general disruption of various critical smart city services.

A good example of the dangers of a false data injection attack is presented in [86], where Rahman and Mohsenian-Rad discuss how attackers can perform false data injections to target the availability of smart grids, even with very minimal information about the grid and its structure. In addition, by injecting false data into an automated waste collection system, attackers can disrupt the waste management of a smart city by causing the waste to move in the wrong direction through the waste collection pipes. These scenarios would have devastating consequences to the service availability and general resource efficiency of smart cities, meaning that injection attacks are among the biggest threats to the success of different smart solutions and services.

In addition to the privacy issues discussed in subsection 4.1.2, MitM attacks can also directly jeopardise the operations of different smart systems through data modifications. In these cases, MitM attacks function in a similar way to data injection attacks – the targeted system is disabled or disrupted with unsuitable data, causing the system to make incorrect decisions and measurements. However, in this situation, attackers do not input false data, but instead, modify the existing data in the system. As a result, despite having similar purposes, injection and MitM attacks function fairly differently, which makes them even more challenging to deal with, as multiple different countermeasures have to be developed in order to protect against both attacks.

Various smart city systems can also be threatened by zero-day attacks, which are based on exploiting previously unknown or unresolved vulnerabilities, also known as zero-day vulnerabilities. These attacks can have extremely serious consequences, as shown by one of the most famous examples of a zero-day attack, Stuxnet, which exploited four different zero-day vulnerabilities in the Windows operating system in order to disrupt Iran's nuclear program [87].

The main challenge with zero-day attacks is that, due to targeting zero-day vulnerabilities, they are extremely difficult to prepare for. Furthermore, this challenge is exponentially larger in smart environments due to the high number of different systems, which increases the potential number of zero-day vulnerabilities that can be exploited by attackers. Consequently, zero-day attacks further complicate the service availability challenge of smart cities, resulting in a wide variety of security requirements.

4.2.2 Recommended solutions

Based on the large number of threats against smart city service availability, any successful smart city project requires extensive security measures in order to ensure resource efficient and sustainable operations in different areas. The design and implementation of these measures involves a wide range of factors, all of which must be considered to achieve the best results.

When it comes to the prevention and mitigation of system failure, the use of simple and robust components and architecture is extremely important. Simpler system architecture reduces the likelihood of faulty hardware, as there are less components that could experience failure and jeopardise the systems' operations in the process. The use of robust components on the other hand, allows systems to function more reliably in difficult and changing conditions. Moreover, high-quality software, developed by skilled and experienced developers, reduces the risk of software-related system failures. Finally, with thorough testing of the deployed smart systems, many of the smart city service availability issues related to system failure can be identified and solved before they can cause harm to the cities' services and operations.

In the case of physical security, robust and durable components are also extremely important, as they make the process of gaining physical access to a system more difficult for potential malicious actors. In addition, smart cities can implement various surveillance-based techniques in order to prevent the physical tampering of their systems, thus making significant progress towards providing more reliably available services to their citizens.

Many smart city services are based around the use of different smart IoT systems and devices, the security of which is often limited by resource constraints, as most of the systems' resources are used for carrying out the systems' desired functionalities. Therefore, resource efficiency is extremely important in the development of the technical security measures used for improving smart city service availability. Additionally, the used solutions should be suitable for a wide range of systems, as designing a separate solution for each type of system would be an impossible task due to the broad and complex nature of smart city architecture and technologies. These objectives can be reached with a wide variety of technical solutions, such as firewalls and different Intrusion Detection Systems (IDSs).

Firewalls secure smart city networks by monitoring the networks and blocking any unwanted or malicious incoming traffic that could threaten the availability of different smart systems and services. Due to the highly connected nature of smart cities, the protection of the different communication networks discussed in subsection 2.2.3 is extremely important to ensuring smart city service availability. Consequently, any resource efficient, sustainable and secure smart city project should implement firewall technologies in their systems, services and operations.

IDSs also provide significant protection to smart city networks, systems and services. The purpose of these systems is to monitor networks in order to detect different suspicious activities and potential incoming attacks against a particular system or service. In addition, IDSs provide fast alerts about these potentially malicious activities, so that they can be mitigated or prevented before they are able to cause too much damage. Consequently, IDSs are an integral part of the availability of different smart systems and services.

IDSs are commonly divided into two subsets, signature- and anomaly-based systems, both of which provide a unique approach to intrusion detection and smart city service availability protection. The main difference with these approaches is that signature-based systems are able to detect known attacks based on stored information of previously performed attacks, whereas anomaly-based systems are more suited for detecting any suspicious and out-of-the-ordinary activities in general.

While both of the beforementioned intrusion detection techniques are useful, anomaly detection is the more promising solution for the protection of smart city service availability due to its higher and more versatile intrusion detection capabilities. By using anomaly detection and inspecting all suspicious activities, smart cities will not need to develop specific measures for each individual attack type, resulting in efficient, reliable and all-encompassing detection of different attacks, including the otherwise hardly detectable zero-day attacks. As a result, while this approach can have some resource consumption -related challenges in the form of a large number of false alarms, the overall impact of anomaly detection in smart city service availability protection is still extremely positive. Moreover, as smart city technologies, particularly ML, continue to improve, the efficiency and reliability of anomaly-based intrusion detection can be developed even further in the future.

The general requirements of ML-based attack detection techniques are presented in a white paper published by Kaspersky [88]. Most notably, the paper suggests that ML-based attack detection systems must be trained with extensive and high-quality data, be built around the current security needs and provide multi-layered attack protection in order to achieve the best results. These factors must also be considered when utilising anomaly detection and other potential future ML-based security measures for smart city service availability improvements.

The solutions recommended in this subsection provide extensive protection against the attacks discussed in subsection 4.2.1. Consequently, they can be used as the general framework for smart city service availability protection. However, despite the effectiveness of these security measures, the smart city threat landscape is constantly developing, meaning that new and increasingly effective and versatile measures must also be developed and implemented constantly in order to ensure effective operations and services in the future.

4.3 People

People are at the centre of smart cities' operations – as discussed in section 2.1, the citizens' quality of life and general opportunities are among the key areas of focus around the concept of smart cities. At the same time, people's actions are one of the major causes of various issues in smart cities, meaning that smart city initiatives must also consider the human factor during the design, development and implementation of different smart solutions and services.

The most major smart city challenges caused by human factors are related to errors and negligence. These factors amplify the challenges discussed in section 4.1 and 4.2, introducing new exploitable vulnerabilities and attack opportunities to potential cyber attackers. As a result, the analysis and mitigation of the threats caused by human errors and negligence is an integral component of any successful smart city initiative.

Human errors are among the most prominent challenges in the field of security in general. The main danger related to human errors is that even the slightest of actions can lead to major issues, thus making the users appealing targets for various cyber attacks. For instance, the Norsk Hydro ransomware attack was enabled by a small action of a single employee, who opened a malicious and infected email attachment that allowed malicious software to be spread across the company's systems [85]. In the smart city context, the likelihood and potential consequences of errors is increased even further due to the use of many different smart systems, as well as a high number of end users with varying technical knowledge.

Email-based attacks, such as the aforementioned attack performed against Norsk Hydro, as well as other forms of phishing attacks, are among the most common and dangerous attacks related to exploiting human errors in different areas. Consequently, protection against phishing attacks is one of the most important areas of focus in resource efficient, sustainable and secure smart city development. In addition, other attacks, such as brute force guessing of weak passwords and attacks against systems with insufficient or faulty security updates and features, threaten smart city operations by exploiting the vulnerabilities caused by human errors.

The second major cause of people-related security challenges, negligence, often occurs when the users of a particular system or service choose to prioritise other factors, such as productivity or convenience, over security. Similar to human errors, negligence can also lead to the use of weak passwords, as well as jeopardise the general security of various systems. Moreover, the frequency of these issues grows exponentially in smart environments, where the citizens use many different systems as part of their daily lives, thus requiring extensive features and seamless performance, while forgetting about security in the process.

User training is integral in preventing and mitigating people-related security challenges. Most notably, many human errors and other undesirable actions can be prevented through user training, where the users of a particular system or service are made aware of all necessary security measures and features, as well as the potential risks and attacks that can come with using that system or service. For instance, the beforementioned Norsk Hydro attack could have possibly been avoided, if the company had informed their employees about the dangers of email-based attacks, as well as recommended alternate file sharing methods, such as online cloud storage services, to their employees and customers.

In smart environments, user training mostly involves simpler and broader matters, as the technical knowledge of the end users, the citizens, can be quite low in many cases. When smart cities implement new systems and services, many citizens can find them quite difficult to use, particularly due to a lack of prior experience and knowledge on such smart systems. Consequently, in order to prevent errors in such situations, citizens must be given simple instructions on the most important personal security measures. These measures can include using secure passwords, recognising and avoiding suspicious and unknown links, installing necessary security updates and creating backups of all important personal files.

User training also helps with preventing negligence among the users of different smart systems and services. Training allows people to understand the potential cyber attacks and issues that can occur as a consequence of neglecting the required security measures, resulting in increased willingness to take security into account. In addition, the available security measures and processes should be as seamless as possible in order to further prevent the users' unwillingness to follow all necessary security recommendations and instructions.

Security policies also play a key role in preventing human errors and negligence in the use of different smart systems and services. In short, a security policy defines the rules and processes that all users of a particular system or service must follow in order to ensure secure use. A well written security policy guides the citizens of smart cities to utilise different smart systems and services in the intended and most secure manner, thus reducing the risks of human errors. Moreover, negligence can potentially be prevented with ML-based security policy enforcing systems that automatically adjust the policy of each individual user based on their previous behaviour in order to prevent further misuse [89], for instance. Based on this discussion, security policies protect smart cities from many people-related security challenges, and their benefits and efficiency will only continue to increase in the future.

All in all, human errors and negligence pose a significant security challenge to smart cities, particularly due to the high number of systems and users, as well as the users' varying levels of technical expertise. However, many of these issues can be mitigated, or even prevented, with suitable user training, as well as the use of extensive and informative security policies, meaning that the challenge might not be as daunting as it originally seems, as long as the correct measures are taken as efficiently as possible.

4.4 Ethics

Ethics is another challenge that must be considered in the development of resource efficient, sustainable and secure smart cities. Most notably, ethical issues can cause major dissatisfaction among the citizens of a smart city, potentially causing them to move out of the city, which will lead to the city losing its most important asset – its citizens. This will also result in major resource losses and sustainability concerns, particularly in the form of lost tax payments and reduced service providing opportunities. As a result, successful smart cities of the future must understand and find solutions against ethical issues in order to guarantee efficient operations, both now and in the future.

In smart cities, the citizens must give up a lot of their personal data in order to utilise the provided smart systems and services. This raises a major ethical question – is it ethical to force the citizens to give up their privacy, especially considering the smart city security and privacy issues discussed in section 4.1? At the same time, the data is necessary for providing the citizens with better and more personalised services, which further complicates this ethical challenge and its impact on different smart city initiatives.

The most effective way to ensure ethical smart city data collection is to secure the privacy of the data through the different data and privacy protection measures discussed in subsection 4.1.3. For instance, if the citizen data collected by different smart systems is extensively secured through authentication, authorisation and encryption, many of the ethical challenges related to this data can be avoided or mitigated, as the data would be much less likely to end up in the hands of malicious actors.

Despite the benefits of the above approaches, the security and privacy of citizen data in smart cities cannot always be entirely ensured. As a result, other ethical data collection and utilisation practices must be implemented as well. Most notably, in order to make the citizens understand the situation, smart cities should be transparent with their citizens, informing them about the data collection and the purposes their data is being used for.

Smart cities can also deal with different data collection -related ethical issues by focusing on the development of alternative solutions where lower amounts of personal data is required to carry out the desired functionalities. Pseudonymisation of data is a key component of this approach – as discussed in subsection 4.1.3, pseudonymisation helps with finding the balance between smart solution performance and citizen data and privacy protection. As a result, wider implementation of pseudonymisation-based smart systems and solutions will protect the collected citizen data from a wide variety of attacks, thus greatly contributing towards more ethical data collection -based systems and solutions in future smart city initiatives.

Even though the different measures discussed above provide a wide variety of ethical benefits to smart cities and their citizen data collection practices, the ethical challenges of different smart city operations cannot be solved completely. However, by utilising the different measures, smart cities should still aspire to make their operations as ethical as possible in order to avoid and mitigate many of the citizen data collection -related challenges limiting the success of their current and future operations.

Another major ethical concern of smart cities is related to the advanced technologies that are used to provide smart systems and services. When the use of technology in different tasks increases, smart cities run the risk of job losses, as many of the previous jobs and service positions could be replaced by autonomous smart devices and systems. As a result, the advancements in technology could work against the citizens' happiness and livelihood, thus introducing a significant ethical challenge – should cities pursue technological advancements, regardless of the risk of reduced job opportunities for their citizens?

Job losses related to the use of smart systems can occur in a wide variety of smart city areas. For instance, with the emergence of smarter and more automated waste management procedures, the need for waste truck drivers and other waste management professionals will decrease significantly, resulting in major job losses. Moreover, the introduction of smart and autonomous buses will cause most of the city's bus drivers to lose their jobs. These job losses, along with various other potential areas where the city job situation can be weakened due to the increased use of technology, limit the potential of different smart city projects and initiatives, as smart cities must find ways to deal with the aforementioned issues before exploring further technological advancements.

The smart city job situation can also be looked at from another perspective. As different technologies become more and more widely implemented in different cities around the world, the demand for technically skilled individuals will also continue to rise. Consequently, new jobs will be created, as more and more people with extensive skills and knowledge of different areas of technology will be required for developing and implementing different smart and technology-based solutions and services. As a result, the emergence of smart city initiatives and technologies will not reduce the number of available jobs, but instead, change the job market to match the needs of the future, allowing smart cities to make further developments and advancements in different areas.

The ethical challenges of smart cities can also be evaluated and explained from the perspective of ethical theories. Most notably, consequentialism, which defines the morality of actions based purely on their consequences [90], can be applied to many of the ethical issues discussed in this section. The positive consequences of smart cities, such as the increased resource efficiency and sustainability, as well as more advanced services and opportunities for the citizens, outweigh many of the potential ethical issues that arise from different smart city developments. However, regardless of these benefits, ethical challenges must still be considered in all current and future smart city projects in order to avoid difficult situations as much as possible.

5 Salo smart city

Salo is a small- to medium-sized city of just over 50,000 inhabitants. The city is located in Southwest Finland, close to various major Finnish cities – around 50 kilometres away from Turku, and around 115 kilometres away from the Finnish capital, Helsinki. [91] As a result, Salo has great opportunities to collaborate with other Finnish cities in different areas of technology and city development.

Collaboration between Salo and other Finnish cities has become particularly apparent in recent years with the Salo smart city project, where the city, as well as the Salo Region Vocational College, work in collaboration with the University of Turku, the Turku University of applied sciences and the city of Somero [92] in order to develop various smart solutions that will shape the future of the city of Salo. Moreover, a local business, Lounea Oy, is one of the key contributors in this project [92].

Technology is also at the centre of Salo's operations. Most notably, the Salo IoT campus consists of many businesses, researchers and educational institutions that are focused on developing various technologies for future smart solutions in different areas. The smart city project of Salo is the next step in this technological development, as different technologies will be used for providing citizens with more resource efficient, sustainable and secure services in different areas of the city, both now and in the future.

This chapter consists of discussion about the different areas of the Salo smart city project. Firstly, the main objectives and components of Salo's smart city strategy are discussed in section 5.1. Secondly, section 5.2 covers the necessary considerations in transitioning Salo towards a more resource efficient, sustainable and secure smart city in the future.

5.1 Project objectives and components

The smart city project is a key part of Salo's current and future operations. In fact, in the Salo city strategy for 2026 [93], the development of a smart and sustainable living environment was identified as one of the key projects that the city will focus on in the coming years. This process of turning Salo into a smart and sustainable city consists of many different areas, all of which need to be understood well in order to deliver the most suitable solutions to the city of Salo and its citizens.

In general, the Salo smart city project encompasses many important components of the city's general development aspirations. For instance, smart solutions can aid Salo's climate and environment program, as well as increase the city's marketability by advertising a smart residential area to potential future citizens. Moreover, optimising the use of resources and developing new, improved and secure services in different areas of Salo are among the key objectives of Salo's smart city program [93]. Based on these objectives, different smart city developments are strongly present in Salo's overall strategic approach. As a result, understanding the relation between the Salo smart city project and Salo's overall strategy is important to any current and future smart solution developments in the city of Salo.

One of the main objectives of the strategy of Salo is to increase the number of citizens by increasing the citizens' well-being, as well as the appeal of the city in general [93]. For the past 10 years, the number of citizens in Salo has been on a steady decline, and the same trend is projected to continue over the next 20 years as well [91], making the objective of increasing the city's appeal extremely important to the general success of Salo.

The smart city project is integral to increasing the appeal of Salo – as discussed in chapters 2 and 3, smart cities provide different smart services and solutions that make the citizens' lives easier and more comfortable in various ways. Additionally, if Salo manages to increase the number of citizens in the near future, more resources will also be required to provide every citizen with the services they desire. This is where the different smart city resource optimisation solutions, discussed in chapter 3, come into play, as they will help Salo with supplying the necessary services with as little resources as possible.

Effective waste management plays a key role in allowing Salo to achieve the aforementioned goals of increased population and comfortability. Firstly, with more people living in the city, more waste will be generated, meaning that Salo will need a smarter and more effective way of managing this additional waste. Secondly, more effective waste management leads to a cleaner and more comfortable city in general, thus increasing the city's appeal to both existing and potential new inhabitants.

Recently, waste management has become an important topic of discussion in the city of Salo. Most notably, in a survey regarding the development of Salo's city centre and its surrounding areas, conducted in 2020, cleanliness was among the most common concerns mentioned by the citizens who answered the survey. Moreover, the respondents mentioned general littering as a prominent issue in the city and suggested the implementation of additional waste bins in various areas. As a result, the development of smarter and more efficient waste management systems and solutions is a key component of the future success of the Salo smart city project.

Mobility is another important area of the strategy and smart city project of Salo. In fact, the development of a more efficient and sustainable mobility system is listed as one of the key future areas of development in the city of Salo, with the system being expected to be ready and deployed by the year 2035 [93]. Based on the discussions in section 3.3, efficient and sustainable mobility is largely enabled by different smart technologies and solutions, such as smart vehicles and data-driven traffic management, meaning that these areas also need to be emphasised in the Salo smart city project.

The citizens of Salo have also identified mobility as an area where further improvements are required. In the survey on Salo's city centre and its surrounding areas, the importance of public transport was mentioned in one of the open comments regarding the city's comfortability improvements, and the general development of better walking and cycling opportunities was heavily suggested by many citizens.

The establishment of a sustainable economy is at the centre of Salo's operations [93], and it is also a key component of the Salo smart city project. As discussed in chapter 3, different smart solutions bring significant cost efficiency and general financial savings to smart cities. Based on this discussion, the city of Salo must develop and implement different cost efficient smart solutions in order to optimise the use of its resources and become more sustainable in the future.

All in all, the purpose of the Salo smart city project is fairly similar to many other smart cities around the world – the city aims to optimise the use of its resources and increase its sustainability, while providing its citizens with smart, secure and effective services that increase their comfortability and quality of life in general. However, as discussed in section 2.3, each smart city project is different from each other, meaning that the suitability of different smart solutions and services in the Salo smart city project must be specifically considered based on the city of Salo and its characteristics.

5.2 Key considerations

As discussed above, different smart solutions have various requirements and limitations that need to be specifically considered from the perspective of the city of Salo, its conditions and general characteristics. However, other smart city projects can also provide some good examples and guidance on what the city should do in order to reach the best possible solutions in resource optimisation, sustainability and security. Most importantly, Salo must find a balance between utilising proven solutions and developing solutions that specifically address the city's needs. The most suitable approach for finding this balance involves taking inspiration from other successful smart city initiatives and solutions, and then making the necessary changes and improvements for applying them to the city of Salo and its operations.

Due to sharing many similarities with the city of Salo, other European smart cities are the most suitable sources of inspiration for the Salo smart city project. Many European cities have various cultural similarities, meaning that the citizens in different cities across Europe often have similar requirements and expectations for the cities' services. Moreover, European cities are often under the same, or similar, laws and regulations, which set different requirements for various services. For instance, the smart services of all cities in countries that are part of the EU must follow the GDPR data protection and privacy rules and regulations.

As a Nordic city, Copenhagen is a particularly good reference point for the Salo smart city project. Moreover, Copenhagen has implemented smart solutions in many areas that are considered important in the city of Salo as well – most notably, Copenhagen's sensor-based waste collection system, as well as its sustainable public transport and traffic management solutions, can also be applied in the city of Salo in the future.

Generally speaking, the requirements and characteristics of smart solutions and services of other Finnish cities share the most similarities with Salo's smart city components. Firstly, smart services in different Finnish cities are guided by the same laws and used by similar people, meaning that the services' requirements are fairly similar across different smart cities in Finland. Secondly, the significant differences between the climate of different seasons in Finland set varying requirements for smart services. For instance, during the winter, different heating solutions require a considerably larger amount of energy compared to warmer seasons. On the other hand, the generation of waste in public areas, such as parks, is increased during the summer, as more people are spending time outside due to the nicer and warmer weather.

In order to deal with the changing conditions and requirements discussed above, the city of Salo can utilise different successful smart solutions deployed in Finnish cities – most notably, the Smart Energy Finland program and the smart waste bins of Kalasatama, discussed in sections 3.1 and 3.2, respectively. These solutions can bring significant improvements to the Salo smart city project, especially if they are slightly modified to specifically suit the needs and objectives of Salo, resulting in more efficient smart energy and smart waste management solutions in the future.

The size of Salo also affects the design and implementation of different smart solutions and services in the city. Salo is a relatively small city, where resources can be quite limited compared to many major smart cities, both in Finland and other parts of the world. As a result, in order to achieve the sustainable economy mentioned in the previous section, different smart solutions deployed in the city of Salo must not require large initial investments. Instead, resource optimisation and sustainability developments in the city must start from cheaper solutions. With time, as different smart solutions become more accessible and widely implemented, the city can make the transition towards bigger and better solutions.

Even though being close to major Finnish cities can be a benefit, especially in terms of the collaboration opportunities discussed earlier, it also causes various challenges to the city of Salo. Cities such as Turku and Helsinki can be seen as more appealing places to live, particularly due to their wider variety of services, as well as better education and employment opportunities, which can then hurt the objective of increasing the general appeal of Salo.

The aforementioned factors were particularly apparent in the Salo city centre survey mentioned earlier, as many citizens requested the implementation of additional services in different areas of the city, and one respondent mentioned the lack of educational opportunities as a reason for moving from Salo to Turku. Moreover, the number of jobs in the city has declined significantly from the early 2000s [91], meaning that in recent years, Salo has become a less appealing city, particularly to the working population.

In order to manage the issues discussed above, the Salo smart city project must provide enough services to satisfy the citizens' requirements, as well as create enough new jobs to make the city appealing for highly educated professionals. Fortunately, these areas can be effectively improved through different smart city initiatives and developments.

The number of services available to the citizens of Salo will naturally increase as the city implements more and more smart technologies and solutions to different areas of the city, from smart energy and smart waste management to smart transportation and various other smart solutions and services. In addition, if these services are enabled with, for instance, AI-based personalisation capabilities, they will become more and more accommodating for each citizen and their needs. Moreover, as discussed in section 4.4, increased use of technology will increase the number of technology-related jobs, thus providing more job opportunities across the city of Salo.

The smart mobility system of Salo, discussed in subsection 5.1, will also help the city's appeal. Efficient travelling opportunities to areas outside the city can allow Salo to maintain even some of those citizens who have received a job opportunity from another city. For instance, if a citizen of Salo receives a job or a place of study in Turku, they can utilise the smart and improved travel opportunities for efficient and fast commutes, allowing them to still live in Salo, despite working or studying in another city. Combining this with various comfortability-increasing services will prevent migration out of Salo, allowing the city to thrive in the future.

In order to provide the different services required for satisfying the requirements of its citizens, Salo must also ensure the security of its operations by addressing the security, privacy and service availability challenges discussed in sections 4.1 and 4.2. As discussed in the aforementioned sections, these challenges can significantly jeopardise the operations of different smart cities and their solutions, meaning that the threats caused by these challenges are also very apparent in the Salo smart city project. Consequently, measures such as encryption, pseudonymisation and anomaly detection should be extensively implemented in order to ensure the future success of the city of Salo and its smart city initiatives.

Based on the above discussions, the Salo smart city project plays a key role in making the city more appealing and secure to both current and future citizens. With successful smart city initiatives, Salo can advertise itself as a city of the future, fit particularly well for young professionals in different fields of technology. These young professionals will be extremely valuable to the city of Salo, as they will greatly contribute to the success of Salo for many years to come.

In addition to young working adults and students, the city of Salo, and its smart city project, must also consider the comfortability of its senior citizens. The number of citizens in Salo aged 75 or above has been on a constant rise, and it is projected to almost double within the next 20 years [91]. As a result, future smart solutions and services in Salo must consider the needs of the elderly as well.

In order to make the city more accommodating for its senior citizens, Salo must ensure that all smart services deployed in the city are as easy to use as possible. Elderly people are often less skilled with technology, as well as less inclined to use technology in general. Therefore, if different services require an extensive understanding of complex devices and technologies, the likelihood of errors and negligence, particularly among older citizens, is increased significantly. This is where the different measures discussed in section 4.3 come into play – for instance, Salo can work towards developing simpler and more understandable systems, as well as increase the number of different training opportunities the citizens can utilise to improve their technical skills.

All in all, the different conditions and characteristics of the city of Salo set various requirements on the Salo smart city project and the services it provides. While Salo can draw inspiration from other successful smart cities in both Finland and other parts of the world, it must also take its own goals and limitations into account. With thorough development and implementation of different smart solutions and services, the Salo smart city project will become more and more effective and successful in the future.

6 Designing a smart waste recycling system for the city of Salo

Based on the discussions in the previous chapter, the city of Salo requires a wide variety of smart solutions for executing their general strategy and smart city project. As a result, thorough design of different smart solutions and systems fit for the city of Salo is an integral part of developing Salo towards a more resource efficient, sustainable and secure future.

The purpose of this chapter is to design and develop a smart waste management solution for the city of Salo, more specifically the Tavola area. The presented solution is a simulated model of a smart waste recycling centre, where the waste bin fill levels are constantly monitored and analysed in order to ensure bin availability and optimised waste collection times. The primary objective of this solution is to optimise the use of resources in the Salo smart city project, as well as increase the city's comfortability by keeping the area as clean as possible.

The system presented in this chapter is partly based on a similar idea as the Kalasatama smart bins discussed in section 3.2, as the waste data gathering is based on sensor-enabled smart waste bins. In addition, similar to London's smart waste monitoring solutions, the system provides further development opportunities by comparing and identifying the most widely used waste bins, thus providing information about the overall waste recycling requirements in the area. For instance, if a specific waste bin is noticed to fill up considerably faster than other bins, additional bins for that specific waste type can be implemented in the area to create a better balance of the generation and collection of waste in the area.

The main reason behind the development of a smart recycling centre over other smart waste management solutions discussed in section 3.2, such as automated and pipeline-based waste collection systems or DL-based waste detection methods, is that compared to the other solutions, the recycling centre is both cheaper and easier to implement. This lines up with addressing the limited resources of Salo discussed in section 5.2, as the city can implement the system and realise its benefits with a fairly low initial investment. As a result, the system presented in this chapter will provide a good starting point for resource efficiency and sustainability developments in the Salo smart city project.

The system presented in this chapter also acts as a general model for the development of other smart systems that control smart sensors and save the sensor data for further analysis. Due to this general approach, the system will not only help with Salo's current resource optimisation and sustainability objectives through smarter waste management and recycling, but it will also provide a base for other future developments in different areas of the city. Moreover, while the system is primarily designed for the Tavola area in the city of Salo, similar solutions can also be applied in other areas in Salo, as well as other smart city projects around the world.

This chapter covers the key areas and characteristics of the smart waste recycling system designed for the Salo smart city project. Firstly, the components and overall structure of the system are discussed in section 6.1. Secondly, the simulation results are presented in section 6.2. Finally, the limitations and future development opportunities of the system are discussed in sections 6.3 and 6.4, respectively.

6.1 System structure

The smart waste recycling solution designed in this thesis focuses on the recycling of four major waste types: carton, plastic, glass and burnable waste. For this purpose, the system includes four waste bins, one for each aforementioned waste type. These waste bins are monitored and analysed to gain information on the generation of waste in the city of Salo and the Tavola area.

In order to carry out the measures discussed above, many technologies and components are required. As a result, in addition to the waste bins themselves, the smart recycling system consists of sensors, a microcontroller, a communication module and a tool for analysing the collected waste data. The overall structure of the system is showcased below, in figure 1. In addition, more detailed descriptions of the aforementioned four main system components are presented in subsections 6.1.1 – 6.1.4, respectively. Finally, a summarizing overview of the system, as well as its different components and processes, are presented in subsection 6.1.5.

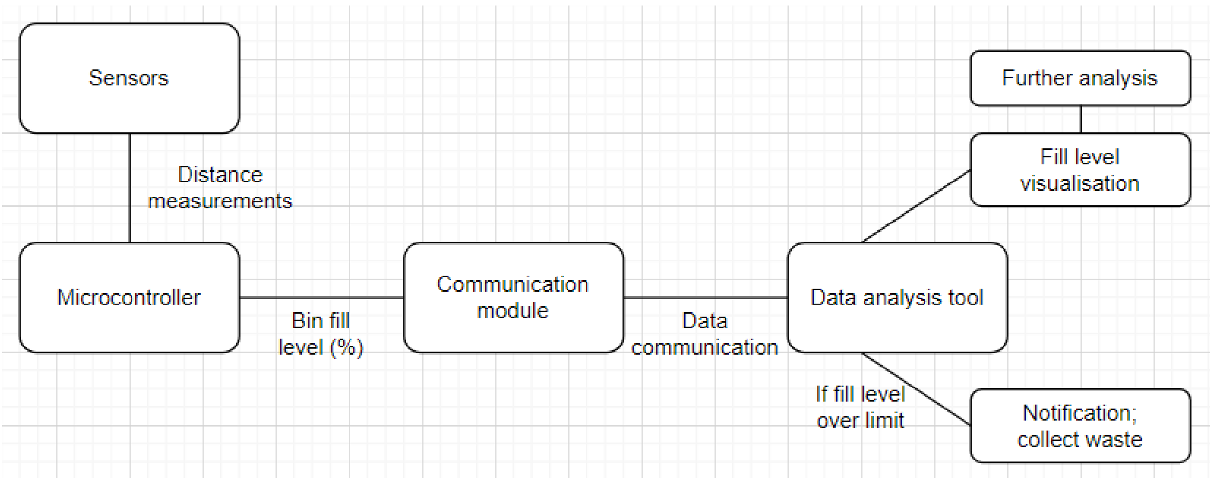

Figure 1: General overview of the designed smart waste recycling centre.

6.1.1 Sensors

The monitoring of the waste bins' fill levels is carried out with HC-SR04 ultrasonic sensors. These sensors are attached to the top of the waste bins, allowing them to gather information about the bins' fill levels by measuring the distance from the sensor to the waste in the bin. The shorter the distance, the higher the fill level, meaning that the sensors' distance measurements can easily be used for determining when the waste bins are close to full, and therefore, should be emptied and collected as soon as possible.

The HC-SR04 sensors include 4 pins – VCC, GND, Trig and Echo. The VCC and GND pins are primarily meant for powering the sensor, as they provide the sensors' input voltage and electrical reference point, respectively. The Trig and Echo pins on the other hand, are the primary pins for measuring the sensors' distance from a particular object – in this case, the surface of the waste in the recycling centre's waste bins. The Trig pin acts as the input, as it initialises the measurement process by sending an ultrasonic pulse, which travels at the speed of sound, after being kept in a high state for a minimum of 10 microseconds. Echo then acts as the output pin, staying in a high state until it receives the returning pulse, allowing it to measure the time in which the pulse travelled to the object and back. These measurements are then sent to the microcontroller in order to calculate the distance based on the measured time. These calculations are explained in the next subsection, 6.1.2.

6.1.2 Microcontroller

Microcontrollers are key components in sensor-enabled smart systems, as they are integral in monitoring and controlling different smart sensors. The Arduino Uno microcontroller was chosen for the smart recycling system designed in this thesis, particularly due to its simplicity and cheap cost, as well as its open source software and hardware [94]. All of these factors are extremely useful for resource optimisation in the city of Salo – the simplicity and cheap cost of Arduino Uno allow for seamless development and implementation of the system, whereas the open-source software and hardware expand the potential of various future developments.

The Arduino Uno microcontroller acts as the central hub of the smart recycling system. Not only is it used for controlling the system and its different components, but it also performs the necessary calculations for determining the bins' fill levels based on the sensor data discussed above. In short, the microcontroller is responsible for converting the sensor data into a more understandable form, where it can be used to analyse practical events, such as waste bin fill levels and waste generation.

The distance between the sensor and the waste is calculated by a simple multiplication of the pulse's speed and travel time to the waste surface and back. In addition, since the measured travel time includes the travel in both directions, the result of the aforementioned multiplication must be divided by two. Moreover, as the distance used in the fill level calculation is in centimetres, and the HC-SR04 sensor measures the time in microseconds, the speed of sound, 343 m/s, must be converted from meters per second to centimetres per microsecond, resulting in the speed of 0.0343 cm/µs. As a result, the sensor data is converted into distance with the following formula:

$$Distance = \frac{0.0343 * [Pulse\ travel\ time]}{2}$$

After the aforementioned calculation, the system must still use the distance measurements for calculating the waste bins' fill levels. Since the sensors measure the distance between the waste surface and top of the waste bin, the distance received with the distance calculation signals the amount of space left in the bin. As a result, in order to calculate the amount of occupied space in the waste bin, the distance value is deducted from the overall height of the bin. Finally, the result of this calculation is divided by the overall bin height, and then multiplied by 100 in order to gain the percentage value of the bins' fill levels, resulting in the following formula:

$$Fill\ level\ (\%) = \frac{[Bin\ height] - [Distance]}{[Bin\ height]} * 100$$

In addition to controlling the sensors and processing their data, the Arduino Uno microcontroller also sends the processed data to the system's communication module. This is an important part of the proposed smart system, as it enables further processing and analysis of the data collected by the system, resulting in various future development opportunities. More detailed discussions of the communication and data analysis components is presented in subsections 6.1.3 and 6.1.4, respectively.

6.1.3 Communication

Communication is an integral part of different smart systems, such as the smart recycling centre described in this chapter, as various communication technologies can be used to transfer the system data to external tools for further analysis and efficient data-driven decision-making. Due to these benefits, the evaluation of the most suitable communication solution for the proposed smart recycling system is extremely important.

As discussed in subsection 2.2.3, a wide variety of communication solutions are used for enabling different smart systems in smart cities, meaning that the smart recycling centre data can be communicated with many different solutions. Moreover, when evaluating different communication solutions, many different factors, from the networks' range, performance and reliability to their security and energy consumption, must be considered. As a result, in order to determine the most suitable communication solution for the smart waste recycling centre, thorough analysis of different solutions is required.

In general, all components of the smart recycling centre are quite close to each other, meaning that the system does not require the long-range communication capabilities of, for instance, LoRaWAN and LTE networks. However, since the receiving device might not be right next to the recycling station, the slightly longer coverage area of Wi-Fi compared to other short-range solutions, such as ZigBee and Bluetooth, can be required, especially if the system is later implemented in other areas as well.

Based on the above discussions, Wi-Fi is a balanced communication solution that fits the purpose of the proposed smart system extremely well in terms of its communication range. Additionally, since the purpose of the system is to act as a model for other smart systems, the moderate communication range provided by Wi-Fi solutions provides better opportunities for future developments, as discussed above.

Wi-Fi is also a promising solution due to its higher data rates, which were discussed in subsection 2.2.3. Not only does this help with service availability by ensuring that all required waste generation and recycling data can be transferred efficiently, the better performance of Wi-Fi also creates a more promising future for the designed smart system. With higher performance potential, the system can be used for more and more purposes in the future, thus allowing the city of Salo to increase its resource efficiency even more effectively.

In general, Wi-Fi is a versatile communication solution, fit for many different purposes. In fact, as discussed earlier in subsection 2.2.3, Wi-Fi communication is suitable for many different smart systems and solutions. This makes it a good and reliable option for the smart system presented in this chapter, as not only does it suit the needs of the smart recycling centre, but it also allows similar systems to be used for other purposes as well.

In addition to its performance and reliability, Wi-Fi is also a suitable communication solution due to its general familiarity and ease of use. Wi-Fi communication is relatively easy to implement in smart systems, meaning that the designed system for smart waste recycling can be deployed efficiently, allowing the city of Salo to start optimising the use of its resources as soon as possible.

Energy consumption is another important factor to analyse. Since resource optimisation is one of the key objectives of the proposed smart system, the used communication solution should not consume an excessive amount of resources through high energy consumption, meaning that energy efficient communication solutions should be used when possible.

In subsection 2.2.3, ZigBee and LoRaWAN networks were identified as the most power efficient communication solutions used in smart cities, meaning that in terms of energy consumption, ZigBee and LoRaWAN would be the most suitable options for the smart waste recycling centre. However, despite the energy efficiency of ZigBee and LoRaWAN communication, Wi-Fi solutions should also be considered, particularly due to their previously discussed benefits in other areas, such as performance and ease of use. As a result, finding the balance between performance and energy consumption is integral in determining the most suitable communication solution for the smart recycling centre, as well as other smart systems in different smart city areas.

Energy efficient Wi-Fi technologies can be used for achieving the aforementioned balance between performance and energy consumption in the smart waste recycling centre. For instance, in the case of short-range systems, the energy efficiency of Wi-Fi can be improved through the implementation of low power Wi-Fi modules [95], meaning that the usual higher energy consumption of Wi-Fi will not be as big of an issue in many smart systems intended for shorter ranges.

In addition to low power Wi-Fi modules, the resource consumption of Wi-Fi can also be reduced with the use of ad hoc Wi-Fi networks. In fact, compared to various LoRa networks, Wi-Fi ad hoc networks can achieve lower energy consumption in short range communication, at distances under 300 meters [96]. Additionally, in [97], Zhou presents a cheap and energy efficient ad hoc Wi-Fi solution based on the ESP8266 Wi-Fi module. As a result, by utilising ad hoc networks, the energy efficiency of Wi-Fi can be improved significantly, resulting in more balanced communication solutions for different smart systems.

A more direct way of specifically improving the energy efficiency of Wi-Fi in the proposed smart waste recycling system is to adopt a similar approach to the Google Nest Protect smoke alarm, which is based on only connecting to the internet when it is absolutely necessary, such as when an alarm occurs or software updates need to be downloaded [98]. In the smart recycling system, this approach can be carried out by only connecting the system to the internet when the level of waste in the bins changes, and therefore, the changed bin fill level must be communicated to the data visualisation and analysis tools. This will reduce the overall power consumption of the smart waste recycling centre, as the Wi-Fi communication module will mostly only consume power during the moments that the system is communicating information, instead of being constantly connected and consuming additional power.

All in all, the benefits of Wi-Fi outweigh its potential disadvantage of higher energy consumption. Most notably, the increased resource efficiency achieved with the smart recycling centre makes up for the slightly higher energy consumption of Wi-Fi, especially if the energy consumption of the system's Wi-Fi communication module can be decreased with low power Wi-Fi modules, ad hoc Wi-Fi networks and, most importantly, selected connectivity only when required. Due to these factors, Wi-Fi is a suitable communication solution for the smart recycling centre from the perspective of energy consumption as well.

Security is the final area of consideration regarding the most suitable communication solution for the smart waste recycling centre. As discussed in chapter 4, security is an integral part of any smart system, as the benefits of different systems cannot be realised if the systems are either unavailable or misused in some fashion. The same concept applies to the communication solution used in the smart recycling centre – if the security of the communication device is compromised, the waste generation and recycling data cannot be used for further analysis and data-driven decision-making. As a result, even though Wi-Fi is a good solution based on the other factors discussed in this subsection, its suitability also depends on its potential security features and flaws.

Due to its constantly increasing popularity, Wi-Fi has become a more and more appealing target for cyber attackers. Most notably, many of the smart city security challenges discussed in chapter 4, such as data breaches and DoS attacks, pose a significant threat to Wi-Fi-based systems. As a result, in order to reliably use Wi-Fi for smart system communication, the security of Wi-Fi must be improved through various countermeasures.

Wi-Fi security can fortunately be improved with various security measures. Most notably, as Wi-Fi technologies have been widely used and researched for a long time, measures such as data encryption, firewalls and VPNs have improved significantly over the years, thus improving the security of Wi-Fi solutions. Moreover, in addition to their energy consumption improvements discussed earlier, ad hoc Wi-Fi networks can also provide security improvements to existing Wi-Fi solutions, particularly in the form of increased data security through advanced encryption techniques [99].

Based on the above factors, as well as the different security measures discussed in chapter 4, Wi-Fi communication can be secured in many different ways, meaning that from the perspective of security, Wi-Fi can be chosen as the communication solution for the smart waste recycling centre designed and presented in this thesis. While security threats and attacks cannot be entirely avoided in almost any system, minimising these challenges will ensure the optimal use of the smart system, resulting in significant resource savings in the city of Salo.

Based on the discussions in this subsection, Wi-Fi is a suitable communication solution for the smart waste recycling centre, particularly due to its efficient performance and ease of use, as well as its versatile security measures. As a result, the ESP8266 Wi-Fi module is used to perform communication in the smart waste recycling centre. The module is responsible for communicating the waste recycling data to an external analytics platform for data visualisation and further analysis.

6.1.4 Data visualisation and analysis

The visualisation of the data collected by smart systems provides a simple and easily understandable overview of the system’s use. In the case of the smart recycling centre, data visualisation provides efficient information about the generation of different types of waste around the city, as well as shows the availability of waste bins in a clear and concise manner.

In the designed smart waste recycling centre, data visualisation and analysis are carried out with the ThingSpeak analytics platform. The ThingSpeak platform is a suitable solution for the proposed smart system, particularly due to its efficiency and versatility in IoT analytics. By using ThingSpeak, the fill level of each waste bin in the recycling centre is presented in their own graph, resulting in simple and effective analysis of the generation of different waste types.

Due to the separate data visualisation of each waste bin, the use of different bins can easily be analysed separately, as the graphs can be inspected individually in order to gain information on a specific waste type. As a result, the system can be used effectively to only analyse the information that is required at a specific time. For instance, if an excessive amount of plastic waste is jeopardising the city's cleanliness and overall comfortability, the information of plastic waste collected by the smart waste recycling centre can be found quickly in order to solve the issue as effectively as possible. As a result, no time or other resources are wasted on analysing information that is not relevant to the current issue, which significantly increases the system's resource efficiency benefits.

In addition to the analysis of separate waste bins discussed above, the smart system also allows for more thorough and comprehensive analysis. In fact, the analysis and comparison of the generation of different waste types is a key feature of the proposed smart system, as it provides the necessary information for improving Salo's resource efficiency, sustainability and comfortability through smart and data-driven waste management. The ThingSpeak platform is used to represent all of the data gathered by the system in a single page, meaning that a simple side-by-side comparison of the graphs representing different waste types allows the system to provide a clear overview of all waste recycled through the smart waste recycling centre, thus providing great opportunities for future waste management developments.

In addition to visualising and analysing waste recycling data, ThingSpeak is also used as a tool for directing waste collection in the smart recycling centre. When a waste bin's fill level reaches 90%, ThingSpeak sends an email alert notifying that the bin needs to be emptied as soon as possible. This approach greatly contributes to ensuring service availability, as all waste bins in the recycling centre will be emptied on time, meaning that the citizens of the area will always have an opportunity to recycle their waste when necessary. Moreover, as the system only sends waste collection alerts when the waste bins are close to filling up, any unnecessary waste collection can be avoided, resulting in further resource savings.

Based on the discussions in this subsection, the performance and potential benefits of the smart waste recycling centre can be optimised through ThingSpeak data visualisation and analysis in order to achieve the best possible results in resource efficient waste management. Not only do the data analytics measures help with enabling current operations, but they are also the driving force behind any potential future developments, making them an integral part of the smart waste recycling centre, as well as any other smart systems deployed in different areas.

6.1.5 System overview

As discussed throughout this section, the smart waste recycling centre designed in this thesis consists of various components, all of which play a key role in enabling the system's performance and intended features. In order to achieve these features, the smart waste recycling system is carried out with the following processes:

1. The HC-SR04 sensors, attached to the top of the waste bins, measure the distance of the free space in the bin.
2. The Arduino Uno microcontroller performs the necessary calculations for transforming the distance measurements to waste bin fill level percentage values. The microcontroller also sends these values to the ESP8266 Wi-Fi communication module.
3. The ESP8266 communicates the information to the ThingSpeak analytics platform.
4. ThingSpeak visualises the fill levels of all waste bins, allowing for further analysis of the city's waste generation and recycling requirements. Finally, when the fill level of a specific bin reaches 90%, ThingSpeak sends an email notification, stating that the bin needs to be collected as soon as possible.

The involvement of these processes and components in the smart recycling system structure are visualised below, in figure 2.

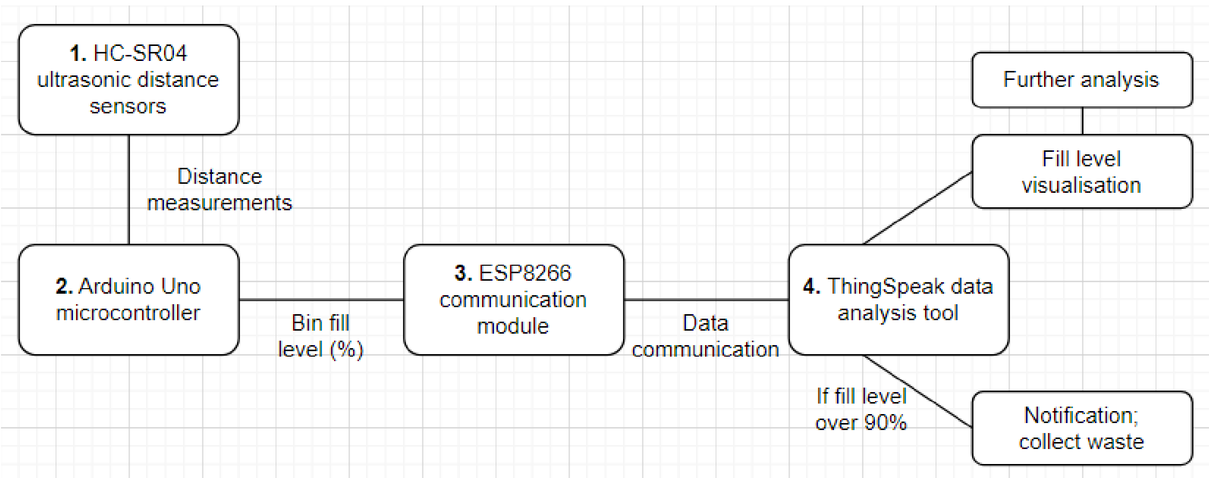

Figure 2: A more detailed description of the general waste recycling centre structure and processes presented in the beginning of section 6.1.

6.2 Simulation

In order to ensure the suitability of the system and its different components and features presented earlier, the system must be tested and evaluated as extensively as possible before its implementation. Not only will the testing examine the features and potential benefits of the system, but it will also provide valuable insight on any limitations that must be addressed in order to improve the system's suitability and performance, so that it can be trusted to improve resource efficiency and general waste management practices in the city of Salo.

The system and its suitability are tested with a simulation, using the Tinkercad and ThingSpeak programs. This testing process involves various key processes surrounding the central features and components of the designed smart wase recycling centre – from the simulation of the circuit behind the smart recycling centre's operations to the visualisation and analysis of the system created data, which is used to make further improvements to the different stages of the waste management process. The simulation circuit and the data analytics results are presented in subsections 6.2.1 and 6.2.2, respectively.

6.2.1 Circuit overview

The Arduino circuit is built and simulated with the Tinkercad program. Tinkercad is a free program that supports the design and implementation of different circuits and components, making it a suitable solution for the purpose of this thesis.

The Tinkercad program is used to simulate the connection of the different system components described in subsections 6.1.1 – 6.1.3. Firstly, the HC-SR04 sensors are connected to the Arduino Uno microcontroller. The sensors' Trig and Echo pins are directly connected to the digital pins of the Arduino Uno board, whereas, due to a limited number of pins on the Arduino Uno board, a breadboard is used to connect the sensors' VCC and GND pins to the 5V and GND pins of the Arduino Uno board, respectively. Secondly, the ESP8266 module is also connected directly to the board, with the exception of the GND connection, which is once again connected through the breadboard. Finally, as the ESP8266 module only operates at a voltage of 3.3V, Arduino's operating voltage of 5V is reduced with two 1kΩ resistors. These connections are shown below, in figure 3.

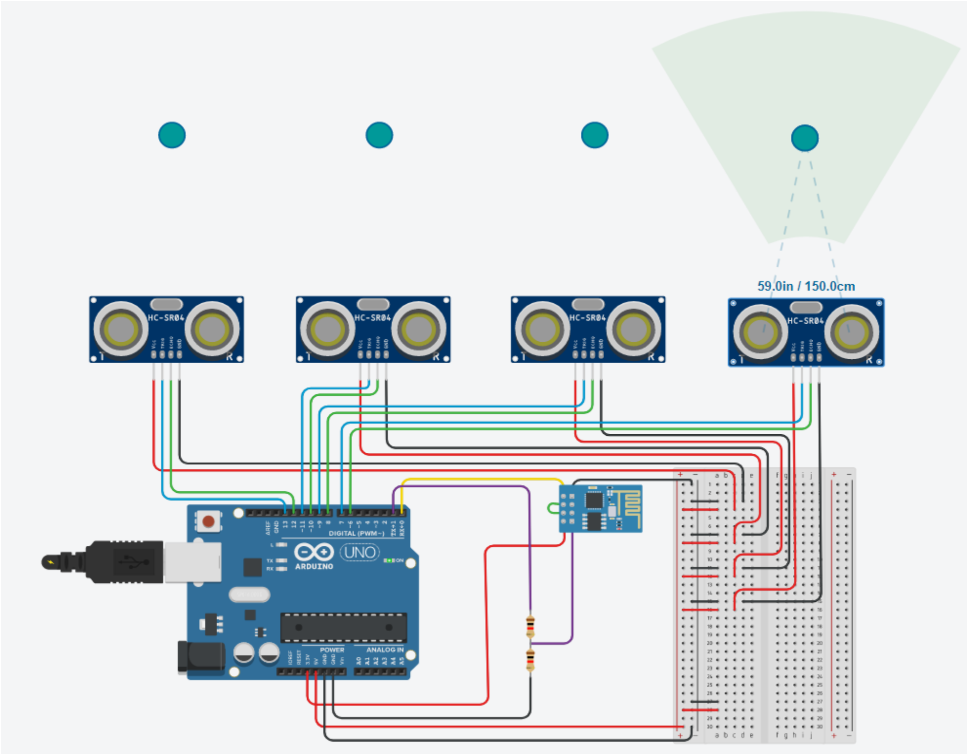

Figure 3: Arduino Uno circuit built with the Tinkercad simulator in order to simulate the designed smart waste recycling centre operations.

As a result of the process described above, the Tinkercad program is able to simulate the operations of the smart recycling centre, from the measuring of waste in the smart waste bins to the calculation and communication of the waste bin fill levels. After this, the final part of the system's testing involves the analysis of the simulation data in order to determine how the system can be used to optimise the use of resources in the Salo smart city project.

6.2.2 Simulation data analytics

As discussed in subsection 6.1.4, the waste generation and recycling data is visualised and analysed with the ThingSpeak analytics platform. However, in order to analyse the data created through the Tinkercad simulation, the data must first be communicated to the ThingSpeak platform. Therefore, the Tinkercad circuit must form a connection with the ThingSpeak channel that has been created for the purpose of analysing the waste data gathered through the simulated system described earlier.

As the created channel is private, the Write API Key of the channel is required for updating the channel. Therefore, the channel's Write API Key must be retrieved from the "API Keys" tab of the ThingSpeak channel interface. Once the Write API Key of the ThingSpeak channel has been retrieved, it is used to make the necessary connection between the simulated smart system and the ThingSpeak channel. The data gathered by each sensor of the simulated system is communicated to a separate field in the ThingSpeak channel, so that the waste generation data of each waste type can be analysed separately. In order to accomplish this, the following code, with "Write_API_Key" replaced with the used channel's own Write API Key, is used:

```
//ThingSpeak Channel Write API Key “Write_API_Key”
String url1 = "/update?api_key=Write_API_Key&field1="; // Sensor 1 data to field 1
String url2 = "/update?api_key=Write_API_Key&field2="; // Sensor 2 data to field 2
String url3 = "/update?api_key=Write_API_Key&field3="; // Sensor 3 data to field 3
String url4 = "/update?api_key=Write_API_Key&field4="; // Sensor 4 data to field 4
```

After the connection between the Tinkercad simulation and the ThingSpeak platform is made, ThingSpeak is used to present the simulation data in a clear and concise manner in order to receive automatic and real-time information about the generation of waste in the smart city. The ThingSpeak data visualisations of the smart recycling centre are shown below, in figure 4.

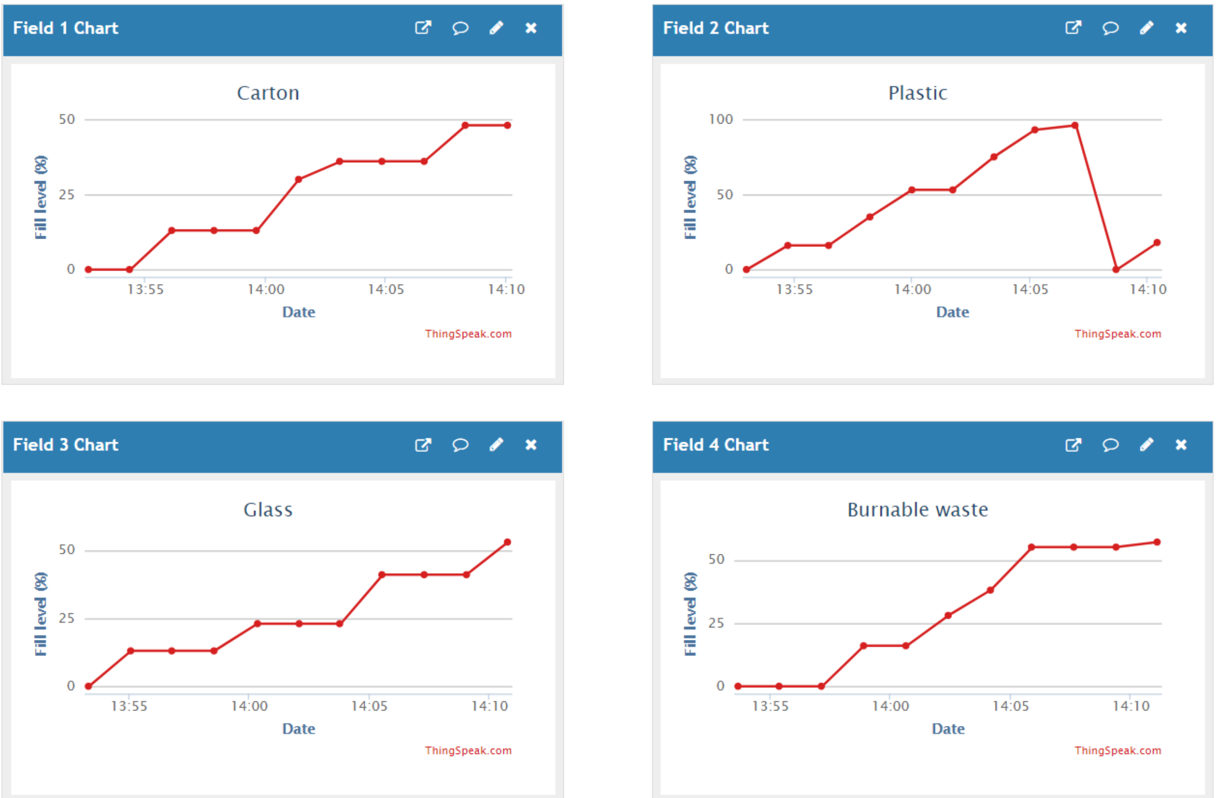

Figure 4: ThingSpeak visualisation of the waste generation data gathered by the smart waste recycling centre simulation.

As shown by the above graphs, the designed smart recycling system provides clear information about the generation of different waste types. As a result, the system provides good opportunities for waste management optimisation, as the generation of different waste types can be seamlessly analysed and compared with each other. For instance, in this specific simulation instance, the data visualisation shows that the generation of plastic waste is significantly higher than the generation of other waste types, meaning that the management of plastic waste must be modified, either by implementing additional plastic waste bins, or by adjusting waste collection times in the area.

The waste bin fill level alert, discussed in subsection 6.1.5, also works well in the simulated system. As soon as the simulated fill level value of a specific bin reached 90%, ThingSpeak sent an email alert, notifying that the bin is full, and therefore, must be emptied as soon as possible. In this simulation, the simulated fill level of the plastic waste bin reached the 90% value, so the sent alert contained a message about the fill level of the plastic waste bin, meaning that the alert system worked as intended. The example alert sent during the simulation can be seen below, in figure 5.

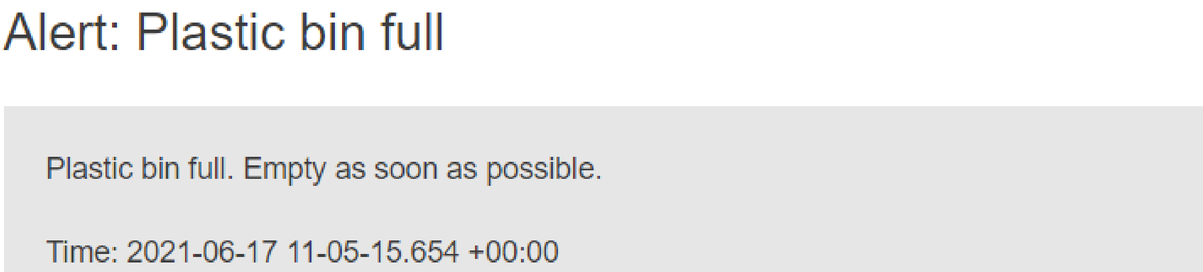

Figure 5: Email alert notifying that a waste bin is full and must be emptied as soon as possible.

Based on the simulation results discussed in this section, the simulated system shows great potential for automating and optimising the waste management and recycling process. When combining the data visualisation and analysis with the waste bin fill level email alerts, the smart recycling centre will provide significant improvements to smart city resource efficiency and sustainability.

6.3 System evaluation

Based on the results of the simulation presented in the previous section, the designed smart system is an effective solution for increasing the efficiency of waste management in the city of Salo. However, analysing any potential issues or limitations with the system is still extremely important, particularly from the resource optimisation perspective – if the service is either unavailable or not functioning as intended, valuable resources will be lost, both during the system's potential downtime and its restoration process.

As the system was carried out with a simulation, the exact characteristics and suitability of the system can only be accurately tested on a theoretical level. While the simulation closely resembles a real environment, and the different features and benefits of the smart waste management system have been discussed and evaluated with both theoretical approaches and practical examples, analysing the complete effectiveness of the system requires testing in a physical environment.

In addition to the slightly insufficient testing of the system's features and effectiveness, the lack of physical testing also limits the evaluation of the system's physical security. As discussed in section 4.2, the physical security of smart systems is an integral component of smart city service availability, and it can be compromised through a wide variety of scenarios. As a result, the evaluation of the physical security of the smart recycling centre is also extremely important.

In the case of the smart recycling centre, physical security is extremely apparent. Firstly, the smart waste bins can be easily accessed by everyone in the area, meaning that the bins, and the sensors inside them, are susceptible to tampering-related disruptions. This means that in order to ensure the physical security of the smart recycling centre, measures such as surveillance and robust system components must be utilised extensively in the construction of the smart recycling centre. Secondly, due to the changing weather conditions of Salo discussed in section 5.2, the different components used in the system must be able to handle both extreme heat and cold, which is another part of the system that requires robust components.

Due to the potential physical vulnerabilities and limitations discussed above, the physical security of the smart recycling centre must be extensively tested in a physical environment, so that the necessary measures of physical security, such as surveillance and more robust components, can be identified before the system is implemented in practice. In addition, the analysis of the suitability of the aforementioned measures, as well as any other useful physical security measures discovered through future testing, can be achieved most effectively with thorough testing in a physical environment. As a result, a purely simulation-based approach does not provide the entire picture of the requirements of the smart waste recycling centre designed in this thesis.

The analysis of the simulation data is also slightly limited, especially due to the general limitations of the ThingSpeak platform. The free version of the service, which was used during the design and development of the smart recycling centre, had several data rate limitations, which introduced some restrictions to the system and its features.

The communication of the bins' fill levels had to be slightly delayed in order to accommodate for the 15 second message update interval limit of the ThingSpeak platform. However, this limitation is fairly negligible, as the delay does not have a significant impact on the system's performance. The ThingSpeak service also only allowed for fairly infrequent sending of email alerts, meaning that in a practical setting, the efficiency of the email alert system might not always be sufficient, and therefore, should be improved when implementing the system in the city of Salo, or other smart cities around the world.

Despite the potential limitations caused by the simulation approach, the system has been designed with these limitations in mind, meaning that the simulation-related limitations have been minimised as much as possible. Most notably, due to the system's simplicity and relatively low number of variables affecting its performance, the system's real performance likely resembles the achieved simulation results discussed in section 6.2 fairly closely. As a result, the simulation testing can be trusted to provide sufficient information about the system's suitability, although physical testing will be required before further development and implementation.

Moreover, even if the system was tested in a physical environment instead of a simulation, there are still other limitations that need to be considered. Most notably, the system is still a prototype, as it has not been used in a real scenario. As a result, the suitability of the system cannot be completely ensured without implementing and testing the system in practice. However, since similar smart waste management solutions have been successfully implemented in other smart cities, as shown by, for instance, the Kalasatama smart waste bin approach discussed in section 3.2, the practical implementation of the smart recycling centre should be a relatively simple process.

All in all, despite some of its minor limitations, the performance and accuracy of the simulated smart recycling centre is at a good level, particularly due to its simple structure, as well as the utilisation of suitable and well-known practices and smart technologies. As a result, the smart recycling system designed in this thesis is a good model for smart waste management, as well as other potential smart systems, both in the city of Salo and other smart city projects around the world.

6.4 Future applications

As discussed earlier in this chapter, the smart system designed in this thesis will not only help with smarter waste recycling in the city of Salo, but it also acts as a model for future smart system developments. As a result, the evaluation of the system's future applications is an important part of the smart system design process.

The smart system designed in this thesis can be applied to various other smart solutions. Most notably, smart systems equipped with distance sensors can be used for further resource optimisation and sustainability improvements through smart lighting and smart parking systems. In these two cases, the distance sensor measurements can be used to determine the citizens' mobility and the vacancy of parking spots in different areas of the city, respectively. This information can then be analysed in a similar fashion to the waste and recycling data analysis presented in subsection 6.1.4 in order to gain an understanding of lighting and parking requirements in the city, resulting in further smart energy and smart mobility improvements.

Based on the above discussion, the smart system proposed in this thesis can be used for smart energy, smart waste management and smart mobility solutions, thus covering all major areas of smart city resource optimisation and sustainability discussed in the thesis. As a result, the system will provide significant improvements to Salo's resource efficiency and sustainability for years to come.

In addition to the solutions discussed above, the smart system can be applied to various other smart solutions through the use of different smart sensors. For instance, the heating of buildings can be monitored, analysed and controlled with the help of temperature sensors, resulting in more energy efficient heating solutions for smart buildings. Moreover, smart city air quality can be monitored and analysed with smart systems consisting of a combination of temperature and gas sensors. Based on these examples, the smart system and its features can easily be modified and reconfigured to suit the needs of many different smart city areas.

Finally, due to its versatile nature, the proposed system structure, consisting of sensors, a microcontroller, a communication module and a data analysis tool, can be applied to a wide variety of smart systems, even those that require longer communication ranges. In these cases, the communication module can be replaced with long-range communication solutions, such as LoRaWAN or LTE, providing further opportunities for the smart system's future applications.

All in all, the smart system designed in this thesis is extremely modifiable and versatile, making it a suitable solution for both current and future smart solutions. With thorough design and use of different components and technologies, the proposed smart system structure can be applied to a wide variety of areas in the city of Salo, as well as many other smart cities around the world.

7 Conclusion

As identified in section 2.1, a city must achieve significant developments in a large majority of the key smart city areas – such as resource efficiency, sustainability, security, smart infrastructure, smart energy, smart transportation, high quality of life and many others – in order to be considered smart. Consequently, the definition of a smart city is not always the same, but it can vary quite a lot based on the city and its specific conditions and requirements.

In order to accomplish the desired developments towards becoming a smart city, cities can, and must, utilise a wide array of technologies to carry out the required solutions and services. Fortunately, due to the versatility and highly developed nature of these technologies, many different types of smart systems and services can be developed effectively. Furthermore, many of these technology-based smart solutions and initiatives have already been carried out in various smart cities around the world, meaning that aspiring smart cities do not have to start their development from scratch.

In terms of fulfilling the resource efficiency- and sustainability-based requirements set on both current and future smart city projects and initiatives, smart energy, smart waste management and smart mobility are the most suitable solutions for achieving the desired smart city characteristics. Based on the discussions in chapter 3, these solutions provide a wide variety of benefits to smart city resource efficiency and sustainability, particularly in the form of automated decision-making and monitoring, as well as various cost efficiency improvements. Moreover, since smart energy, smart waste management and smart mobility solutions can all be carried out with many different technologies, they provide an extremely versatile base for resource efficiency and sustainability developments in all types of smart cities, regardless of size, location or other conditions.

Most of the privacy challenges in different smart city solutions are related to the collection and use of sensitive and personal information, especially due to the wide variety of attacks that can jeopardise the security and privacy of this information. Attacks such as spyware and eavesdropping can lead to the exposure of this information, leaving it to the hands of malicious actors, which is why the protection of data and privacy through different measures, such as GDPR regulation, encryption and data anonymisation, is becoming more and more important.

The different threats to the availability of smart systems and services, DoS, ransomware, injection, MitM and zero-day attacks, as well as general system failure and lack of physical security, set a wide variety of challenges on different smart city projects – if a smart city is not able to provide the services required and expected by its citizens, the entire city and its operations can be disrupted in a drastic manner. Consequently, the various solutions recommended in chapter 4, such as the use of robust system components, firewalls and anomaly-based attack detection, play a key role in the success of both current and future smart cities. Furthermore, smart cities can also utilise user training, security policies and the emergence of technology-based jobs in order to deal with different human error-, negligence- and ethics-related issues, respectively. With these measures, as well as the privacy measures discussed above, smart cities can mitigate the impact of the different challenges that threaten their resource efficiency, sustainability and general security.

Despite being smaller in size, the city of Salo and its smart city project shares many similarities with other smart city projects around the world, with resource optimisation and sustainability as some of its main objectives. However, the development and implementation of different smart solutions and services in Salo is complicated by its ever-changing conditions and resource limitations. Due to the limitations, the city of Salo should begin with utilising simpler and more low investment solutions, such as the smart waste recycling centre designed and presented in chapter 6, to continue their development towards a smart, resource efficient and sustainable city of the future.

7.1 Research results

This section provides a concise summary of the answers found to the research questions set in section 1.1. This summary contains the key results discovered during this research, as well as provides information on the sections of the thesis where potential additional insight on the topics can be found.

1. Which characteristics make a city "smart", which technologies are required for achieving these characteristics, and how are smart city projects carried out in different cities around the world?

   The key smart city characteristics identified in section 2.1 include resource efficiency, sustainability, security, eco-friendliness, smart infrastructure, smart buildings, smart energy, smart transportation, smart healthcare, smart education, smart governance and smart economy, as well as a high quality of life for all citizens. A city can be considered "smart" if it has most of these identified characteristics.

Smart city technologies were discussed in section 2.2. Smart cities should utilise sensors, IoT, communication solutions, big data and AI to achieve the abovementioned characteristics. These technologies enable the development of different smart solutions, thus increasing the efficiency and success of smart cities in general.

Finally, London, Barcelona, Copenhagen, New York, Dubai, Singapore and various Finnish cities were identified as good examples of successful implementations of the aforementioned smart city technologies and characteristics. A more accurate description of these cities' smart city strategies was given in section 2.3.

2. What measures can be taken to increase the resource optimisation and sustainability of different smart city projects and solutions?

   For resource optimisation- and sustainability-focused improvements in smart cities, three major areas of focus were identified in the thesis: smart energy, smart waste management and smart mobility. A detailed discussion of the technologies and benefits, as well as various practical examples, of these solutions were presented throughout chapter 3.

3. What are the most prominent challenges that threaten the resource efficiency, sustainability, security and general success of smart cities, and what measures should be taken to deal with these challenges?

   In chapter 4, four major challenges were identified: security and privacy, service availability, people and ethics. Some of the key identified solutions for overcoming these challenges include data encryption and anonymisation, anomaly detection, user training and security policies. Each challenge and their recommended solutions were presented in more detail in their respective sections and subsections throughout chapter 4.

4. What are the key objectives and requirements of the Salo smart city project, and how can the city of Salo utilise the measures and solutions discovered in questions 2 and 3 to increase their resource efficiency, sustainability and general appeal?

   The Salo smart city project should increase the city's appeal as a technologically advanced city of the future by providing a wide variety of smart services that improve the citizens' quality of life in various ways. The city can take inspiration from other European cities in particular, but it must also have the ability to adapt and make changes to existing solutions to suit its specific needs and changing conditions. Finally, Salo must ensure the security of their operations by utilising the different security measures recommended throughout chapter 4.

5. Which smart solutions can be used to address the considerations identified in question 4, as well as increase the resource efficiency and sustainability of the Salo smart city project in general?

   In this thesis, a smart waste recycling centre was designed to help the city of Salo with optimising the use of its resources, as well as increasing cleanliness and comfortability in the city. The system is based on real-time monitoring, information collection and visualisation of waste bin fill levels, which is then used to optimise waste collection times and guarantee the availability of waste recycling stations for the citizens. The features and overall structure of the solution were covered in section 6.1.

   The effectiveness of the designed smart waste recycling centre was tested with a simulation. The achieved simulation results indicated an effective and suitable system for smart city resource efficiency and sustainability, although the simulated approach also introduced some limitations due to a lack of practical testing and implementation. More detailed discussions about the simulation and the system's effectiveness were presented in sections 6.2 and 6.3, respectively.

   Due to its general nature, the smart solution designed in this thesis also acts as a general model for other potential smart solutions in the city of Salo and other smart cities around the world. The potential future applications of the solution were discussed in section 6.4.

All in all, the achieved results of this thesis provide extensive answers to the determined research questions. The large number of references, both academic material and web sources, provided a good and comprehensive view of the different topics inspected in the thesis. However, due to the scope and complexity of the topic, there is still plenty of room for further research and other future work in the different focus areas of the thesis.

7.2 Potential future work

The topics discussed in this thesis provide a wide range of possibilities for future research. The smart city field is constantly developing, meaning that the development of new solutions for smart city resource efficiency and sustainability will only continue to increase in the future, resulting in more research opportunities and requirements. Moreover, the constantly changing threat landscape will exacerbate the existing smart city challenges discussed in chapter 4, as well as introduce a wide variety of other potential challenges. As a result, future research should also focus on further development of the different countermeasures recommended throughout chapter 4, as well as any new developments that arise due to potential future technological advancements.

In addition to the future research opportunities discussed above, other potential future work involves addressing the limitations and developing the future applications of the smart waste management system discussed in sections 6.3 and 6.4. Most notably, the practical implementation and application to other smart solutions provide many opportunities for future work.

All in all, the possibilities in the field of smart cities are nearly endless. As a result, the topic of efficient, sustainable and secure use of smart city resources, as well as all the different concepts, systems and solutions surrounding this topic, provide a great number of opportunities for future researchers. Due to the ever-developing nature of the topic, future research work in the field is not only extremely promising, but also absolutely necessary in order to ensure the future success of different smart city projects around the world.

References

[1] European Commission, “Smart cities.” [Online]. Available: https://ec.europa.eu/info/eu-regional-and-urban-development/topics/cities-and-urban-development/city-initiatives/smart-cities_en [Accessed Feb. 16, 2021].

[2] W. D. Eggers and J. Skowron, “Forces of change: Smart cities,” 2018. [Online]. Available: https://www2.deloitte.com/content/dam/insights/us/articles/4421_Forces-of-change-Smart-cities/DI_Forces-of-change-Smart-cities.pdf [Accessed Feb. 16, 2021].

[3] B. S. P. Mohanty, U. Choppali, and E. Kougianos, “Everything you wanted to know about smart cities: The Internet of things is the backbone,” *IEEE Consum. Electron. Mag.*, vol. 5, no. 3, pp. 60–70, 2016.

[4] S. Musa, “Smart cities - A road map for development,” *IEEE Potentials*, vol. 37, no. 2, pp. 19–23, 2018.

[5] D. Sikora-Fernandez and D. Stawasz, “The concept of smart city in the theory and practice of urban development management,” *Rom. J. Reg. Sci.*, vol. 10, no. 1, pp. 86–99, 2016.

[6] State of Green, “SMART CITIES: Creating liveable, sustainable and prosperous societies,” 2018. [Online]. Available: https://stateofgreen.com/en/uploads/2018/05/Smart-Grid.pdf [Accessed Mar. 26, 2021].

[7] M. G. Alvarez, J. Morales, and M. J. Kraak, “Integration and exploitation of sensor data in smart cities through event-driven applications,” *Sensors (Switzerland)*, vol. 19, no. 6, p. 1372, 2019.

[8] X. Liu and O. Baiocchi, “A comparison of the definitions for smart sensors, smart objects and Things in IoT,” in *7th IEEE Annu. Inf. Technol. Electron. Mob. Commun. Conf. IEEE IEMCON 2016*, Vancouver, Canada, 2016, pp. 1–4.

[9] M. J. McGrath and C. N. Scanaill, “Sensor Network Topologies and Design Considerations,” in *Sensor Technologies*, Berkeley, CA: Apress, 2013, pp. 79–95.

[10] Q. Chen *et al.*, “A Survey on an Emerging Area: Deep Learning for Smart City Data,” *IEEE Trans. Emerg. Top. Comput. Intell.*, vol. 3, no. 5, pp. 392–410, 2019.

[11] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, “Internet of things for smart cities,” *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, 2014.

[12] European Commission, “Internet of Things - Brochure,” 2019. [Online]. Available: https://digital-strategy.ec.europa.eu/en/library/internet-things-brochure [Accessed Mar. 01, 2021].

[13] K. Patel and Keyur, “Internet of Things-IOT: Definition, Characteristics, Architecture, Enabling Technologies, Application & Future Challenges.,” *Int. J. Eng. Sci. Comput.*, vol. 6, no. 5, pp. 6122–6131, 2016.

[14] S. Chen *et al.*, “A Vision of IoT : Applications , Challenges , and Opportunities With China Perspective,” *IEEE Internet Things J.*, vol. 1, no. 4, pp. 349–359, 2014.

[15] A. Haidine, S. El Hassani, A. Aqqal, and A. El Hannani, “The Role of Communication Technologies in Building Future Smart Cities,” in *Smart Cities Technologies*, Rijeka, Croatia: InTech, 2016, pp. 55–76.

[16] A. Gaur, B. Scotney, G. Parr, and S. McClean, “Smart city architecture and its applications based on IoT,” *Procedia Comput. Sci.*, vol. 52, no. 1, pp. 1089–1094, 2015.

[17] I. Yaqoob, I. A. T. Hashem, Y. Mehmood, A. Gani, S. Mokhtar, and S. Guizani, “Enabling communication technologies for smart cities,” *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 112–120, 2017.

[18] I. Jawhar, N. Mohamed, and J. Al-Jaroodi, “Networking and communication for smart city systems,” in *2017 IEEE SmartWorld Ubiquitous Intell. Comput. Adv. Trust. Comput. Scalable Comput. Commun. Cloud Big Data Comput. Internet People Smart City Innov. SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI 2017*, San Francisco, California, USA, 2017, pp. 1–7.

[19] Bluetooth, “Bluetooth Technology Overview.” [Online]. Available: https://www.bluetooth.com/learn-about-bluetooth/tech-overview/ [Accessed Nov. 16, 2021].

[20] Accenture Strategy, “Smart cities: How 5G Can Help Municipalities Become Vibrant Smart Cities,” 2017. [Online]. Available: https://www.accenture.com/t20170222T202102__w__/us-en/_acnmedia/PDF-43/Accenture-5G-Municipalities-Become-Smart-Cities.pdf [Accessed Mar. 26, 2021].

[21] A. V Joshi, *Machine Learning and Artificial Intelligence*. Cham, Switzerland: Springer, 2020.

[22] R. Kitchin, “The real-time city? Big data and smart urbanism,” *GeoJournal*, vol. 79, no. 1, pp. 1–14, 2014.

[23] M. Chen, S. Mao, and Y. Liu, “Big data: A survey,” *Mob. Networks Appl.*, vol. 19, no. 2, pp. 171–209, 2014.

[24] O. V. Erokhina, D. R. Mukhametov, and A. V. Sheremetiev, “New Social Reality: Digital Society and Smart City,” in *2019 Wave Electron. its Appl. Inf. Telecommun. Syst. WECONF 2019*, St. Petersburg, Russia, 2019, pp. 1–6.

[25] J. McCarthy, "What is artificial intelligence?," 2007. [Online]. Available: http://jmc.stanford.edu/articles/whatisai/whatisai.pdf [Accessed Apr. 16, 2021].

[26] Encyclopædia Britannica, "Artificial intelligence." [Online]. Available: https://www.britannica.com/technology/artificial-intelligence [Accessed Apr. 16, 2021].

[27] S. Palminteri and M. Pessiglione, "Chapter Five - Reinforcement Learning and Tourette Syndrome," in *International Review of Neurobiology*, 1st ed., vol. 112, United States: Academic Press, 2013, pp. 131–153.

[28] W. Liu, Z. Wang, X. Liu, N. Zeng, Y. Liu, and F. E. Alsaadi, "A Survey of Deep Neural Network Architectures and Their Applications," *Neurocomputing*, vol. 234, pp. 11–26, 2017.

[29] Y. Lecun, Y. Bengio, and G. Hinton, "Deep learning," *Nature*, vol. 521, no. 7553, pp. 436–444, 2015.

[30] B. Jan *et al.*, "Deep learning in big data Analytics: A comparative study," *Comput. Electr. Eng.*, vol. 75, pp. 275–287, 2019.

[31] J. Chin, V. Callaghan, and I. Lam, "Understanding and personalising smart city services using machine learning, the Internet-of-Things and Big Data," *IEEE Int. Symp. Ind. Electron.*, pp. 2050–2055, 2017, doi: 10.1109/ISIE.2017.8001570.

[32] London Assembly, "Smarter London Together." [Online]. Available: https://www.london.gov.uk/what-we-do/business-and-economy/supporting-londons-sectors/smart-london/smarter-london-together [Accessed Mar. 02, 2021].

[33] IESE Business School, "These Are The Smartest Cities In The World For 2019," *Forbes*, 2019. [Online]. Available: https://www.forbes.com/sites/iese/2019/05/21/these-are-the-smartest-cities-in-the-world-for-2019/?sh=3939877e1429 [Accessed Apr. 20, 2021].

[34] M. Gascó, "What makes a city smart? Lessons from Barcelona," in *Proc. Annu. Hawaii Int. Conf. Syst. Sci.*, Konua, Hawaii, USA, 2016, pp. 2983–2989.

[35] Ajuntament de Barcelona, "Barcelona Smart City Tour." [Online]. Available: https://bcnroc.ajuntament.barcelona.cat/jspui/bitstream/11703/90889/1/8655.pdf [Accessed Feb. 16, 2021].

[36] City of Copenhagen, "Ambitious Growth Policies." [Online]. Available: https://international.kk.dk/artikel/ambitious-growth-policies [Accessed Feb. 17, 2021].

[37] City of Copenhagen, "Liveable green city." [Online]. Available: https://international.kk.dk/artikel/liveable-green-city [Accessed Feb. 17, 2021].

[38] New York State, “New York Smart Cities Innovation Partnership.” [Online]. Available: https://esd.ny.gov/new-york-smart-cities-innovation-partnership [Accessed Feb. 18, 2021].

[39] Smart Dubai, “Smart Dubai 2021.” [Online]. Available: https://2021.smartdubai.ae/ [Accessed Feb. 18, 2021].

[40] Smart Nation Singapore, “Smart Nation: The Way Forward.” [Online]. Available: https://www.smartnation.gov.sg/docs/default-source/default-document-library/smart-nation-strategy_nov2018.pdf?sfvrsn=3f5c2af8_2 [Accessed Mar. 01, 2021].

[41] Business Finland, “Smart city solutions from Finland,” 2017. [Online]. Available: https://www.businessfinland.fi/48f0a2/globalassets/julkaisut/Smart-City-Solutions-from-Finland.pdf [Accessed Mar. 02, 2021].

[42] Smart & Clean Lahti, “Hi there! Welcome to Smart & Clean Lahti.” [Online]. Available: https://www.smartlahti.fi/ [Accessed Mar. 04, 2021].

[43] L. Bătăgan, “Smart Cities and Sustainability Models,” *Inform. Econ.*, vol. 15, no. 3, pp. 80–87, 2011.

[44] H. Ahvenniemi, A. Huovila, I. Pinto-Seppä, and M. Airaksinen, “What are the differences between sustainable and smart cities?,” *Cities*, vol. 60, pp. 234–245, 2017.

[45] G. Dileep, “A survey on smart grid technologies and applications,” *Renew. Energy*, vol. 146, pp. 2589–2625, 2020.

[46] D. H. Spatti and L. H. B. Liboni, “Emerging Technologies for Renewable Energy Systems,” in *Smart Cities Technologies*, Rijeka, Croatia: InTech, 2016, pp. 193–210.

[47] New York State Energy Research and Development Authority (NYSERDA), “Toward a Clean Energy Future: A Strategic Outlook 2021–2024,” 2021. [Online]. Available: https://www.nyserda.ny.gov/About/Publications/Program Planning Status and Evaluation Reports/Strategic Outlook [Accessed Mar. 07, 2021].

[48] E. O’Dwyer, I. Pan, S. Acha, and N. Shah, “Smart energy systems for sustainable smart cities: Current developments, trends and future directions,” *Appl. Energy*, vol. 237, pp. 581–597, 2019.

[49] C. Gezer and C. Buratti, “A ZigBee smart energy implementation for energy efficient buildings,” in *IEEE Veh. Technol. Conf.*, Budapest, Hungary, 2011, pp. 1–5.

[50] H. Al Haj Hassan, A. Pelov, and L. Nuaymi, “Integrating cellular networks, smart grid, and renewable energy: Analysis, architecture, and challenges,” *IEEE Access*, vol. 3, pp. 2755–2770, 2015.

[51] S. Li, Q. Ni, Y. Sun, G. Min, and S. Al-Rubaye, "Energy-Efficient Resource Allocation for Industrial Cyber-Physical IoT Systems in 5G Era," *IEEE Trans. Ind. Informatics*, vol. 14, no. 6, pp. 2618–2628, 2018.

[52] Business Finland, "Smart Energy Finland." [Online]. Available: https://www.businessfinland.fi/en/for-finnish-customers/services/programs/smart-energy-finland [Accessed Mar. 24, 2021].

[53] S. Ben Atitallah, M. Driss, W. Boulila, and H. Ben Ghezala, "Leveraging Deep Learning and IoT big data analytics to support the smart cities development: Review and future directions," *Comput. Sci. Rev.*, vol. 38, 2020.

[54] Greater Copenhagen, "About Greater Copenhagen." [Online]. Available: https://www.greatercph.com/about [Accessed Mar. 26, 2021].

[55] A. Luusua, H. Pihlajaniemi, and J. Ylipulli, "Northern Urban Lights: Emplaced Experiences of Urban Lighting as Digital Augmentation," in *Architecture and Interaction*, Cham, Switzerland: Springer, 2016, pp. 275–297.

[56] S. Weekes, "UK council smart lighting pilot monitors air quality and footfall," *SmartCitiesWorld*, 2020. [Online]. Available: https://www.smartcitiesworld.net/news/news/uk-council-smart-lighting-pilot-monitors-air-quality-and-footfall-5084 [Accessed Apr. 06, 2021].

[57] European Commission, "Copenhagen installing 20,000 Street Lamps to protect Cyclists and reduce Carbon Emissions." [Online]. Available: https://ec.europa.eu/environment/europeangreencapital/copenhagen-street-lamps/ [Accessed Mar. 29, 2021].

[58] L. G. Anthopoulos, "The smart city in practice," in *Understanding Smart Cities: A Tool for Smart Government or an Industrial Trick?*, Cham, Switzerland: Springer, 2017, pp. 47–185.

[59] European Environment Agency, "Urban sustainability issues - Resource-efficient cities: good practice," 2015. [Online]. Available: https://www.eea.europa.eu/publications/resource-efficient-cities-good-practice [Accessed Mar. 17, 2021].

[60] London Assembly, "Waste policy." [Online]. Available: https://www.london.gov.uk/what-we-do/environment/waste-and-recycling/waste-policy [Accessed Mar. 18, 2021].

[61] Ajuntament de Barcelona, “Waste Prevention Plan.” [Online]. Available: https://ajuntament.barcelona.cat/ecologiaurbana/en/what-we-do-and-why/productive-and-resilient-city/waste-prevention-plan [Accessed Mar. 17, 2021].

[62] Ajuntament de Barcelona, “Zero Waste.” [Online]. Available: https://ajuntament.barcelona.cat/ecologiaurbana/en/zero-waste [Accessed Mar. 17, 2021].

[63] P. K. Gupta, V. Shree, L. Hiremath, and S. Rajendran, “The use of modern technology in smart waste management and recycling: Artificial intelligence and machine learning,” in *Recent Advances in Computational Intelligence*, vol. 823, Cham, Switzerland: Springer, 2019, pp. 173–188.

[64] M. Flores and J. Tan Jr, “Literature Review of Automated Waste Segregation System Using Machine Learning: A Comprehensive Analysis,” *Int. J. Simul. Syst. Sci. Technol.*, vol. 20, no. 2, 2019.

[65] Smart Nation Singapore, “Smart Towns.” [Online]. Available: https://www.smartnation.gov.sg/what-is-smart-nation/initiatives/Urban-Living/smart-towns [Accessed Mar. 18, 2021].

[66] Arup Associates, “Waste Management Strategy,” *Mayor of London,* 2017. [Online]. Available: https://www.london.gov.uk/sites/default/files/58._waste_management_strategy_2018.pdf [Accessed Mar. 18, 2021].

[67] Fiksu Kalasatama, “Fiksu ja kestävä kaupunginosa.” [Online]. Available: https://fiksukalasatama.fi/rakennuspalikat/fiksu-ja-kestava-kaupunginosa-ilmastotavoitteet/ [Accessed Apr. 23, 2021].

[68] Rööri Jätkäsaari, “RÖÖRI | Jätkäsaaren jätteen putkikeräys Oy eli RÖÖRI huolehtii Jätkäsaaren jatepalveluista.” [Online]. Available: https://jatkasaarenroori.fi/en/ [Accessed Nov. 15, 2021].

[69] Juniper Research, “SMART CITIES – WHAT’S IN IT FOR CITIZENS?” *Intel newsroom*. [Online]. Available: https://newsroom.intel.com/wp-content/uploads/sites/11/2018/03/smart-cities-whats-in-it-for-citizens.pdf [Accessed Mar. 31, 2021].

[70] European Commission, “Cities of tomorrow: Challenges, visions, ways forward,” 2011. [Online]. Available: https://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/citiesoftomorrow/citiesoftomorrow_final.pdf [Accessed Mar. 31, 2021].

[71] European Commission, “Questions and Answers: Sustainable and Smart Mobility Strategy,” 2020. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_2330 [Accessed Mar. 31, 2021].

[72] State of Green, “SUSTAINABLE URBAN TRANSPORTATION: Creating green liveable cities,” *Think Denmark - White papers for a green transition*, 2016. [Online]. Available: https://stateofgreen.com/en/uploads/2016/06/Sustainable-Urban-Transportation.pdf?time=1616506125 [Accessed Mar. 30, 2021].

[73] S. Vasebi, Y. M. Hayeri, C. Samaras, and C. Hendrickson, “Low-level automated light-duty vehicle technologies provide opportunities to reduce fuel consumption,” *Transp. Res. Rec.*, vol. 2672, no. 24, pp. 60–74, 2018.

[74] Smart Nation Singapore, “Autonomous Vehicles.” [Online]. Available: https://www.smartnation.gov.sg/what-is-smart-nation/initiatives/Transport/autonomous-vehicles [Accessed Mar. 30, 2021].

[75] Kestävä Helsinki, “Smart Mobility,” 2019. [Online]. Available: https://kestavahelsinki.hel.fi/fi/kestavia-ratkaisuja/smart-mobility [Accessed Mar. 30, 2021].

[76] Turku-Southwest Finland European Office, “EU-hankkeet tutuiksi: Prystine -hankkeessa saadaan autonomiset ajoneuvot näkemään,” 2020. [Online]. Available: https://www.turkueuoffice.fi/uutinen/2020-03-26_eu-hankkeet-tutuiksi-prystine-hankkeessa-saadaan-autonomiset-ajoneuvot-nakemaan [Accessed Nov. 15, 2021].

[77] M. Veres and M. Moussa, “Deep Learning for Intelligent Transportation Systems: A Survey of Emerging Trends,” *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 8, pp. 3152–3168, 2019.

[78] Smart Dubai, “Smart Mobility.” [Online]. Available: https://2021.smartdubai.ae/smart-mobility [Accessed Mar. 31, 2021].

[79] K. Noy and M. Givoni, “Is ‘smart mobility’ sustainable? Examining the views and beliefs of transport’s technological entrepreneurs,” *Sustain.*, vol. 10, no. 2, p. 422, 2018.

[80] Q. Covert, D. Steinhagen, M. Francis, and K. Streff, “Towards a Triad for Data Privacy,” in *Proc. 53rd Hawaii Int. Conf. Syst. Sci.*, Manoa, Hawaii, USA, 2020. pp. 4379–4387.

[81] European Commission, “The GDPR: new opportunities, new obligations,” 2018. [Online]. Available: https://ec.europa.eu/info/sites/default/files/data-protection-factsheet-sme-obligations_en.pdf [Accessed Aug. 26, 2021].

[82] The European Union Agency for Cybersecurity (ENISA), “Cyber Security for Smart Cities - An architecture model for public transport,” 2015. [Online]. Available: https://www.enisa.europa.eu/publications/smart-cities-architecture-model [Accessed Jun. 01, 2021].

[83] J. O. Agyemang, J. J. Kponyo, and I. Acquah, “Lightweight Man-In-The-Middle (MITM) Detection and Defense Algorithm for WiFi-Enabled Internet of Things (IoT) Gateways,” *Inf. Secur. Comput. Fraud*, vol. 7, no. 1, pp. 1–6, 2019.

[84] A. Hern, “University College London hit by ransomware attack,” *The* Guardian, 2017. [Online]. Available: https://www.theguardian.com/technology/2017/jun/15/university-college-london-hit-by-ransomware-attack-hospitals-email-phishing [Accessed Jun. 15, 2021].

[85] B. Briggs, “Hackers hit Norsk Hydro with ransomware. The company responded with transparency,” *Microsoft*, 2019. [Online]. Available: https://news.microsoft.com/transform/hackers-hit-norsk-hydro-ransomware-company-responded-transparency/ [Accessed Jun. 17, 2021].

[86] M. W. Rahman, R. Islam, A. Hasan, N. I. Bithi, M. M. Hasan, and M. M. Rahman, “Intelligent waste management system using deep learning with IoT,” *J. King Saud Univ. - Comput. Inf. Sci.*, 2020, doi: 10.1016/j.jksuci.2020.08.016.

[87] S. Al-Rabiaah, “The ‘Stuxnet’ Virus of 2010 As an Example of A ‘APT’ and Its ‘Recent’ Variances,” in *21st Saudi Comput. Soc. Natl. Comput. Conf. NCC 2018*, Riyadh, Saudi Arabia, 2018, pp. 1–5.

[88] Kaspersky, “Machine Learning for Malware Detection.” [Online]. Available: https://media.kaspersky.com/en/enterprise-security/Kaspersky-Lab-Whitepaper-Machine-Learning.pdf [Accessed Sep. 21, 2021].

[89] K. Ghazinour and M. Ghayoumi, “An autonomous model to enforce security policies based on user’s behavior,” in *2015 IEEE/ACIS 14th Int. Conf. Comput. Inf. Sci. ICIS 2015 - Proc.*, Las Vegas, Nevada, USA, 2015, pp. 95–99.

[90] Stanford Encyclopedia of Philosophy, “Consequentialism.” [Online]. Available: https://plato.stanford.edu/entries/consequentialism/#WhaCon [Accessed Sep. 22, 2021].

[91] City of Salo, “Tietoa Salosta.” [Online]. Available: https://salo.fi/kaupunki-ja-paatoksenteko/organisaatio/tietoa-salosta/ [Accessed Apr. 30, 2021].

[92] Lounea, “Salon, Someron ja Lounea Oy:n tavoitteena älykkäät yhteisöt.” [Online]. Available: https://www.lounea.fi/salon-someron-ja-lounea-oyn-tavoitteena-alykkaat-yhteisot [Accessed Apr. 30, 2021].

[93] City of Salo, "Salon kaupunkistrategia 2026," 2018. [Online]. Available: https://salo.fi/wp-content/uploads/2020/09/strategia_2026.pdf [Accessed Apr. 27, 2021].

[94] Arduino, "Introduction." [Online]. Available: https://www.arduino.cc/en/guide/introduction [Accessed Jun. 09, 2021].

[95] M. S. Mahmoud and A. A. H. Mohamad, "A Study of Efficient Power Consumption Wireless Communication Techniques/ Modules for Internet of Things (IoT) Applications," *Adv. Internet Things*, vol. 06, no. 02, pp. 19–29, 2016.

[96] G. Klimiashvili, C. Tapparello, and W. Heinzelman, "LoRa vs. WiFi Ad Hoc: A Performance Analysis and Comparison," in *2020 Int. Conf. Comput. Netw. Commun. ICNC 2020*, Big Island, Hawaii, USA, 2020, pp. 654–660.

[97] X. Zhou, "Research on Wi-Fi Probe Technology Based on ESP8266," in *2017 5th Int. Conf. Mechatronics, Mater. Chem. Comput. Eng. (ICMMCCE 2017)*, Chongqing, China, 2017, pp. 163–167.

[98] Google Nest Help, "How often Nest Protect connects to the internet." [Online]. Available: https://support.google.com/googlenest/answer/9293089?hl=en [Accessed Nov. 16, 2021].

[99] C. S. Elvitigala and B. H. Sudantha, "An Ad-Hoc Network based on Low cost Wi-Fi Device for IoT Device Communication," in *Int. Conf. Inf. Tech. Res. (ICITR 2017)*, Katubedda, Sri Lanka, 2017.