# Hybrid Simulation Modelling to Support the Development of Recycling Infrastructures

**Aloisius Rabata Purnama**

Department of Engineering
University of Cambridge

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# Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

Aloisius Rabata Purnama
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## Abstract

An enormous amount of waste material arises internationally due to linear economic structures in which natural materials are converted into products which are discarded after use. This problem could be addressed by a shift towards a circular economy, whereby products are kept in use for longer and the material is recovered at end-of-life as a valuable resource. Recycling is therefore central to the development of a circular economy. However, recycling levels are low in many countries, often due to lack of recycling infrastructures. This research aims to support the development of waste management and recycling infrastructures by developing a model to experiment with new systems, particularly looking at the balance between centralised and delocalised systems for collection, sorting and recycling.

The model utilises hybrid simulation modelling due to the accuracy and flexibility that the method provides. The model was developed using an agent-based architecture which includes three submodels to describe the process, logistics, and communication. With this architecture, the model has the capability to simulate a wide range of waste management systems. The frameworks developed in this research provide a new approach to using hybrid simulation modelling. Moreover, the frameworks can be used as guidelines for the development of future tools and models.

The model was implemented into two case studies, in different geographic locations. The first case study investigated the waste management structures in Singapore and compared the performance of centralised and distributed systems. The results showed that the facility processes are more favourable in a centralised system due to economies of scale. On the other hand, the logistics perform better in a distributed system. The balance between centralised and distributed structures can be analysed using the model developed in this research, informing decision-making processes for future developments. The second case study applied the model to analyse the potential for introducing new waste management infrastructures in Indonesia, working with a company currently tasked with reducing waste mismanagement in small cities and rural areas. The results validated the model capability in experimenting with new systems and offered insights into the relative performance of centralised and distributed waste management systems. The work has provided a valuable additional dimension to the feasibility studies and contributes to the recommendations. Both case studies have demonstrated the viability and applicability of this hybrid simulation model as a tool that can be adapted to optimise waste management infrastructures in different environments.

*This thesis is dedicated to my parents...*

*For providing me with wings to reach the sky.*

*Also to my wife...*

*For the love, support, and happiness that you gave me.*

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# Chapter 1

# Introduction

## 1.1 Background

Waste materials are created globally in enormous quantities, presenting significant problems with many different economic, social and environmental aspects. The waste arises from many years of implementing a linear economy in which natural resources are processed into products and then discarded as waste after use. The problems need to be addressed at all levels and covering all the different aspects, including avoiding waste and improving the end-of-life management of materials. This thesis addresses one aspect of the waste management stage, investigating ways of improving the environmental and economic performance.

In terms of economics, there is a loss of value when the materials are discarded as waste. Over a billion tonnes of food is lost annually which costs around USD 940 billion (EPA 2020, UNEP 2021). The clean-up costs and loss of plastic value has been estimated to be around USD 13 billion each year (Deloitte 2018, UNEP 2014).

There are various environmental issues coming from waste, such as greenhouse gas emissions from landfill, water and soil contamination, and marine litter. These issues consequently induce other problems such as climate change and loss of biodiversity (EEA 2014). Furthermore, the waste may cause a foul odour and dirty environment which adversely impacts the social and health aspects of the nearby population.

In order to limit or even reduce waste generation, businesses must shift from the linear economy to the circular economy. The main principle in the circular economy is minimising waste and resource consumption (Geissdoerfer et al. 2017). This can be achieved by reduce, reuse, remanufacture, and recycle.

Reduction of resource usage and waste can be attained through design. The design needs to improve product longevity, incorporate waste as a raw material, and consider the end-of-life treatment of the products. In addition, behaviour change campaigns to reduce overconsumption are necessary but must be planned carefully to avoid unintended consequences. For instance, switching from plastic to paper straws replaces waste from one material to another and often is used as a greenwashing opportunity (Viera et al. 2020). On the other hand, introducing a charge on plastic bags has been shown to reduce usage by 97% and to encourage reuse (DEFRA 2020). In terms of environmental benefits, reusable items are generally better in the long term than single use items (Fetner and Miller 2021). This is however depends on a large number of factors such as washing methods and material weights. Hence, waste reduction campaigns must be designed carefully in order to achieve sustainability.

Reuse is commonly done at an individual scale. In order to achieve a larger scale of circular economy, the reuse systems must operate at a commercial scale. Specific to packaging materials, there are three types of commercial reuse systems, namely closed loop, open loop, and hybrid (ISO 2013). The closed loop reuse system is when the original company reuse their own packaging. The open loop is when any company could reuse the packaging, such as bringing reusable a coffee cup to any coffee shop. The hybrid reuse system is when an auxiliary product is used for the original packaging, for example, a shampoo pouch to transfer the content to a reusable bottle. A reuse system is important to achieve circularity, but requires design in packaging, system, and infrastructures.

Remanufacturing can be defined as restoring the product into a like-new condition (Atasu et al. 2008). Remanufacturing involves product return, disassembly, cleaning, repair or replacement of parts, and reassembly (Johnson and McCarthy 2014, Matsumoto et al. 2016). This process has been conducted for products such as automobile parts, machineries, and engines. Since remanufacturing extends the life of products, a substantial energy and material savings may be achieved. There are several challenges for remanufacturing, such as labour intensity, lack of customer acceptance, large inventories, etc (Kurilova-Palisaitiene et al. 2018, Matsumoto et al. 2016).

Recycling is defined as converting waste into resource. It has been well studied that recycling may contribute significant energy savings and reduce carbon emissions. The reduction of energy is estimated to be around 67-88% for various types of plastic (Association of Plastic Recyclers 2018), 74% for steel, and 90% for aluminium (EIA 2014). Despite of the large energy savings, there is a lack of recycling infrastructures, especially for plastic materials. As a result, many developed countries still rely on export for recycling.

In the waste hierarchy, the priority is in the order of reduce, reuse, and recycle. This is because waste prevention uses less resource than waste treatment. Therefore, waste reduction should be prioritised whenever possible. Suitable reuse and remanufacturing systems should be implemented for the appropriate products to maximise the product's life. After that, the generated waste should be recycled to extract the most value and reintroduce the waste as a resource to the system.

To achieve circular economy, there are immense amount of necessary work in all areas (reduce, reuse, remanufacture, and recycle). This research focuses on recycling, at the bottom of the hierarchy. This is because waste material volumes are enormous, and by improving recycling, a significantly greater portion of the waste could be converted into valuable resource. To enable a high recycling rate, this research aims at improving waste management and recycling infrastructures.

The lack of recycling infrastructures in the UK can be observed in the reliance on waste export for recycling, especially for plastic waste. As shown in Figure 1.1, a substantial amount of plastic waste was exported to China and Hong Kong in 2016. In July 2017 however, China announced the waste import ban to be enforced in January 2018 (Greenpeace 2017). The purpose was to promote the protection of human health & safety and the environment (WTO 2017). Even prior to the enforcement date, Chinese government issued fewer waste import permits (Resource Recycling 2017). This created a large shift in waste export from China to Malaysia, Vietnam, Indonesia, and Turkey as shown in Figure 1.1. In 2019, most of these countries followed China's footstep to reduce the waste import from other countries (CNBC 2019, Resource Recycling 2020). Because of that, Turkey was the only country that imported a significant portion of UK plastic waste in the first half of 2021.

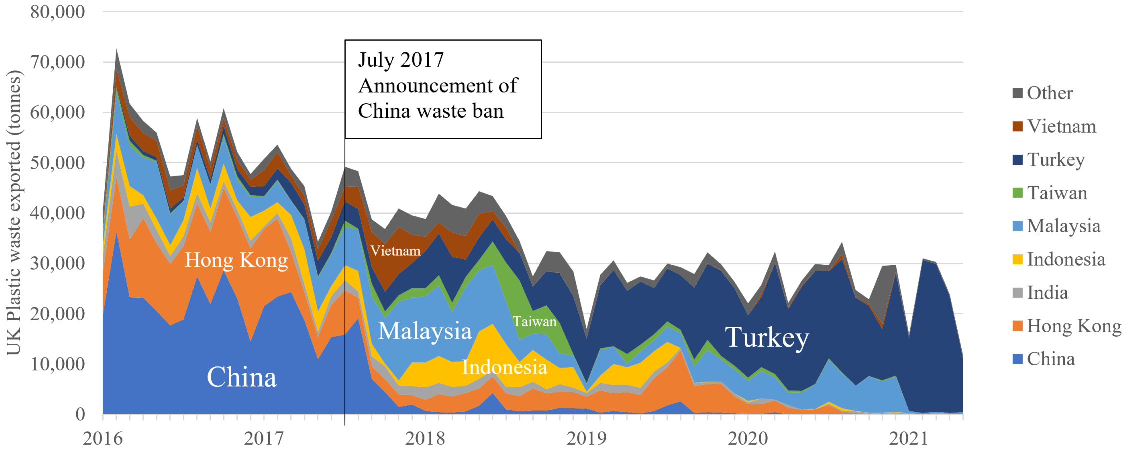


**Figure 1.1** Graph of UK plastic waste export to non-EU countries from January 2016 to May 2021. Obtained from interactive table from HMRC (2021).

Ever since China banned waste import, the waste problem has been an urgent issue which will become increasingly worse as more countries have closed their door on waste import. Therefore, it is crucial for countries to build their own recycling infrastructures to reduce the reliance on export.

In order to tackle the lack of recycling infrastructures, this research aims to develop a model to support the complex planning of building more infrastructures. Utilising modelling and simulation can provide a risk-free environment to test new systems. As a result, the model could open up more possibilities to achieve better recycling infrastructures.

The insights from the model could also contribute to the decision-making process and enable a more robust recycling infrastructure. This could create a more attractive investment opportunity and lead to more infrastructure being built.

## 1.2 Research Questions

As mentioned in the previous section, a potential solution for waste problems is to build more recycling infrastructures. Hence, a model which assists in designing and testing new systems would be valuable. The model however must take into account different conditions and configurations of waste management systems, especially for new and hypothetical systems. Furthermore, the model must generate valuable insights for future recycling infrastructures. Therefore, the research questions to be answered in this research are:

1. How to develop a model which can simulate new waste management and recycling systems?
2. What are the important factors to be considered for the development of recycling infrastructures?

The first question is related to the methods of developing the model for waste management systems. The structure of the model is described in Chapter 3. The modelling methods and criteria for model are explored in Chapter 2 and the model development is addressed in Chapter 4. The applicability of the model is demonstrated in Chapter 5 where two case studies from different countries were conducted.

The second question refers to the insights that can be derived from the model. The insights are obtained from the analysis of real systems in Chapter 5. Therefore, the model contributes to a deeper understanding of waste management systems and hence support the decision-making process for new infrastructures.

## 1.3 Thesis Outline

In this thesis, there are a total of 7 chapters. This includes Chapter 1 which describes the problem and motivation of the research. Due to the lack of recycling infrastructures in many developed countries, there is a high reliance on waste export for recycling. However, most countries are beginning to refuse waste from other countries and thus it is becoming a more urgent matter to develop in-country recycling capabilities. The model developed in this research has the potential to support the development of waste management and recycling infrastructures.

In Chapter 2, a literature review was performed to assess waste management systems, simulation modelling methods, and existing research in the field. This provided a background knowledge on waste management, suitable simulation modelling methods, modelling criteria for this research, and identifying the research gaps.

Chapter 3 describes the methodology and defines the structure of the research and the model. The structure then drives the model development method in Chapter 4. The model consists of an agent-based architecture and three submodels to describe the process, logistics, and communication. Since the model requires facility locations, an approximation method was developed to determine facility locations.

In Chapter 5, the model was applied to two case studies. The first case study investigated the waste management systems in Singapore to compare the performance of centralised and distributed systems. The second case study analysed new waste management infrastructures in Indonesia. The case studies demonstrated the capability of the model to simulate new systems in two different countries.

Chapter 6 provides further analysis on the case studies, model characteristics, and revisits the research questions. Finally, Chapter 7 concludes the thesis by summarising the research, identifying the research contributions, and offering recommendations for future research.

# Chapter 2

# Literature Review

This chapter covers the literature review on waste management system, modelling methods, and modelling criteria for this research. The first section includes various sorting and recycling technologies. The second section explores suitable modelling methods for experimenting with new waste management and recycling systems. Finally, the third section describes important modelling criteria which need to be fulfilled for this research. By summarising the literature review, research gaps could be identified.

## 2.1 Overview of Waste Management System

Developed cities commonly have a formal waste management system in place. In general, a waste management system consists of collection points or waste sources, sorting facilities, recycling facilities, and residual waste treatment facilities (Demirbas 2011). A typical waste management system is illustrated in Figure 2.1.

The waste comes from a large number of sources which is collected by the sorting facility. At the source, the waste can be separated into various types depending on the countries. In Germany, the waste is separated into paper, plastic, organic, glass, and residual (HVNS 2020). In Singapore, the waste is separated into two types, namely dry mixed recyclables and general waste (National Environment Agency n.d.*b*). In countries with low environmental awareness such as Indonesia, the waste is barely separated but some waste sorting is taking place in the informal sector (Aprilia et al. 2012). Hence, sorting facilities in different geographical locations would have different target materials.

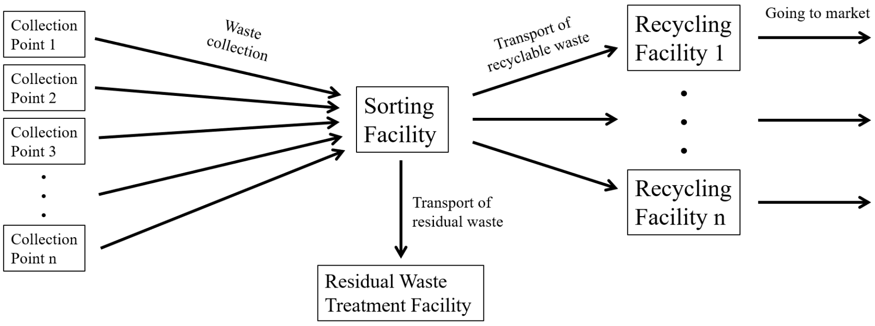


**Figure 2.1** A typical formal waste management system in developed cities.

The subsequent sections describe the sorting, recycling, and residual waste treatment facility. The sorting facility collects the waste from the collection points and segregates the materials that could be recycled. After that, the materials are sent to the appropriate recycling facilities. The recycling facility then recycles the material into usable products (EPA n.d.*c*), most commonly as raw material for further processing such as flakes or pellets for plastics (SoCalConnected 2014) and ingots for metals (Norsk Hydro 2015). Inevitably, some materials are considered unrecyclable and thus considered as residual waste which is transported to the appropriate facility. The most common residual waste treatment facilities are incinerator and landfill.

### 2.1.1 Sorting facility

The purposes of the sorting facility are to collect and sort the waste based on the material types for recycling. The recycling of various materials is discussed in the next section.

At the basic level, the waste can be categorised into organic and inorganic waste. Organic waste originates from living organisms, whereas inorganic waste from non-biological origin (Peace Corps n.d.). The organic waste can decompose naturally, for example food waste and garden waste. The organic waste, especially kitchen waste, is typically wet and difficult to separate from the inorganic waste after being mixed in the bins. Hence, inorganic waste which is contaminated with organic waste is usually considered unrecyclable. Thus, it is best to separate the bins between organic and inorganic waste.

The inorganic waste consists of dry materials that usually can be recycled. There are various types of materials such as paper, cardboard, metal, plastic, and glass. Different technologies are required to sort the waste streams into various types.

The simplest waste sorting process is manual sorting where labourers are used to pick up waste on a moving conveyor belt. Manual sorting is versatile for many different materials with a relatively low capital investment (HSE n.d.). When only manual sorting is used, the process can become labour intensive and has a lower materials recovery rate than other technologies. However, manual sorting can complement other technologies such as to achieve better recovery rate or remove unwanted items from the process (Viridor 2010, Welle 2005).

After the manual presorting, the waste passes through a trommel which is a rotary drum with meshes to remove fine particles (Milton Keynes Council 2016, Viridor 2010). Furthermore, a ballistic separator is used to separate 2D materials, such as paper, cardboard, and plastic films, from 3D materials, such as bottles, cans, etc (Machinex n.d.).

The metal in the waste stream can be categorised as ferrous (containing iron) and non-ferrous metal. The ferrous metal is recovered by using a strong magnet. The magnetic separator must be constantly maintained to remove accumulated magnetic materials which can reduce the efficiency (Tech-FAQ n.d.). The non-ferrous metal such as aluminium cans and copper can be separated by using an eddy current separator. If some ferrous metal leaks to the eddy current separator, the eddy current field can rapidly heat up the ferrous metal and significantly damage the belt (Messenger 2016).

For plastic material, the sorting is commonly done by using sensors, either near-infrared (NIR) or optical sensor (PlastiCircle 2018). The NIR sensor can detect plastic types based on the infrared spectrum. The optical sensor can separate the plastic based on colour and shapes. The optical sorter can also be used for other materials such as glass, paper, etc. The sensor is usually placed above the conveyor belt and air jets are used to separate the plastic target material. Depending on the optimisation, the efficiency of an NIR sorter can range from $80 - 95\%$ (4R Sustainability Inc 2011). With an additional manual sorting after NIR, it could reach 99% (WRAP 2010). Other than sensor based, plastic can be separated by using density, such as air separator and float sink tank (Scheirs 1998).

After all the recyclable materials are separated, the materials are baled by using a baling machine. This compacts the material into a certain dimension which aids the storage and transportation stage (Baidya et al. 2016). The remaining waste from the sorting process is considered as residual waste which is also compacted into bales. Eventually, the bales of residual waste are sent to a treatment facility, such as incinerator or landfill.

There are new sorting technologies being developed which could greatly support waste management. One technology is by using a robot arm to pick waste (BHS 2017, Machinex 2021). The robot arm could replace manual labour since this new technology has a better sorting efficiency, speed, and reliability.

Despite many available sorting technologies, manual sorting is the most common method because of low capital costs and easy set up. At a higher waste volume, more sophisticated and costly sorting technologies can be justified, allowing higher throughput, accuracy and efficiency.

### 2.1.2 Recycling facility

After the recyclable waste is recovered by the sorting facility, the next stage is to recycle the materials into usable raw materials and products.

For the organic waste, two widely used recycling processes are composting and anaerobic digestion (Lin et al. 2018). Composting relies on oxygen for the bacteria to decompose the organic waste into nutrients for the soil. Without proper aeration, anaerobic decomposition could occur which produces methane and foul odour. On the contrary, anaerobic digestion relies on anaerobic decomposition to harvest the methane gas for energy. In this process, the organic waste is sealed in an airtight container with various parameters to optimise methane production.

Most recycling for metal, glass, and plastic is done by using mechanical recycling. Despite different materials, there are some commonalities in the process. Paper recycling is different from the other materials whereby water and chemical are used to form a paper pulp (Greentumble 2018).

There are 4 main components of mechanical recycling, namely presorting, shredding, cleaning, and melting (Allwood et al. 2012, Discovery Inc 2018, Norsk Hydro 2015, SoCalConnected 2014). The presorting uses similar technologies as described in the sorting facility, but for a different purpose. In the sorting facility, the sorting technology is used to recover recyclable materials whereas in the recycling facility, the purpose of the presorting is to remove the unwanted materials from the recycling process. This is because the unwanted contamination can significantly reduce the output quality, especially for plastic (Allwood et al. 2012). Thus, there are usually multiple presorting steps involved to ensure high-quality recycled products.

The intention behind the shredding process is to reduce the material size for easier processing (Capel 2008). For instance, plastic flakes are more uniform and easier to process than plastic bottles. Moreover, the shredding process can increase the surface area of the material for the cleaning process. The presorting steps can be done both before and after the shredding process.

The cleaning process varies greatly depending on the material. An example for plastic, the cleaning involves multiple steps, namely removing caps and labels mechanically, washing to remove food residue and adhesive, and finally drying (SoCalConnected 2014). Another example in the aluminium can recycling process, the labels are removed by using high temperature (Discovery Inc 2018).

After all the necessary presorting, shredding, and cleaning steps, the final step of mechanical recycling for many materials is the melt processing. As mentioned earlier, the steps prior to this process are crucial especially for plastics because the presence of contamination could substantially decrease the quality of the recycled material (Allwood et al. 2012). The melt processing step normally produces raw materials for further process, for instance, plastic pellets, aluminium ingots, or rolled steel. Therefore, the material becomes uniform and more versatile for a wider range of applications. Depending on the facility, the melt processing step could also be used to produce final products instead of raw materials. For glass, clean glass fragments are used directly in the glass production process to form final products. This is due to the extreme melting temperature of above 1400°C (Callister and Rethwisch 2011).

Mechanical recycling components (presorting, shredding, cleaning, and melting) can be arranged in numerous different ways depending on the company and material input. For example, aluminium window frame recycling facility starts with shredding, then multiple presorting steps to remove other materials, another shredding step into a finer particle size, and a final presorting by using X-ray to remove aluminium with heavy metals before melting the aluminium into ingots (Norsk Hydro 2015). An aluminium cans recycling facility begins with shredding and multiple presorting steps to remove other materials but followed by cleaning the labels and paints by using high temperature before melting the aluminium into ingots (Discovery Inc 2018).

In addition to mechanical recycling, plastic can be chemically recycled which alters the chemical structure of the material. One of the most common chemical recycling processes is pyrolysis (Qureshi et al. 2020). In this process, high temperature of above 300°C is applied to the plastic which breaks the long carbon chains into smaller hydrocarbon molecules that have a similar property as oil and can be used as fuel (Miandad et al. 2019). A promising future research is to use chemical recycling process to convert the polymer back into the monomer (Coates and Getzler 2020). With this kind of technology, the monomer can be converted again into polymer without any loss of material properties.

Paper recycling follows a different process from the other materials whereby the paper is converted to pulp. Prior to this process however, but the paper needs to be presorted to remove contamination. Some of the feasible technologies are rubber rollers, ballistic separator, and optical sorter (Milton Keynes Council 2016). After the presorting, the paper is then shredded and mixed with water and chemicals such as hydrogen peroxide, sodium hydroxide, and sodium silicate (Greentumble 2018). The chemicals aid in breaking down the fibres of the paper so other contaminants can be filtered out. If necessary, virgin wood fibre can be added to the mixture to improve the quality of the final paper product. The slurry solution called pulp is pressed with rollers to remove the excess water. After that, the paper is dried by passing it through heated rollers. The paper is finally rolled into a giant roll of various dimensions depending on customer's request. From each recycling process, paper fibre is getting shorter and generally can be recycled at a maximum limit of seven times (EPA n.d.*b*).

Recycling is a well-known process that converts waste material into usable products. The recycling process benefits largely from a robust collection and sorting infrastructure. A large part of the recycling process involves removing undesirable material and thus the end recycled product is relatively clean, pure, and of higher quality. Out of sorting and recycling process, there are some materials which are unrecyclable and thus considered as residual waste. The residual waste is treated at a facility which is discussed in the next section.

### 2.1.3 Residual waste treatment facility

The residual waste from the sorting and recycling process is sent to a treatment facility. The two most common residual waste treatment facilities are incinerator and landfill.

Waste incineration is widely used in some European countries to avoid landfill while generating electricity (Gardiner 2021). In addition to recovering the energy, incineration can reduce the mass of waste by 70% and volume by 90% (Lam et al. 2010). Therefore, incineration is a crucial aspect of waste management in Singapore and Japan due to land scarcity (National Environment Agency n.d.*d*, Whiting 2019).

There are three main parts of the incineration process, namely combustion, energy recovery, and air pollution control (Lam et al. 2010). A key parameter for the combustion process is the calorific value of the waste. For instance, plastic has a high calorific value of $40-47$ MJ/kg which is similar to fossil fuel and better than coal, around 26 MJ/kg (Al-Salem et al. 2009, DBEI 2018, Zevenhoven et al. 1997). The heat from combustion is used to produce steam which drives a turbine and generate electrical energy. However, the moisture content in the residual waste has adverse impacts on waste incineration. Since water absorbs the heat for evaporation, the water content reduces the calorific value of waste and consequently lowers the electricity generation and increases greenhouse gas emissions (Yang et al. 2012). The water content primarily originates from food waste. Therefore, it is important to separate food waste from dry materials in order to minimise water content.

Air pollution control is extremely important. Not only because of strict regulations, but also due to hazardous by-products, such as dioxins, particulate matters, and acidic gases. Thus, modern incinerators have an advanced pollution control system (Lam et al. 2010). Due to this system, the final gas released from the incineration process is carbon dioxide. At a high concentration however, carbon dioxide can be harmful to both human health and the environment (Jacobson et al. 2019).

After incineration, there are two types of ash being produced, namely fly ash and bottom ash. The fly ash is removed from the flue gas by the air pollution control system, whereas the bottom ash falls to the bottom. The incinerator ash must be treated with care since the ash may contain heavy metals, chloride, and dioxins (Ko et al. 2013, Lam et al. 2010, Sun et al. 2016). After the harmful substances are removed, the ash can either be landfilled or used as aggregates for construction (Blasenbauer et al. 2020).

The final option for treating residual waste is landfill. There are many reasons that landfilling is an undesirable option and even banned in some European countries (PlasticsEurope 2017). Firstly, it is because a landfill takes up an enormous land area which will more valuable and important as the population increases. This problem intensifies even further in the long term as more waste is being generated over time.

Secondly, the organic waste residue in the landfill decomposes into methane gas (EPA n.d.*a*). The methane can be detrimental to the environment because methane is 30 times more powerful than carbon dioxide at inducing global warming (Princeton University 2014, Song et al. 2009). In a sanitary landfill, the methane gas can be harvested for energy. However, in an open dump landfill, the methane is hazardous for the environment and prone to cause an explosion. Thirdly is the health and safety issue in the surrounding area. This issue is significantly worse in an open dump landfill. Communities that live near an open dump landfill have a substantially higher risk for illnesses such as respiratory disease, eye infection, diarrhoea, etc (De and Debnath 2016, Etea et al. 2021, Singh et al. 2021).

More effort should be dedicated to avoiding waste being thrown into a landfill. Some developed countries discourage the use of landfill by introducing a landfill tax or even a landfill ban. These policies however must be supported by a decent waste recycling and incineration infrastructure. With a better infrastructure, a significant amount of waste can be converted into valuable resources and thus diverted from landfill.

## 2.2 Modelling Waste Management Systems

By using modelling, new waste management and recycling systems can be explored and analysed. Thus, assisting in developing more recycling infrastructure and consequently tackling the waste problem.

This literature review is conducted to provide a foundational knowledge, explore existing research, and discover research gaps in modelling waste management systems. This review starts with an overview of the field of modelling and simulation from an operations and supply chain perspective and subsequently focusing on simulation modelling.

There are different terminologies associated with the word “modelling” and “simulation”. In the computer science field, *modelling* implies building a model and *simulation* running (or solving) the model. However, in the operations and supply chain field, the word “simulation modelling” is used, where *simulation* is regarded as a modelling technique and *modelling* as the whole process of building and solving the model (Brailsford et al. 2019). Since this review focuses on operations and supply chain, the latter terminology is used.

### 2.2.1 Overview

A model can be valuable to support the decision-making process in solving real world problems. As computers become cheaper and more powerful, research in modelling has increased significantly over the years (Brailsford et al. 2014).

Models can generally be categorised into qualitative and quantitative models. The former model focuses on the qualitative aspects such as languages and opinions. Thus, it can support experts in exploring and organising thoughts, for example, conceptual framework, strategies, drivers, etc (Hosseini et al. 2019, Mangiaracina et al. 2015). The quantitative model involves quantifiable data and often mathematical models (Goertzen 2017, INFORMS n.d.). This type of model is particularly good in solving problems and create predictions by using existing data.

The classification between these two types of models can sometimes be ambiguous. The qualitative model is often classified into the field of operations and supply chain management, whereas the quantitative model in field of operations research (Fuller and Martinec 2005, INFORMS n.d.). Despite being in different fields, there are some overlaps because both model types are aimed to achieve the same purpose, specifically to assist decision-making. One particular overlap is when the model includes both qualitative and quantitative aspects.

To limit the scope of the research, this research is mainly focusing on the quantitative models. The two most common quantitative models in operations research are mathematical optimisation and simulation modelling with the former being the more popular model type (Brandenburg et al. 2014, Hillier 2012, Mangiaracina et al. 2015, Oliveira et al. 2016). The popularity could arise because mathematical optimisation supports decision-making in a conspicuous and direct way. The system is described in mathematical equations and the model tests different configurations to achieve the objective function, usually minimising costs. As a result, the model provides the most optimal decision to produce the desired results.

A majority of research in the optimisation is addressing the facility location problem. The location problem is commonly combined with other problems such as routing, inventory, capacity, etc (Melo et al. 2009). For example, a model for the location-routing problem would be able to calculate the costs while simultaneously considering the location, fleet size, and routing options (Janjevic et al. 2019). By comparing different configurations, the model would be able to provide the most optimal location and routing to achieve the lowest costs. However, considering all possible configurations involves an immense number of possible cases, e.g. $2^{120} \times 10^{110}$ (Kwag and Ko 2019). Hence, there are many proposed solutions to significantly reduce the computational time. Despite being a well-established research area, more research is needed due to the critical role of location in supply chain (Melo et al. 2009).

The optimisation model however is unsuitable for this research mainly due to the lack of flexibility. As mentioned previously, this research requires a model which can assist in designing new systems. Because of that, there is a large number of possible variations between different systems, for instance, different target materials, route planning decision, processing steps, etc. Since an optimisation model requires the system to be expressed in mathematical equations, it can be challenging to develop different sets of equations dependent on the system. Due to the lack of flexibility, an optimisation model is considered unsuitable for this research.

In simulation modelling, the model imitates the system and simulates the behaviour of the system instead of using mathematical equations (Hillier 2012, Lee 2016). As a result, simulation modelling requires much less mathematical sophistication which makes it more intuitive, thus gaining some popularity among researchers and practitioners (Kleijnen 2005). Furthermore, a simulation model is easier to create than an optimisation model and hence can be utilised for a range of different systems.

Simulation modelling offers different values than optimisation, i.e. measuring system performance, provide insights into the system, and testing what-if scenarios (Kleijnen 2005, Oliveira et al. 2016). Thus, simulation modelling enables the exploration of different systems to improve the performance based on indicators such as environmental impacts and costs. This is particularly interesting for waste management for two reasons. First is because a better infrastructure is needed to ensure better resource efficiency and recycling. Second is because there are limited studies that use simulation modelling in waste management context. Therefore, this research focuses on simulation modelling and the next section investigates the suitable simulation modelling methods for this research.

### 2.2.2 Simulation modelling methods

This section describes the three most widely used simulation methods which are discrete-event simulation (DES), system dynamics (SD), and agent-based modelling (ABM). These methods can also be combined to form hybrid models (Brailsford et al. 2019, Jahangirian et al. 2010). Simulation modelling has been used in many different industries. However, there are limited studies in the context of waste management which are explored further in the sections ahead.

#### Discrete-event simulation (DES)

DES is a popular simulation method in business and manufacturing because many industrial processes involve separate occurrences (or discrete events), such as cut, weld, paint, or transport (de Sousa Junior et al. 2019, Oliveira et al. 2016).

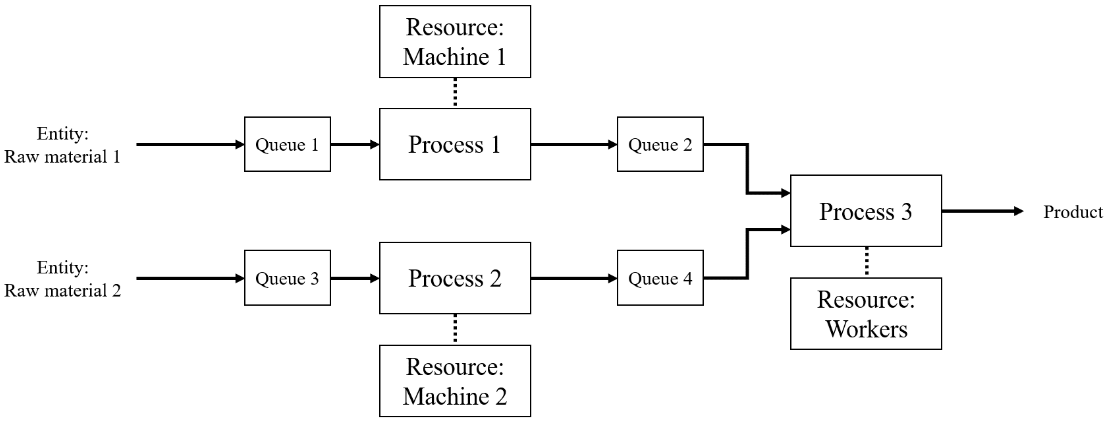


**Figure 2.2** An example of a simple DES model.

An example of DES model is shown in Figure 2.2. In this example, Raw Material 1 goes to a holding area labelled Queue 1. Process 1 can only be executed when the machine (Machine 1) is ready, and the output of Process 1 is placed in Queue 2. Raw Material 2 goes to a similar process and the output is placed in Queue 4. When the materials in Queue 2 and Queue 4 and the resources for Process 3 are ready, then Process 3 can be conducted to produce the product. From this simple model, we can identify the bottlenecks and measure performance, e.g. resource utilisation and lead time. It is also possible to expand the model, such as having more detailed process steps and adding stochastic process time and failure rates.

DES involves modelling sequences of processes and queues which are performed over the entities. The fundamental building blocks of a DES model are (Brailsford et al. 2014):

- Entities: individual items that flow through the system, for example raw materials in manufacturing and orders in supply chain.
- Queues: holding areas before entities can go through a process.
- Processes (or activities): work to be performed on entities, for example machine operations and vehicle travelling.

- Resources: required resources to run the processes, e.g. operators, equipment, and machines.

Despite being a popular method, there are limited DES studies in waste management context. In the study by de Oliveira et al. (2019), municipal waste management scenarios between landfill, recycling, and energy recovery were evaluated by costs and carbon emissions. Gonçalves et al. (2019) assessed the costs and emissions of tire waste by using different transport configurations, e.g. different vehicle types, fuels, and mode of cooperation. In the work by Barletta et al. (2016), automated sorting technology for electronic waste was compared with the current operation and analysed based on the profitability, energy consumption, and social impact to the stakeholders. Derived from these studies, the general direction of the research is the simulation of different scenarios followed by an analysis of the performance. Therefore, DES enables the users to test the viability of various systems which operate in discrete-event behaviour.

### System dynamics (SD)

There are qualitative and quantitative aspects of an SD model as shown in Figure 2.3a and b, respectively. The qualitative aspect involves the construction of causal loop or influence diagrams (Brailsford et al. 2014). The purpose of the diagrams is to show the relationship between the elements in the system and could be valuable in identifying unintended consequences.

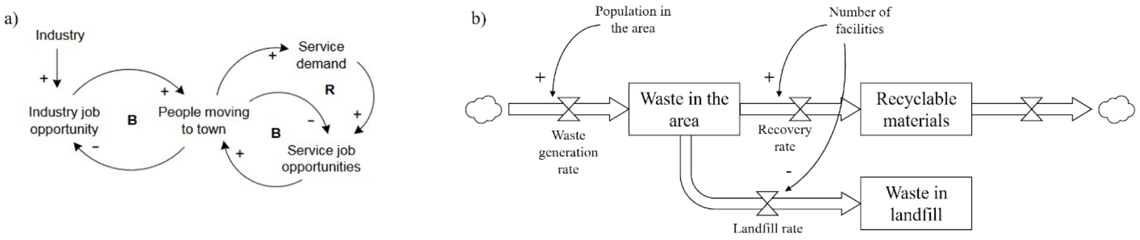


**Figure 2.3** An example of the: a) qualitative (Haraldsson 2004) and b) quantitative aspect of an SD model. The B loop is a balancing loop while the R loop is a reinforcing loop.

The example in Figure 2.3a describes the relationship between number of people in a town with job opportunities (Haraldsson 2004). The presence of an industry would increase job opportunities and consequently attract people to the town. However, more people reduce the job opportunities as the vacancies are being filled. This loop is called a balancing loop since the two elements balance each other out. This is similar to the smaller loop between people moving to town with service job opportunities. As the number of people grows, the area would require more service for the people and subsequently increase the service job opportunities. Eventually, the job opportunities would attract more people to come to town and the loop continues. This loop is called a reinforcing loop where the value keeps increasing or decreasing indefinitely.

The quantitative aspect is associated with the stock and flow diagram which is analogous to water tanks connected by pipes (Brailsford et al. 2014). It is thus suitable to simulate a continuous process. The example in Figure 2.3b illustrates a simple waste generation model of a town. The clouds on the diagram represents materials outside the system. The waste generation rate increases with the population. Some waste is recovered into recyclable materials while the other waste goes into a landfill. More facilities would lead to a higher recovery rate and lower landfill rate. The recyclable materials can then be sold outside of the system. The population in Figure 2.3b could be linked to Figure 2.3a. However, combining the model in Figure 2.3a would require quantification of some qualitative aspects, such as job opportunities and service demand.

Compared to DES, there are many more research studies which use an SD model for waste management context. In the literature, SD model has been used to simulate various systems such as municipal, food, and electronic waste. Some of the measured performance indicators were environmental performance (carbon emissions, energy consumption), financial performance (profitability), inventory (amount of waste generated, recycled, or landfilled), and population. These systems were simulated in a continuous time frame.

Most SD models test different scenarios in a similar way to sensitivity analysis. Rather than changing the system, the studies observe the effects of parameter values and forecast the system behaviour. An exception is a separate SD model by Wang et al. (2020) to simulate different policies (e.g. deposit return scheme, tax refund, mandatory recycled content) which affected the main SD model for PET bottle recycling.

### Agent-based modelling (ABM)

Compared to DES and SD, ABM is the newest method but has the fastest growth in terms of the usage. The popularity could arise because ABM is relatively straightforward to learn and very flexibility to simulate many different situations (AnyLogic n.d., Bonabeau 2002).

In ABM, an agent is defined as an autonomous entity, meaning that the agent makes its own decisions based on the behaviour rules. The behaviour rules also determine how the agent interacts with other agents in the system. Therefore, ABM creates the system behaviour from a bottom-up approach, namely the sum of individual actions and interactions of the agents (AnyLogic n.d., Brailsford et al. 2014, Railsback and Grimm 2019). Depending on the problem, the agent could represent people, vehicles, or even microorganisms. During the simulation, some indicators are utilised to measure system's performance.

Similar to DES, despite rising in popularity, there are only a few waste management studies that use ABM. In the study by Skeldon et al. (2018), food waste processors were modelled to make decisions for their operations, business contact, and facility expansion under the influence of landfill tax and financial incentives for processing food waste. Meng et al. (2018) did some experimentation on the charges for disposing waste which affect the resident's behaviour and subsequently profitability of recycling facility and incinerator. Similarly, Brouillat and Oltra (2012) investigated the effect of fees that are charged to either the consumers or producers as a part of extended producer responsibility. The fees then affected the virgin materials used in the system, recycling rate, and technological innovation.

These studies have a similar direction to the studies that use DES, specifically ABM models are used to simulate and analyse different scenarios. However, compared to DES, ABM models have different capabilities which enables different performance metrics, for instance, social interactions and other behaviours. This is because ABM models consist of multiple types of agents which make decisions and interact with other agents.

### Hybrid model

Each simulation method is unique with its own strengths and is suitable for different applications. DES describes the system as a series of separate events and is well-suited for a system with clear a step-by-step process. On the other hand, SD defines the system as a continuous flow which corresponds well with a continuous industrial process. ABM is different because the system in ABM is described as interactions of agents with individual behaviours, hence suitable for a system with complex interactions.

However, most real-world problems are too complex to be accurately modelled by one method (AnyLogic n.d., Brailsford et al. 2019). This therefore gives rise to a hybrid model which is constructed by combining multiple methods. This allows different methods to complement each other, such as representing different parts of the system. Consequently, a hybrid model could lead to a more accurate representation of the system. Specific to this review, the hybrid model only considers the combination of DES, SD, and ABM as the most widely used simulation modelling methods.

The most common hybrid model is combining SD and DES because of the natural dichotomy between continuous (SD) and discrete (DES) models (Brailsford et al. 2019). When modelling the same system, the result from a hybrid SD-DES model was similar to the result from a single SD model (Jovanoski et al. 2012). The minor difference in the results was due to a more accurate inventory in the SD-DES hybrid model. However, the larger potential of the hybrid model lies in the ability to model a more complex production, such as machine maintenance and random product defects.

There are limited software options to combine all three techniques. The first and still the only commercial software to combine all three techniques is AnyLogic (Brailsford et al. 2019). In an example from AnyLogic (n.d.), the ABM was used for the supply chain between manufacturers and distributors. The distributors will generate demand and send an order to the nearest manufacturer. This demand goes to the DES model which processes the order and arranges the warehouse to prepare the products. The warehouse receives the finished products from an SD model of the production line. Since the production is affected by the number of staffs, the workforce is also modelled in the SD model. Since the models are built in the same software, the variables in different models can be connected with ease.

Hybrid simulation modelling has been used for waste management. In the work by Elia et al. (2018), two systems were compared for the collection of electronic waste, either based on schedules or waste amount. SD was used for waste generation, ABM for routing process, and DES for waste collection at customer's location. From the simulation, total distance and truck utilisation were evaluated. Another work by Shi et al. (2014) explored municipal waste by comparing mixed-recycling bins with source-separated bins. The simulation model used ABM for the entities in the system, namely, waste sources, facilities, and trucks and DES for the agent's behaviours. The results from this study were operation costs, recycling rate, and facility utilisation. Similar to other simulation modelling studies, hybrid models are used to analyse different scenarios.

For this research, hybrid simulation modelling is a promising method to model new waste management systems for two reasons. First is the accuracy of the model where different parts of the system can modelled with the suitable methods. The logistics of waste management can be modelled with DES because logistics follows a discrete-event behaviour. Since the processes in sorting and recycling facilities are generally continuous, SD can be utilised to represent the processes. The complexity of the system mainly comes from the immense number of entities, particularly the collection points. Hence, ABM can be used to model the vast number of entities and their interactions in the system.

The second reason to select hybrid simulation modelling is the flexibility aspect. Since different parts of the model use different modelling methods, a change in a specific part would have a minimal disruption to the model. This could be valuable when simulating new systems which is necessary in this research. Therefore, hybrid simulation modelling is a suitable method for simulating waste management systems in this research.

## 2.3 Assessing Existing Simulation Modelling Research

As mentioned in the previous section, there are only few studies in the waste management context. Because of that, a literature review is carried out in a broader context of operations and supply chain. This enables a more comprehensive assessment of existing research in simulation modelling.

This review starts with defining a set of modelling characteristics that would suit the objective of this study. To reiterate, the objective of this study is to support the development of better waste management infrastructures. This is achieved by creating a model which utilises simulation modelling method to support the experimentation of new systems. The ideal model for this research would have the following characteristics: **multiscale modelling**, **uncertainty analysis**, **flexibility**, and **validation**. These characteristics would enable an objective evaluation of the current research in the literature.

Similar to the previous section, the scope is limited to the three most common simulation modelling methods, i.e. discrete-event simulation (DES), system dynamics (SD), and agent-based modelling (ABM). Within the operations and supply chain field, 425 papers published between 2010 and 2020 were identified. The less relevant papers were excluded which leaves 150 papers for further analysis. The models in these papers are scrutinised against the specified characteristics, specifically on how these characteristics are addressed. The subsequent sections show the summary of the review without referencing all of the reviewed papers. This is done to avoid an overwhelming number of in-text citations, especially since a large proportion of these papers have many similarities.

### 2.3.1 Multiscale modelling

Multiscale modelling refers to modelling a system at multiple different scales simultaneously (Weinan and Lu 2011). In the context of this research, the different scales are operations and supply chain. The operations aspect relates to the activities within the company while the supply chain includes the activities outside the company (Florida Tech n.d.). Despite being a multiscale model, the knowledge of the system is still crucial in order to accurately model the system and how it is connected at all levels (Hosseini and Shah 2011).

In the literature however, the design of the model depends on the defined problems and modelling methods. When the problem focuses on a single scale (such as logistics), then a single scale model might be preferred since it can achieve the objective in a more straightforward way than a multiscale model. In contrast, when some interdependencies are present between operations and supply chain, a multiscale model could represent the system more accurately. In waste management, the operations and supply chain are correlated, for instance, the process relies on waste collection and subsequently affects the supply chain of facility output. Thus, a multiscale model is more suitable for waste management systems.

With regards to the modelling methods, most DES and ABM models describe the system as a single scale, either focusing on supply chain or operations. Some multiscale SD models are developed in which the model simultaneously considers supply chain, inventory, and sometimes demand. The most suitable method to create a multiscale model is the hybrid simulation modelling. This is mainly because hybrid simulation model uses different models and methods for various parts of the system, such as the supply chain part with DES or ABM and the process part with SD. Therefore, a hybrid model can be developed as a multiscale model with ease.

### 2.3.2 Uncertainty analysis

Uncertainty is inseparable when modelling a real-world system. This uncertainty could arise not only from a system's behaviour, but also from data uncertainty. In a large waste sorting facility, waste could come from millions of people across many regions. The output of sorting facility could also be sent to other facilities and sometimes internationally. Thus, obtaining accurate waste data can be arduous and incorporating uncertainty is necessary. From the research papers, there are two ways to address uncertainties which are through stochastic modelling and sensitivity analysis.

In terms of modelling uncertainty, the two types of models are deterministic and stochastic models. In a deterministic model, the system is modelled without randomness. Most research uses a deterministic model because of the simplicity of the model and consequently, the effectiveness for designing new processes. The stochastic model is modelling a system with stochastic or random variables. The pattern of random variables generally follows a probability distribution function, most notably normal distribution. Thus, a stochastic model can take into account the uncertainty within the system variables. However, It does not compensate for a lack of knowledge about the phenomena in the system (Sarkar et al. 2002).

A deterministic model would likely be valuable as a beginning stage of model development. Particularly, ensuring that the model is functioning as expected and can deliver the desired values. Afterwards, the randomness could be introduced to the model which converts the model into a stochastic model. A common way to integrate randomness is by replacing a variable value with a probability distribution function. This process is straightforward especially since many programming languages have inbuilt probability distribution function. The stochastic model is frequently coupled with Monte Carlo simulation (multiple iterative runs) and statistical analysis.

A popular method to analyse uncertainty is by using sensitivity analysis. Sensitivity analysis can be broadly defined as investigating the potential changes of parameter values on the model results (Pannell 1997). Another way to evaluate uncertainty is through scenario analysis. This is inherently the purpose of simulation modelling which is to analyse different what-if scenarios.

One of the purposes of sensitivity analysis is to identify the critical factors. By exploring different parameter values, certain parameters would have a significant effect on the modelling output and thus can be identified as critical. In terms of data accuracy, those critical parameters require a great deal of attention. Sensitivity analysis could also establish the relationship between input and output. Despite having a low data accuracy, the effects on the output can be anticipated. This also allows the assessment of different assumptions which provides flexible decision recommendations. Thus, the users could make an informed decision without knowing where the true values of certain factors (Pannell 1997, Saltelli 2002).

There are various approaches to analyse uncertainty. Deterministic modelling is a good step towards developing a new model for evaluating different scenarios. However, the model must allow the integration of random variables and Monte Carlo simulation.

Finally, sensitivity analysis is necessary to identify the crucial factors and provide a deeper system analysis.

### 2.3.3 Flexibility

Flexibility refers to the ability for the model to adapt to the changes when simulating different systems. For this research, the model would be used to explore a number of new systems. Hence, the system will constantly change in order to obtain the desirable system configurations. The analysis could potentially induce other iterations to further improve the system. Moreover, the flexibility enables the model to be applied to a wider range of systems in various countries.

However, flexibility must be treated with a caution. Flexibility requires some generalisation that allows the model to be translatable into different contexts. However, this is directly opposite to having details in the model which is imperative for modelling accuracy. Hence, the right balance of flexibility and details are necessary which depends on the objectives and context of the study.

There are different levels of flexibility observed in the literature. The first level is a model which is created for a specific company or product type. An example is having specific process steps for the production of paracetamol from renewable feedstock (Tsolakis and Srai 2017). This type of model is valuable for the analysing a particular context due to the greater details and accuracy. The details are implemented at the cost of some flexibility which is most likely inessential for the specific context.

The second level has a larger context which is designed for an industry. One example is a model for wood supply chain (Windisch et al. 2015). The model consists of general supply chain processes for the industry. Thus, having sufficient accuracy and flexibility within the industrial context. This model is relevant for performance improvement, but incapable of simulating radically different systems.

The third level is a model which consists of a general model and multiple submodels. The general model provides the overall structure and flexibility while the submodels provide the necessary details. This is suitable for systems which require great flexibility such as a complex system with many different components which can be modelled with submodels (Barbosa and Azevedo 2019, Long 2018). The downside of this approach is the complexity of the model.

For this study, the aim is to develop better waste management infrastructures. Hence, the model should enable experimentation with new waste management systems. The model would therefore need to adapt to different systems and the potential changes without significant effort. As a result, flexibility is an important aspect which suggests the use of a general model coupled with detailed submodels. This matches well with the hybrid simulation modelling since the submodels can be developed by using various simulation modelling methods.

### 2.3.4 Validation

Model validation is the process of determining whether the model can achieve the intended purpose (Kerr and Goethel 2014, van der Merwe et al. 2018). Validation ensures that the model is working correctly, represents the system accurately, and generates meaningful results. Hence, validating model calculation and results are necessary for the model to be used in real world operations. In this review, three validation methods are explored, namely expert validation, calculation checks, and model observation.

The first method is by using expert validation. Experts who are knowledgeable about the system can give their opinions whether the model is reasonable (Landry et al. 1983, Sargent 2013). This ensures model accuracy and also avoid the wrong conclusions (Brailsford et al. 2014, Landry et al. 1983). A key element in expert validation is a clear presentation of the modelling logic and results. This enables other researchers and experts to scrutinise the model for validation purposes. There are numerous ways to describe a model and these are mostly influenced by the author's style. In general, research papers with diagrams are far better than texts in conveying logical structures. A well-drawn diagram can communicate the message in a systematic, concise, and visually appealing way.

In simulation modelling, the model diagrams are influenced by the methods. For SD, diagrams are noticeably common in the literature because the diagrams are also used as the SD model (causal loop diagram or stock and flow diagram or both). Thus, a screenshot of the model can be used as a diagram for the paper. This is different to DES and ABM where the models are less visual. As a result, the author would need to build a separate diagram to describe the model. For DES, some papers include flowcharts which illustrate the step-by-step process in the system. Most ABM models are explained by using texts presumably to provide description of the agents in the system. Despite of that, ABM models with diagrams have clearer structures and are hence easier to understand.

The second method is by checking the calculation and results. This can be considered as a compulsory step since a small mistake in the calculation could lead to the wrong conclusion. The results can often be estimated by using a simple manual calculation. This can be useful as a sanity check to make sure the results are within a reasonable range. Alternatively, the model results can be compared against existing historical data or other relevant studies (Kerr and Goethel 2014, Landry et al. 1983, Muir et al. 2019).

The third method is observing the behaviours of entities in the model. By tracing specific entities during the simulation, the accuracy of the behaviours can be evaluated (Landry et al. 1983). This can be supported when visual components of the simulation can be displayed. Some examples of the visual aspects are graphs of performance indicators and movements of entities in the system. As the simulation model runs, this observation can ensure that the performance measures and the model are behaving correctly (Sargent 2013).

In the literature, only a limited number of studies addressed model validation despite being important for real world application. However, this might show an incomplete story because there is a possibility that some validation steps were unreported in the research papers. For instance, published papers went through peer-reviews and hence were validated by researchers in the field. Nevertheless, the model would still need a clear presentation for external validation, especially by experts in the field.

## 2.4 Research Gaps

In terms of recycling technology, most are readily available in the market. Thus, a new recycling system could have numerous options, starting from the most basic manual process to the most sophisticated automated process. This reaffirms the need for tools and models for system design, planning, and assessment. Through literature review, there are research gaps identified as follows:

1. Limited studies in the waste management and recycling context.
2. Lack of a model that is capable of experimenting with new systems.

The first research gap was identified when analysing simulation modelling methods. Simulation modelling is well-known in the operations research field and has been applied to many industrial contexts. Despite being a large research area, only a few studies analysed waste management systems. Thus, it is a unique opportunity to explore the application of simulation modelling in the waste management context.

Regarding the second research gap, most simulation models are designed to analyse a particular system rather than exploring new systems. As a result, the models in the literature are designed without fulfilling the criteria outlined in Section 2.3.

Depending on the objective, the models commonly cover either the operations or the supply chain, but rarely both. This is likely since the objective is to analyse a particular system. The uncertainties in most studies are covered relatively well with probability distribution functions and sensitivity analysis. However, the models are unlikely to have been designed for flexibility which is crucial when experimenting with different systems. Model validation is relatively uncommon despite being important in the model accuracy.

In order to fulfil the second research gap, hybrid simulation modelling is the most suitable method for this research. Compared to the criteria in Section 2.3, a hybrid model could efficiently address the multiscale modelling and flexibility characteristics. The uncertainty in a waste management system could be analysed with stochastic modelling and sensitivity analysis. Lastly, it is important to ensure that the model has a clear presentation and robust validation steps.

## 2.5 Literature Review Conclusion

A waste management system in developed cities typically consists of sorting, recycling, and residual waste treatment facilities. The system is designed according to the conditions of the local area, especially due to different waste composition. Hence, systems in different regions would have different operations and sets of equipment.

Simulation modelling is a suitable method for modelling new waste management systems. This is mainly because simulation model is more flexible to represent various different systems. Three most common modelling methods were reviewed, namely discrete-event simulation (DES), system dynamics (SD), and agent-based modelling (ABM). These three methods can also be combined to form a hybrid simulation model. Hybrid simulation modelling was found to be the most suitable due to the accuracy and flexibility of the method.

Based on existing research on simulation modelling, four modelling characteristics were defined. The first is to represent multiple scales of the system (both operations and supply chain). The second is the ability to evaluate uncertainty in the system. The third is flexibility where the model requires minimal intervention for different systems. The final characteristic describes the validation to ensure model accuracy.

# Chapter 3

# Research Methodology

In this chapter, the structure of the research and the data flow framework are discussed. The research structure provides the overall directions of the research such as the problems, literature review, and model development. The dataflow framework describes the flow of input and output data around the model. The framework is then utilised as the foundation for the model development in Chapter 4.

## 3.1 Overall Research Structure

The overall research structure in this thesis is summarised in Figure 3.1. The research begins with the identification of the problems and the potential solution as described in Section 1.1. The problems highlighted in this research are the excessive amount of waste, reliance on waste export, and lack of recycling infrastructures. Thus, the potential solution is to develop a model that supports development of new waste and recycling infrastructures. Because of that, the model would need to be able to analyse new system designs and what-if scenarios. Hence, the research questions in Section 1.2 are aimed at developing this model and generating insights from the model.

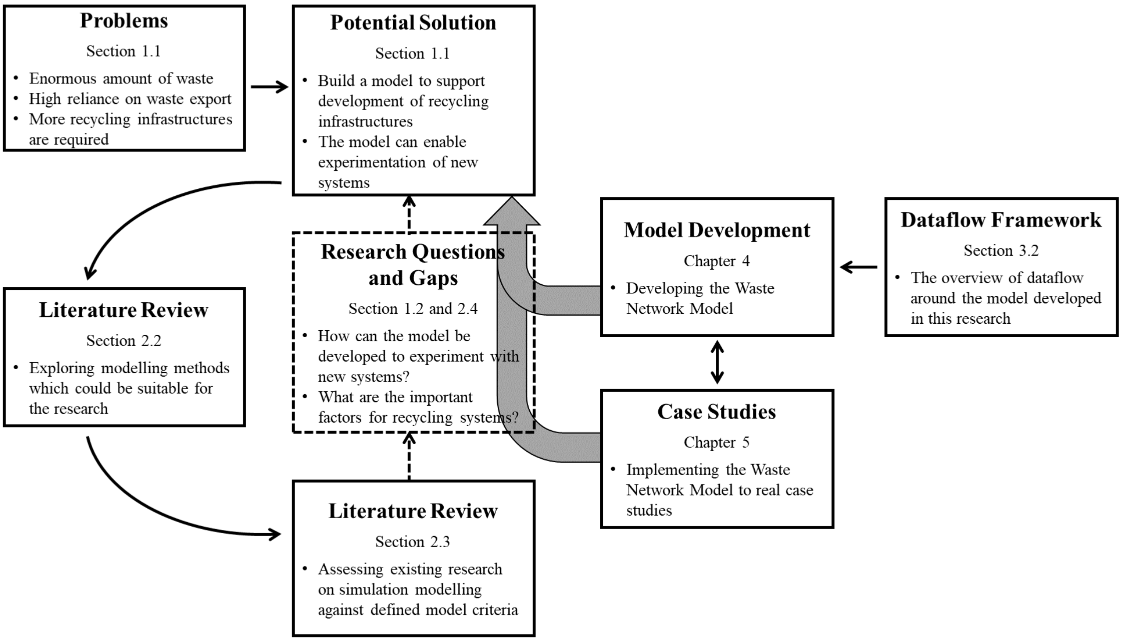


**Figure 3.1** Overall research structure.

A literature review in Section 2.2 is conducted to explore the suitable modelling methods for the model. Hybrid simulation modelling was selected due to the accuracy in system behaviour and flexibility. The logistics, processes, and entity interactions can be modelled by using DES, SD, and ABM, respectively. Furthermore, changes in different parts of the model would have minimal disruption to the other parts.

As mentioned in the literature review, the only commercial software that can incorporate all three methods of DES, SD, and ABM is AnyLogic. Furthermore, AnyLogic supports the integration with geographical information system (GIS) which is important to map the system in real geographical locations. Hence, AnyLogic was selected as the software for developing the model.

A set of criteria is defined to assess the existing research and models. As described in Section 2.3, the criteria represent the characteristics of an ideal model that can effectively achieve the objective of this study, i.e. support the experimentation of new waste management and recycling systems. The characteristics are multiscale modelling, uncertainty analysis, flexibility, and validation.

From the literature review, a research gap was identified as the lack of a model for evaluating new systems especially in the waste management context. In order to answer the research questions and gaps, a dataflow framework was built.

The dataflow framework in Section 3.2 provides the structure which leads to the model development in Chapter 4 and subsequently, implementation into case studies in Chapter 5. The case studies can also be considered as a part of model development because some parts of the model require specific details based on the case study. The model development and case studies demonstrate the model's capability as the potential solution and answer the research questions and gaps.

## 3.2 Dataflow Framework

The dataflow framework developed in this research describes the dataflow around the model and follows a system architecture framework. A system architecture is defined as a conceptual model describing the structure and behaviour of a system (Jaakkola and Thalheim 2010). This serves as a blueprint for the development of a system and improves the understanding of system behaviour (Carnegie Mellon University 2017).

A common system architecture is the 3-tier architecture which consists of user interface (UI), logic, and data layer. The UI layer shows the interaction between users and the tool which can be broadly categorised as user input and model output. The logic layer is the processing capabilities of the model such as computing the data to generate the model output. Finally, the data layer includes the stored data in a usable format for the computation in the logic layer.

The dataflow framework is shown in Figure 3.2. There are two types of data which originate from the user input, namely current scenario data and new user-designed plans. The first data are used as a baseline to benchmark the performance against the

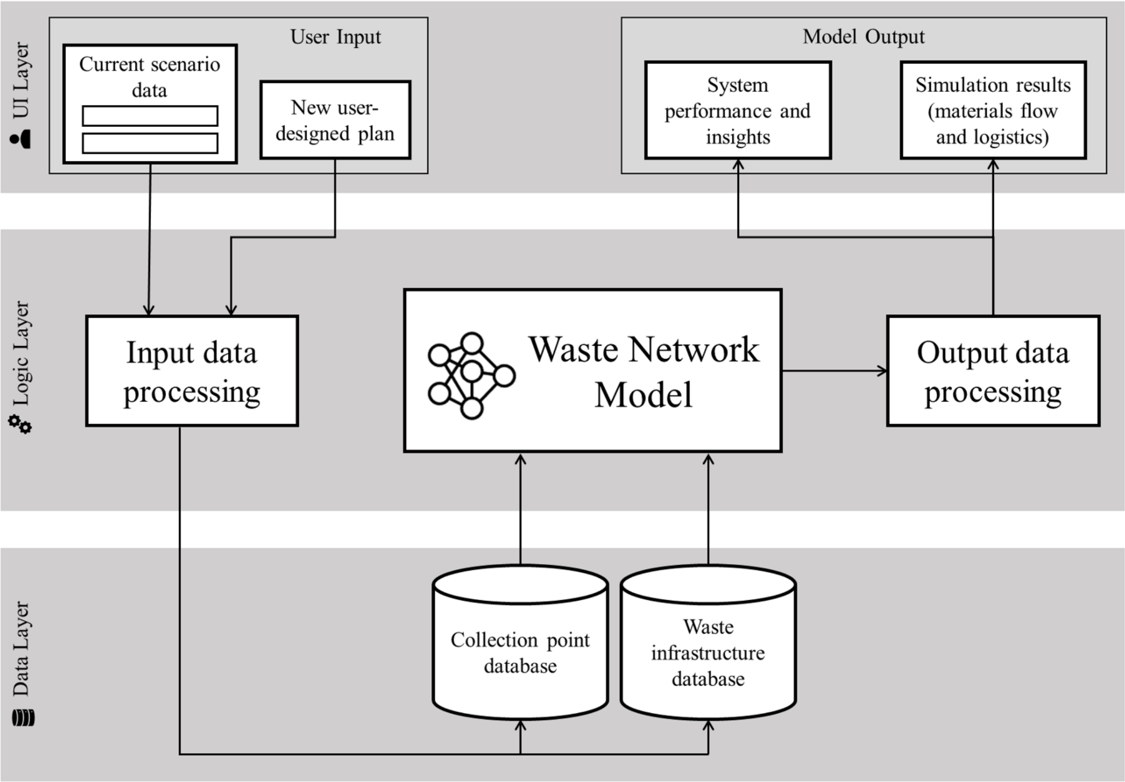


**Figure 3.2** The dataflow framework for this research. The arrows in the diagram represent dataflow.

second dataset which represents new system designs (or what-if scenarios). The first data can also be used to validate the model results.

After the data are received, the data are converted into a recognisable format for the model in the input data processing step. Since the datasets from different companies are radically different, the input data processing step is mostly done manually. In some cases, reasonable assumptions and estimates can be used to replace the necessary but unavailable data. The processed data is then stored into databases in the data layer. The data are organised into two databases, namely collection point and waste infrastructure database.

The collection point database stores the data of all collection points in the system. In general, the main components of collection point data are the location, waste generation, and collection schedule. Since the locations are commonly recorded as addresses, an Excel VBA macro was developed to convert the addresses into latitude and longitude via Google Geocoding.

The waste infrastructure database contains the type, location, process, and logistics data of the facilities involved in the system. There are three possible facility types, namely sorting, recycling, and residual waste treatment facility. The process data include the throughput, input and output composition, and conversion rate of each facility. The logistics data comprise of the logistics decision and vehicle data (such as truck type and maximum load).

The main computational engine is the Waste Network Model which I had developed. This model simulates a waste management system by utilising simulation modelling method. To account for the uncertainties of a real-world system, the model has the capability to run stochastic modelling and Monte Carlo Simulation. The model development method for Waste Network Model is discussed in more detail in Chapter 4.

After the simulation, the output results go through various data processing. Firstly, the data are reorganised from a long list of numbers into a table by using a custom Excel VBA macro. The data can then be processed further to produce simulation results and measure the system's performance through environmental and economic indicators. Thus, a deeper analysis and insights into the system could be generated.

In summary, there are three important steps in the logic layer of the dataflow framework. The first step is the input data processing which is mostly done manually due to the large variability of available data. The second step is modelling the system with the Waste Network Model. The development of the model explained in more details in Chapter 4. Finally, the third step is the output processing step which produces the simulation results, and system performance and analysis.

## 3.3 Summary of Research Methodology

This chapter describes the overall research structure and the dataflow framework. The research begins with identifying the problems of waste and potential solutions to develop a model to support more recycling infrastructures. The research questions are then designed to develop the model. Based on literature review in Chapter 2, the most suitable modelling method for the model is hybrid simulation modelling. The main research gap in Section 2.4 is found to be the lack of a model which can evaluate new recycling systems.

In order to address the research questions and gaps, the dataflow structure around the model is constructed in the form of a 3-tier system architecture. The three layers in the framework are user interface, logic, and data layer. The main component of the framework is the Waste Network Model which can simulate the waste infrastructure and the interactions inside the network. The development of Waste Network Model is discussed in Chapter 4. The model is then implemented into case studies in Chapter 5 because some parts of the model depend on data from the case study. Therefore, the model and case studies could fill research questions and gaps and assist in the development of more recycling infrastructures.

# Chapter 4

# Waste Network Model Development Methods

This chapter is about the methods for developing the Waste Network Model. The model is developed by using an agent-based architecture. For each agent type, there are three submodels which describe the agent behaviours in terms of the process, logistics, and communication. The simulation produces material and logistics results which can be converted to other performance indicators. Since facility location is an important parameter for the model, an approximation method was developed.

## 4.1 Agent-Based Architecture

The model was developed by using hybrid simulation modelling based on a typical waste management system as shown in Figure 2.1. In this system, there are numerous sources of waste which are referred to as collection points. The waste is then collected by the sorting facility. After the sorting process, the recyclable waste is delivered to the appropriate recycling facility while the residual waste to a residual waste treatment facility which often is an incinerator.

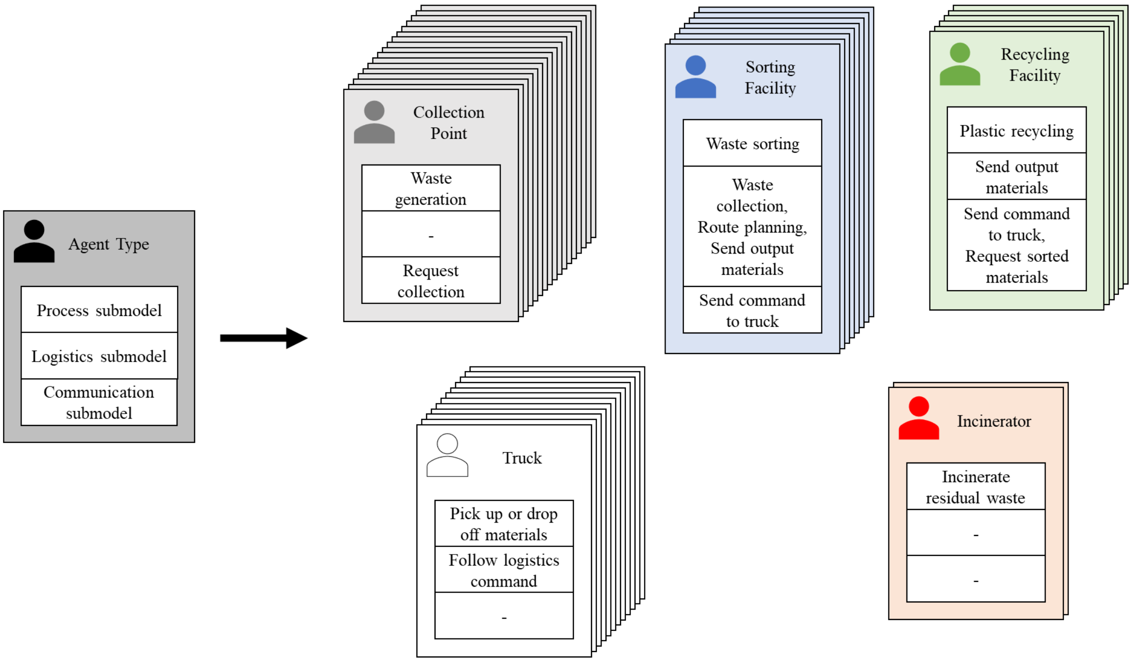


**Figure 4.1** The agent-based architecture of the Waste Network Model.

In a waste management system, there are thousands of collection points and multiple facilities involved. Due to the vast number of entities in the system, it is more appropriate to model the system based on a bottom-up rather than a top-down approach. Hence, the model was built based on an agent-based architecture whereby each entity is regarded as an agent with individual behaviours. The system is then composed of a collection of agents. This agent-based architecture allows flexibility for the model to add and remove agents without affecting other parts of the model. This is especially important when experimenting with various systems because of the major changes required. Furthermore, the model can be expanded to simulate more complex agent behaviours which could be valuable for future research.

The agent-based architecture for the Waste Network Model is shown in Figure 4.1. There are five different agent types in the system. Four of which are derived from the general waste management system as shown in Figure 2.1, namely, collection points, sorting facility, recycling facility and incinerator. The fifth agent type is the truck which transports the materials between agents. The behaviour of each agent type is

**Table 4.1** Model parameters for each agent type in the model.

| **Agent type** | **Type of parameter** | **Model Parameters** |
|---|---|---|
| Collection point | Location | • Latitude and longitude |
| | Process | • Waste generation rate |
| | Communication | • Collection schedule |
| Sorting Facility | Location | • Latitude and longitude |
| | Process | • Composition of output<br>• Sorting rate of each material<br>• Residual waste rate |
| | Logistics | • Transportation route, type, number of trucks, maximum load capacity |
| Recycling Facility | Location | • Latitude and longitude |
| | Process | • Recycling conversion rate<br>• Recycling loss rate |
| | Logistics | • Transportation route, number of trucks, maximum load capacity |
| Truck | Logistics | • Defined in the sorting and recycling facility |
| Incinerator | Location | • Latitude and longitude |
| | Process | • Incineration rate |

determined by three submodels which are process, logistics, and communication. The agents with the same agent type have the same set of submodels, but with unique parameter values.

The parameters for the model are summarised in Table 4.1. The locations are based on the real geographical locations and consequently, the model is integrated with geographical information system (GIS). As mentioned earlier, AnyLogic was used as the software for model development since it can be integrated with GIS and is the only software that support all three methods (ABM, DES, and SD).

The agent-based architecture acts as the general model which remains constant when simulating different systems. The submodels provide the necessary details, but require some updates to accurately simulate different systems. Since the user interface to update the submodels are unavailable, the user would require some competencies in AnyLogic. The submodels discussed in subsequent sections can be used as templates when updating the model. In the future, a user interface could be developed to increase the usability of the model.

### 4.1.1 Process submodel

The process submodel refers to the materials amount and processing by each agent. Within facilities in the system, the process is commonly continuous, e.g. sorting facility uses conveyor belts and recycling facility uses extruders. Because of that, the process is suitable to be modelled with system dynamics (SD). The process shown in Figure 4.2 is the most simplified version of converting the input into output. In this form, the process submodel is flexible for various processes and steps to be added whenever more details are available. The process flow rates in Figure 4.2 are obtained from the parameters in Table 4.1. For the sorting facility, the output composition determines the number of output materials.

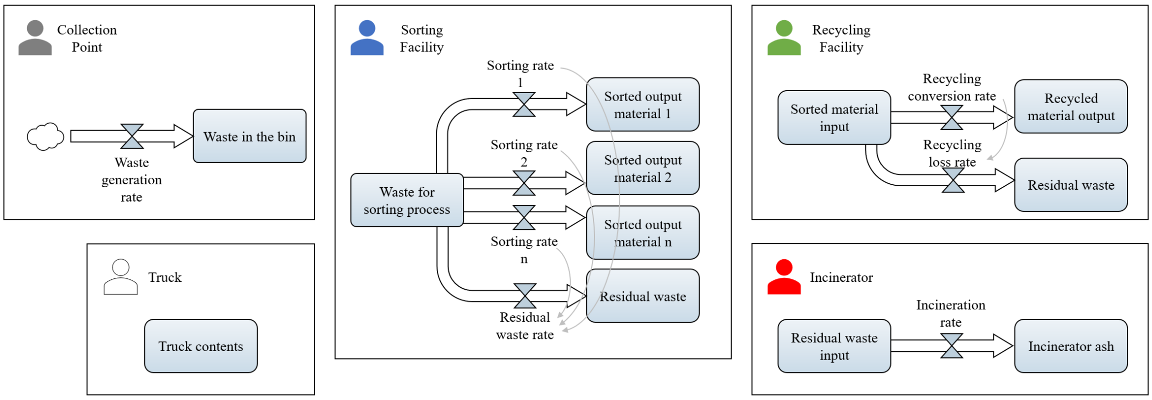


**Figure 4.2** The process submodel based on SD of each agent type. The rates are defined by the parameters and the grey arrows show the dependencies of the flow.

In the sorting facility, the incoming waste is sorted into multiple recyclable materials and the remainder is considered as residual waste. The recycling facility follows a similar logic where the sorted recyclable material is converted into recycled material with a by-product of residual waste. The incinerator converts the residual waste into incinerator ash. Despite being labelled as an incinerator, this agent type could also act as a landfill in which the incineration rate is always zero. The transfer of materials between agents is handled by the truck agent which is specified in the logistics submodel. Hence, the process submodel in the truck agent only accounts for the amount of materials in the truck.

### 4.1.2 Logistics submodel

The logistics submodel is used for transporting the materials between agents. Since logistics is a step-by-step process, discrete-event simulation (DES) is suitable for modelling the logistics of the system. As apparent in Figure 4.1, most logistical activities are defined at the sorting facility.

The waste collection process shown in Figure 4.3 starts with the list of collection points to collect on the given workday. Subsequently, a route is prepared by using one of two options. The first option is to import the collection route data as parameters. In this case, the route is planned either by the facilities or with an external route planning tool. The second option is integrating the route planning logic in the simulation model. The latter option is more suitable when route data is unavailable or the model requires dynamic route planning which can be beneficial for what-if scenarios.

A route planning logic was prepared to ensure that the model can function without waste collection route data. The logic used the nearest neighbour algorithm with a constraint on the truck load as shown in Figure 4.4. The nearest neighbour algorithm is one of the simplest and most famous algorithms for the travelling salesman problem (Johnson and McGeoch 1997). The solution from this algorithm is less than optimal, but still reasonable. In this way, the computational load can be light and the simulation can run relatively fast. In the future, a better route planning optimisation model could be utilised.

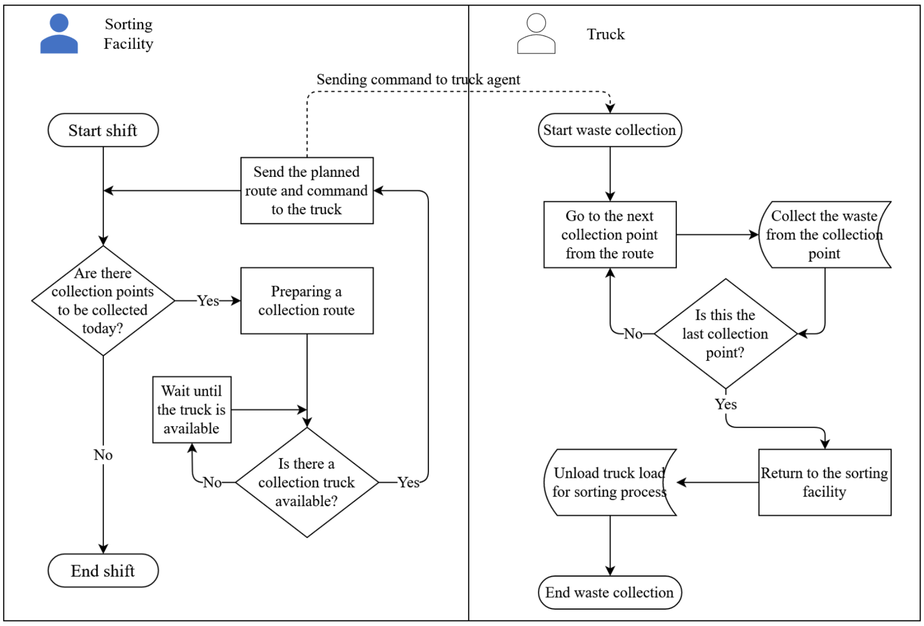


**Figure 4.3** DES flowchart for waste collection.

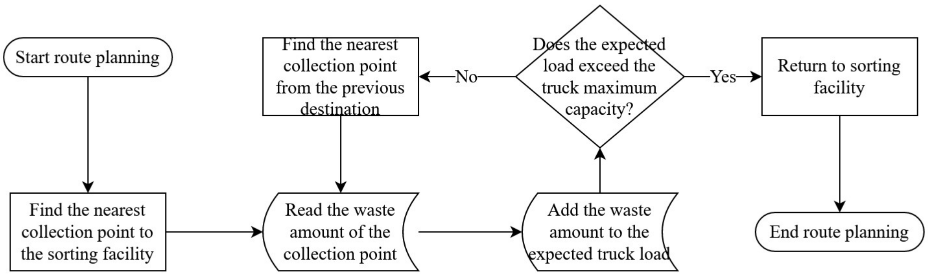


**Figure 4.4** DES flowcharts for route planning by using nearest neighbour algorithm.

After obtaining the route, the sorting facility finds the next available truck for waste collection. This truck then receives the route and a command from the sorting facility to start the waste collection. The truck follows the route to collect waste from each collection point and stores the amount in the truck content variable in the process submodel (shown in Figure 4.2). Once the collection is complete, the truck returns to the sorting facility and unloads the truck content as waste input for the sorting process. The waste collection process repeats until the waste from all collection points for the given day are collected which indicates the end of the shift.

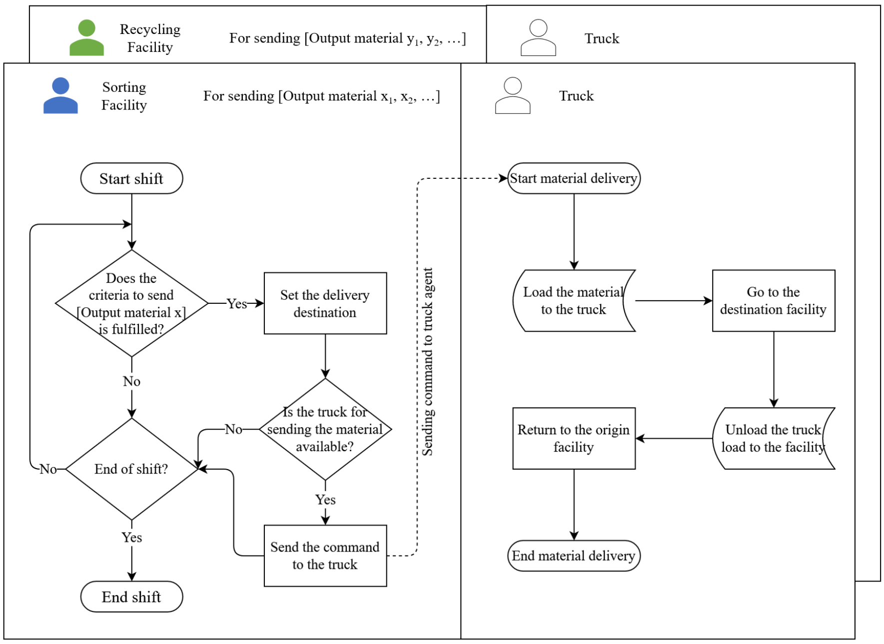


**Figure 4.5** DES flowcharts for sending the output materials.

As a part of model verification, the waste collection must be finished before the defined work shift. If the time goes beyond the work shift, then the sorting facility will require more collection trucks, and the simulation must be restarted. This iterative process can be used to determine the number of collection trucks required when this data is unavailable.

The DES flowcharts for sending output materials are shown in Figure 4.5. When the criteria to send output material is fulfilled, the delivery process can start. For example, the criteria could be to receive an order for the material and have a sufficient inventory for the order. For residual waste, an example criterion is whether the inventory reaches the maximum capacity of the truck. Afterwards, the destination is set and the facility then checks for an available truck. If the trucks are still unavailable by the end of the shift, then the delivery will be conducted the next working day. When a truck is available, the command to start the delivery process is sent to the truck. The trucks for sending the output materials are generally different from the waste collection trucks.

The material delivery is straightforward where the truck is loaded with the material, departs to the specified destination, unloads, and returns to the origin facility. It would be possible to increase the complexity of the delivery such as to enable multiple destinations and other various interactions between facilities. This could be updated according to the operations of the system.

### 4.1.3 Communication submodel

The communication submodel allows social interactions between agents which is inherently supported by the agent-based architecture. The communication between agents is comprised of sending messages and requests. It is assumed that all messages and requests are immediately accepted by the receiving agent without any miscommunication. In this research, more emphasis is placed on indicators to measure environmental and economic performance. Therefore, the communication in the system has a minor effect compared to the process and logistics. As a result, the architecture in Figure 4.1 incorporates the basic communication for the logistics to run. However, it would be possible to include more sophisticated interactions when necessary.

The communication by the collection point is done by sending a request to the sorting facility for waste collection. All the collection requests are compiled into a list for the waste collection flowchart in Figure 4.3. This is slightly different from the real-world practice where the sorting facility is the one checking the schedule of all collection points. This was done to reduce computational inefficiencies in such a way that the sorting facility only deals with the relevant collection points rather than all collection points. Despite the slight modification, both approaches yield the same outcome which is the list of collection points to be collected for the day.

For the sorting facility, the communication is linked with the logistics of output materials in Figure 4.5. In this submodel, the sorting facility sends a command to the truck agent to start the delivery. As indicated in Figure 4.5, the recycling facility also does a similar action to send the output materials. Furthermore, the recycling facility can place an order for a sorted recyclable material from a sorting facility. The order can be defined in many different ways depending on how the facility operates.

## 4.2 Simulation Output Data

For this study, the simulation runs for a period of 1 year since this time period is appropriate for system design and planning. For environment and economic performance, the suitable output data from the simulation are material data and logistics data which can be used for further analysis.

The material data measures the daily amount of input and output of each material from each agent. Thus, a specific analysis of certain agents in the system is possible and the data can be combined to provide an overview of the system. The materials in the system depend on the case study because different sorting facilities would have different target materials. Hence, this will need to be updated according to the case study.

The logistics data includes distance travelled and tonne-kilometre (tkm) of various transportation routes. Some of the common routes are waste collection, sorting facility to recycling facility, and sorting facility to incinerator. Each truck measures both distance and tkm of every trip. The tkm is calculated by monitoring the load and the distance travelled. An example of the tkm calculation is shown in Figure 4.6.

An example of tkm profile for waste collection is shown in Figure 4.6a. The truck arrives empty at the first collection point and the load increases as the truck visits more collection point. At the final collection point, the truck returns to the sorting facility and unload the truck content. The waste collection repeats as necessary throughout the simulation and the total tkm is the area under the line. Figure 4.6b illustrates the tkm of a return trip when delivering output materials.

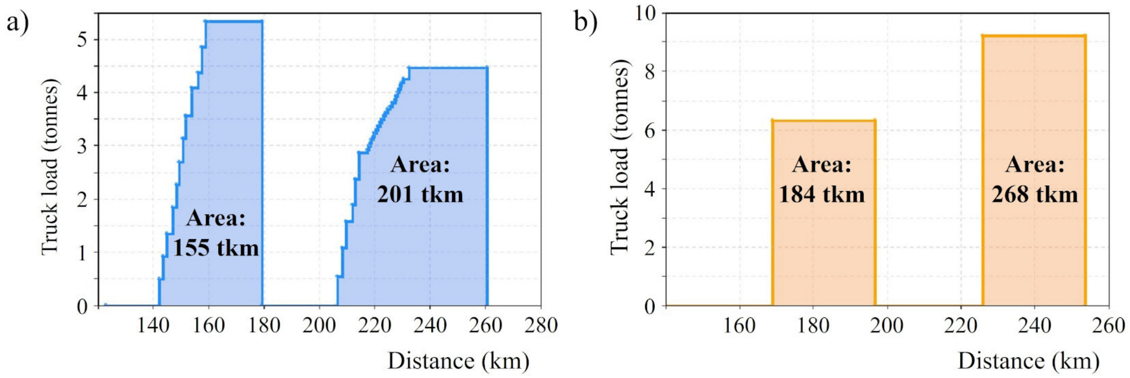


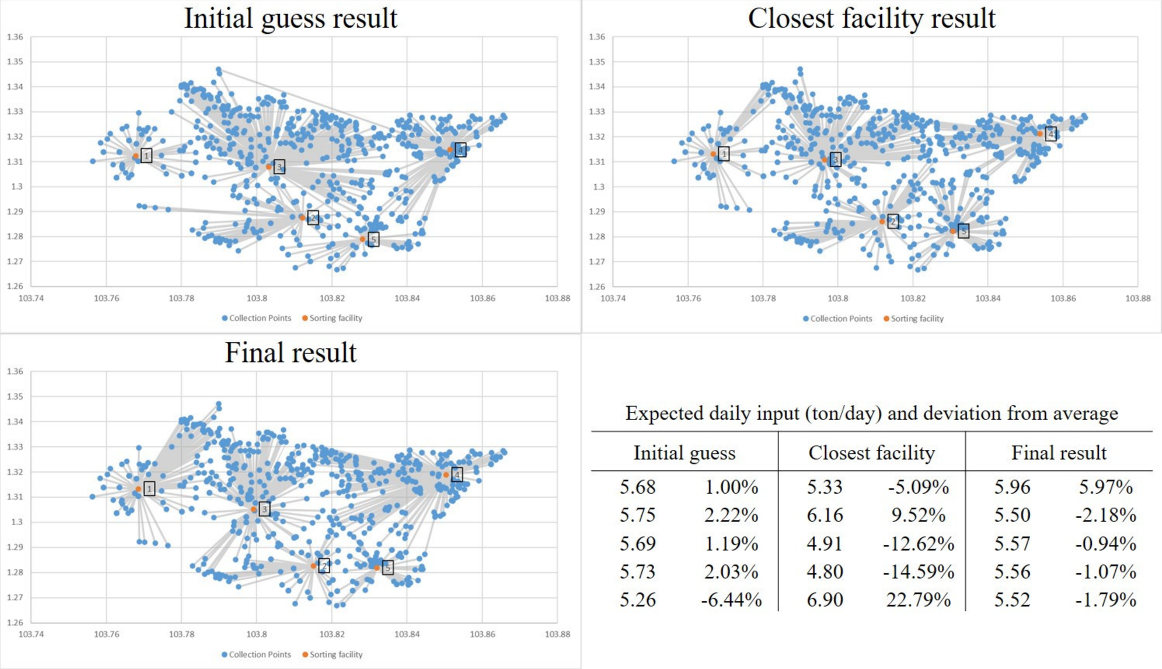
**Figure 4.6** An example calculation for the tkm in this research, a) for waste collection and b) for transporting output materials.

Both material and logistics data provide the basic information of the system. These data can then be used for further analysis such as environmental and economic performance. Additional data would be required for such analysis, for instance electricity and fuel consumption, carbon emissions, labour, etc. Therefore, the performance of the system can be measured.

## 4.3 Facility Location Approximation

When designing what-if scenarios, the location of various facilities must be determined. In most cases however, the location data are unavailable since the scenarios are hypothetical. Thus, an approximation method was developed to estimate the location of sorting facilities to cover the collection points. The idea behind this method is to distribute the facilities uniformly across the region.

The facility location approximation method is based on a heuristic approach which consists of 3 parts, namely making the initial guess, matching with the closest facility, and equalising daily waste input. The result of each approximation step is illustrated in Figure 4.7.



Expected daily input (ton/day) and deviation from average

| Initial guess | | Closest facility | | Final result | |
|---|---|---|---|---|---|
| 5.68 | 1.00% | 5.33 | -5.09% | 5.96 | 5.97% |
| 5.75 | 2.22% | 6.16 | 9.52% | 5.50 | -2.18% |
| 5.69 | 1.19% | 4.91 | -12.62% | 5.57 | -0.94% |
| 5.73 | 2.03% | 4.80 | -14.59% | 5.56 | -1.07% |
| 5.26 | -6.44% | 6.90 | 22.79% | 5.52 | -1.79% |

**Figure 4.7** An illustration of the location results from each approximation step.

The first approximation step is the initial guess to obtain the average location of the collection points. The example in Figure 4.7 was taken from a region which consists of 714 collection points. The number of sorting facilities was determined to be 5. Hence, all collection points were grouped with the nearest neighbour to form a total of 5 groups. The average location of each group is the initial guess location of the sorting facility. It was assumed that the land is flat, and the distance is proportional to the latitude and longitude.

The second step is aimed to minimise the distance between collection points and sorting facilities. Thus, the collection points are matched with the nearest sorting facility. Each collection point is assigned with a vector $R_i$. The vector $R_i$ represents the distance between the collection point $(cp)$ to each sorting facility $(i)$ which is calculated from the latitude and longitude as follows:

$$R_i = \sqrt{(lat_{cp} - lat_i)^2 + (long_{cp} - long_i)^2}$$

Then, the nearest sorting facility ($i_m$) is the sorting facility with the lowest $R_i$ which can be expressed as:

$$i_m = argmin(R_i)$$

This calculation is repeated for all collection points and thus matching the collection points with the nearest sorting facility.

The final step is to equalise the expected incoming waste of all sorting facilities towards the average value by adjusting the collection coverage. The coverage boundary can be adjusted by modifying the vector $R_i$ to

$$R_i = \sqrt{(lat_{cp} - lat_i)^2 + (long_{cp} - long_i)^2} + a_i$$

where $a_i$ is an arbitrary number assigned to each facility $i$. As $a_i$ value increases, the boundary moves towards sorting facility $i$ and away from the neighbouring facilities. Hence, $a_i$ would be higher in the area with a high waste concentration. The value of $a_i$ is determined iteratively starting with increasing the $a$ value of the sorting facility with the highest daily input. This would alter the input of other facilities and the $a$ value for the other facilities are adjusted. This adjustment is done until the waste input of all sorting facility is within 5% of the average or a specified number of loops is reached. In some cases, the waste input deviates more than 5% from the average as shown in Figure 4.7 because the waste from collection points varies greatly.

This method could provide reasonable facility locations for this research. However, since the estimation excludes geographical terrains, the location facilities might be unrealistic such as in the middle of the lake. This could be avoided by manually separating the collection points into groups. Furthermore, the planning area of the facilities might be unsuitable for the operations such as located in a residential area. Thus, the method could be integrated with planning area information for future research.

## 4.4 Method Summary

This chapter covers the model development for the Waste Network Model. Derived from a typical waste management system, an agent-based architecture was developed. Each agent within this architecture has three submodels which are process, logistics, and communication. The process submodel takes into account the material processing, the logistics submodel considers the transport of materials, while the communication submodel involves message exchanges between agents. In order for the model to function properly, these submodels require some data based on the case study. The simulation generates material and logistics data which can be used for further analysis, such as environmental and economic analysis. A facility location approximation method was developed to accommodate the lack of location data for hypothetical waste management systems. The method was based on heuristic approach to distribute the facilities uniformly across a region.

# Chapter 5

# Case Studies

In this chapter, the model was used to investigate two case studies. These case studies are important for the model since some parts of the model require case study specific data. The first case study was about investigating the potential of introducing a distributed plastic recycling system in Singapore. In the second case study, new waste management infrastructures in Indonesia were explored. Both case studies demonstrated the applicability and flexibility of the Waste Network Model to simulate real world scenarios.

## 5.1 Distributed Plastic Recycling in Singapore

The word 'distributed' can have different definitions based on the context. In this report, it is referred to as multiple geographical locations. Thus, distributed recycling can be defined as recycling closer to the waste generation points as illustrated in Figure 5.1. In this way, transportation would be significantly reduced which can be translated to the costs since waste collection typically represents 23% of the operating costs (Hestin et al. 2015). Furthermore, there is a potential reduction on fuel consumption which could provide some environmental benefits. This is particularly attractive for plastic

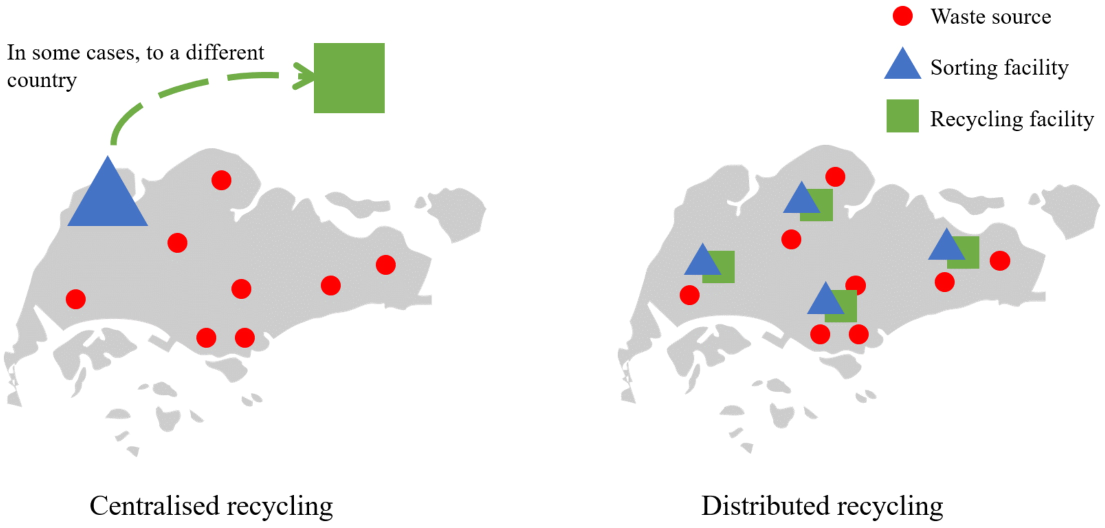


**Figure 5.1** Illustration for centralised and distributed recycling.

waste because plastic is lightweight compared to other materials. Distributed recycling also allows waste processing in a smaller batch which could limit the contamination from one bin to the others.

There are only a few studies on distributed recycling and most are focusing on 3D printing instead of the systems approach. Hence, a literature review was conducted on a similar but more active area which is distributed manufacturing.

### 5.1.1 Distributed manufacturing and recycling review

Distributed manufacturing can be defined as manufacturing at multiple locations and scales, closer to the point of consumption (Srai et al. 2016). In other words, distributed manufacturing is aimed at minimising the distance to consumers which is similar to distributed recycling. In distributed recycling, the waste from consumers is collected instead of sending products for consumption.

Because of the similarity, the characteristics of distributed recycling can be derived from distributed manufacturing. According to Srai et al. (2016), there are five characteristics of distributed manufacturing, namely, localisation, digitalisation, new production technologies, customisation, and enhanced user participation. These characteristics can be utilised as strategic areas to yield more advantages when using distributed systems. This could increase profitability and contribute to better recycling system designs.

Localisation is described as fulfilling local needs and using local resources (Kohtala 2015). The local aspect of distributed manufacturing can also support the creation of local jobs (Harrison et al. 2017, López-Avilés et al. 2019). The local jobs would support the social aspect of sustainability and add a portfolio to corporate social responsibility. Furthermore, the smaller scale facilities would have less inventory costs (Petrulaityte et al. 2017, Srai et al. 2016) and require lower initial investment per facility compared to a large-scale facility (Mourtzis and Doukas 2013).

Distributed manufacturing can provide an important advantage when transportation is a significant part of the costs and carbon emissions. By being local, the transportation costs of both raw materials and products are greatly reduced. Consequently, lowering the distance enables the products to reach the market faster (Kumar et al. 2020, Tsimiklis and Makatsoris 2019). Since waste collection relies heavily on transportation, distributed recycling could potentially offer a substantial benefit through transport reduction.

Distributed manufacturing consists of many facilities within a network. This introduces the requirement for the use of digital technologies to enable effective quality control, connection, and communication between multiple locations (Bessière et al. 2019, Petrulaityte et al. 2017, Srai et al. 2016). The communication can also be extended to the consumers to support end-user interaction and customisation. In distributed recycling, the communication could support waste collection scheduling, clearer recycling instructions, and provide further sustainability education. Therefore, enabling a more efficient waste collection and recycling process.

New production technologies for distributed manufacturing could provide many advantages such as flexibility and improved product quality. The flexibility enables the manufacturing of products at different quantities and variations for consumers (Matt et al. 2015). In the context of distributed recycling, the flexibility would be valuable when it allows process customisation to recycle different input quantities and types. This is particularly important because the amount and types of waste could fluctuate unpredictably. The flexibility could enable more waste to be recycled, thus improving resource efficiency and better waste elimination (López-Avilés et al. 2019, Veldhuis et al. 2019). In terms of the product quality, it is crucial to use new recycling technologies that could deliver a consistent, reliable, and high-quality output. However, the development of this new technology is still very much needed.

The concept of user participation overlaps with the idea of social manufacturing, i.e. involving consumers in the manufacturing process (Jiang et al. 2016). Having manufacturing facilities closer to consumers could change producer-consumer relationship leading to the term *prosumer* (Graham et al. 2017, Kohtala 2015). The interaction could also be enhanced with the use of digital platforms. The main idea behind involving consumers is because consumer participation has the potential to improve the overall effectiveness of the value chain (Poesche and Kauranen 2016).

In the case of recycling, consumer participation already exists since waste is coming from the consumers. Countries with better systems to allow consumer participation generally have a high recycling rate (OECD 2020). This is because the recyclable waste is well separated by the consumers which leads to less contamination. This in turn enables a higher recycling rate and a better quality of recycled products. On the contrary, countries with poor waste separation from consumers have low recycling rates due to a higher contamination level. Therefore, the participation from consumers can make a difference in the overall recycling system.

Although there are many benefits, distributed manufacturing has some disadvantages due to the smaller scale operations, such as lower efficiency, higher energy and water usage, and higher costs per unit output (López-Avilés et al. 2019, Sinclair et al. 2018, Srai et al. 2016, Veldhuis et al. 2019). To achieve the same capacity, the combined floor area of distributed manufacturing would be larger than centralised manufacturing (Veldhuis et al. 2019). This implies a higher total capital investment and property costs despite lower investment per facility (Angeles-Martinez et al. 2018, Claesson and Hilletofth 2011, Mourtzis and Doukas 2013).

When transport is a minor part of the process, the higher energy consumption could undermine the transportation benefit in distributed manufacturing, leading to overall higher costs and carbon emissions. Therefore, small scale facilities need to be properly designed and equipped with new technologies to achieve better sustainability (Angeles-Martinez et al. 2018, Petrulaityte et al. 2017).

Economic and business viability are significant challenges for distributed manufacturing (Kumar et al. 2020, López-Avilés et al. 2019). Despite being small, the revenue must be sufficient for the business to be profitable. For this to happen, the scale needs to be large enough to cover the expenses (López-Avilés et al. 2019). Furthermore, more facilities would mean that more labourers are required which could significantly increase the operational costs. In addition, smaller scale could be more susceptible to the uncertainty in local customer demands (or supply of waste in the recycling context) which in turn creates unpredictable financial performance (Claesson and Hilletofth 2011, Srai et al. 2016). Therefore, careful planning and economic assessment would be necessary for distributed recycling.

Distributed manufacturing requires an effective coordination of the network for quality control and logistics. Since the facilities are in multiple locations, distributed manufacturing is more complicated than centralised manufacturing in terms of quality control, inventory, and production scheduling (Angeles-Martinez et al. 2018, Harrison et al. 2017, James 2017, López-Avilés et al. 2019, Petrulaityte et al. 2017). This is especially true when the network consists of different small companies due to the difficulties of data sharing and data security (James 2017, Srai et al. 2016).

Thus, advanced digital technologies should be implemented to support the network coordination.

Despite being closer to consumers, the interaction with consumers is complex, dynamic, and unpredictable (Jiang et al. 2016). In a recycling system, it is desirable for the consumers to segregate the waste according to material types. For a new system with a new participation scheme, the consumers would need to form a new habit which requires time and effort. The adoption rate of this new system would also vary depending on many different aspects, such as age group, education level, environmental consciousness, etc. Hence, to maximise the consumer adoption and value of the participation, companies would need to develop new platforms, design new consumer experiences, and innovate their business models (Bogers et al. 2016, Srai et al. 2016).

Most of the studies on distributed manufacturing and recycling are qualitative. These qualitative aspects provide important strategical directions to implement distributed systems. However, it would be necessary to conduct quantitative analysis to determine whether the advantages could outweigh the disadvantages. Therefore, this case study focuses on the quantitative aspect to evaluate viability of distributed recycling. In addition to addressing the research gaps on modelling waste management systems, this case study could also cover the research gap on distributed recycling. In terms of the performance metric, the two most common areas are the environmental and economic aspects which were explored in this case study.

### 5.1.2 Scenarios

This case study has been published in a journal paper (Kerdlap et al. 2021*a*). My contribution includes writing the paper, designing and simulating the systems, and checking the results. The system boundary is illustrated in Figure 5.2 which follows a

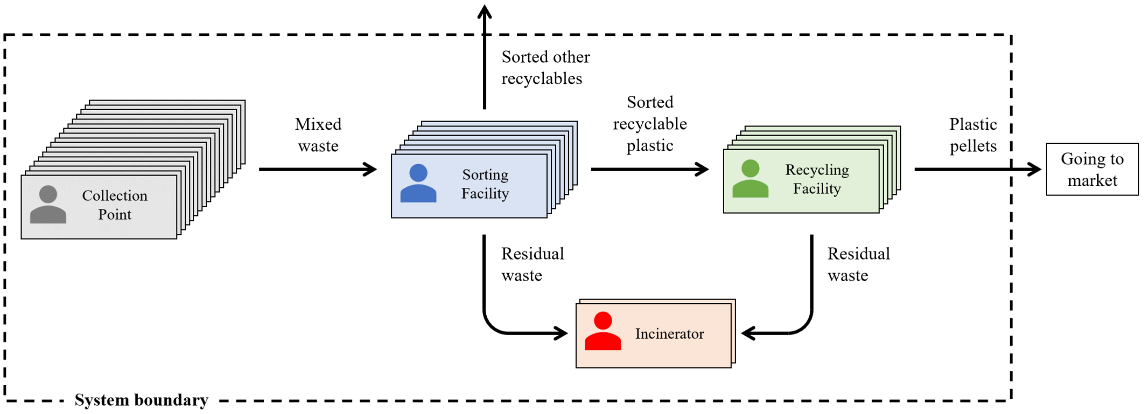


**Figure 5.2** The system boundary for Singapore case study.

typical waste management system in Figure 2.1 where the waste from the collection points is collected and sorted by the sorting facilities.

This case study focuses mainly on plastic since this waste stream has the lowest recycling rate in Singapore (National Environment Agency 2019). Thus, after the waste is sorted, the recyclable plastic is sent to recycling facilities while the other recyclable waste is considered outside of the system boundary. The recycling facilities then recycle the plastic into pellets which are sold to the market. The residual waste from both sorting and recycling facilities is sent to an incinerator. Within the same system boundary, three categories of system are created, namely, (A) centralised, (B) semi-distributed, and (C) distributed. From these three categories, there are in total five scenarios and the schematic of all scenarios are shown in Figure 5.3.

In the centralised system, large-scale sorting and recycling facilities are involved in the waste management system. There are two scenarios from this category. The first scenario is A1 which represents the business-as-usual case in Singapore. The waste is sorted in 4 large-scale sorting facilities owned by 4 Public Waste Collectors (PWCs) in Singapore. After the sorting process, the waste is sent to a large-scale recycling facility in Malaysia. The residual waste from the sorting process is delivered to an incinerator in Singapore, whereas the residual waste from the recycling process is sent to a landfill in Malaysia.

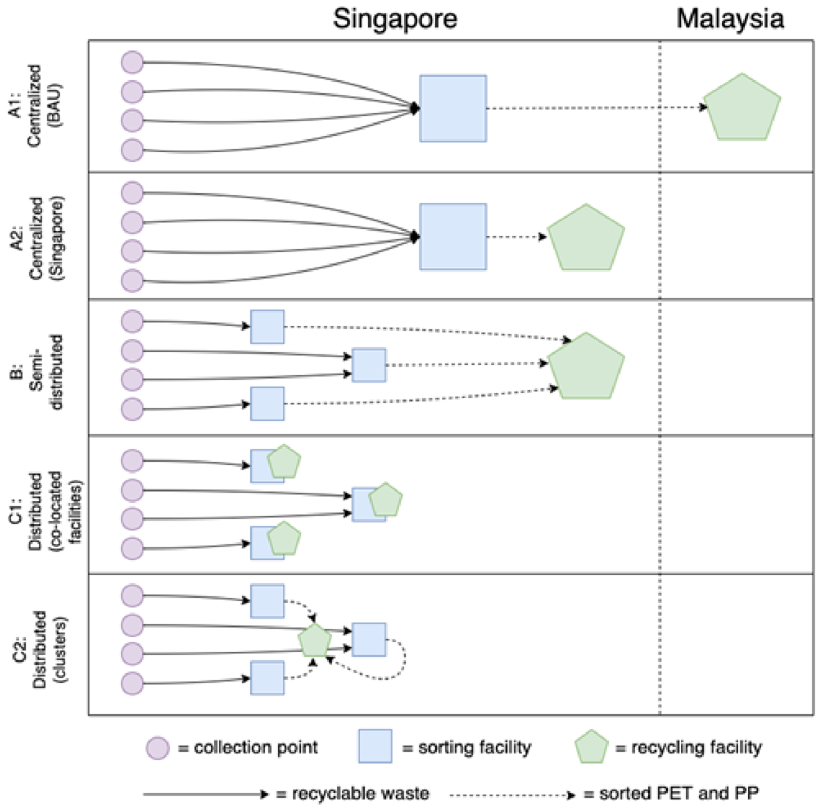


**Figure 5.3** The schematic of all 5 scenarios in this case study (Kerdlap et al. 2021*a*).

In the second scenario A2, the sorting facilities remains the same as scenario A1, but the recycling facility is in Singapore instead of Malaysia. Thus, the residual waste from recycling is incinerated in Singapore. This scenario assumes that the plan for the Integrated Waste Management Facility is finished and has the capability to recycle plastic (National Environment Agency n.d.*a*).

In the semi-distributed system, small-scale sorting facilities are responsible for sorting the plastic waste and transporting the plastic to a large-scale recycling facility for further processing. Thus, reducing the distance to the waste source while simultaneously integrating the process efficiency from an existing infrastructure. One scenario was analysed, scenario B, which involves 35 small-scale sorting facilities to sort out the plastic. The plastic is sent to a recycling facility while the rest of the material is collected by the 4 large scale sorting facilities to sort the other recyclables and residual waste. The recycling facility in this scenario is the same as the large-scale recycling facility in scenario A2.

The distributed system uses small-scale sorting and recycling facilities. There are two distributed scenarios which are called C1 and C2. The small-scale sorting facilities in both of these scenarios are the same as scenario B. The difference lies in the configurations of the recycling facilities. In scenario C1, the small-scale recycling facilities are co-located with the sorting facilities. Thus, both sorting and recycling processes are taking place in one location. In scenario C2, there are 7 small recycling facilities distributed across Singapore. Each facility is located in a cluster of sorting facilities. Thus, better transportation than scenario B and better facility utilisation than scenario C1.

**Table 5.1** Summary of facility configurations in all scenarios (Kerdlap et al. 2021*a*).

| **Facility** | **Scenario A1:** Centralised BAU | **Scenario A2:** Centralised Singapore | **Scenario B:** Semi-Distributed | **Scenario C1:** Distributed co-located | **Scenario C2:** Distributed clustered |
|---|---|---|---|---|---|
| Sorting | 4 large scale sorting facilities in Singapore | | 35 small scale sorting facilities in Singapore* | | |
| Recycling | 1 large scale recycling facility in Johor Bahru, Malaysia | 1 large scale recycling facility in Singapore | | 35 recycling facilities co-located with the sorting facilities | 7 small scale recycling facilities in Singapore |
| Incinerator | 1 incinerator based on Tuas South Incineration Plant | | | | |
| Landfill | Landfill in Malaysia | Not used | | | |

*The 4 large scale sorting facilities is present in the distributed scenarios to collect and sort the other recyclables and residual waste from the small scale facilities.

As summarised in Table 5.1, there are 5 scenarios in this case study, namely A1 Centralised BAU, A2 Centralised Singapore, B Semi-Distributed, C1 Distributed co-located, and C2 Distributed clustered. Throughout all 5 scenarios, the collection points remained consistent and the changes are in the location, number, and scale of the sorting and/or recycling facilities.

### 5.1.3 Case study specific submodel updates

The general submodels developed in this research is described in Chapter 4. However, there are some necessary updates which are specific to this case study. The first update was the materials involved which are PET (Polyethylene terephthalate) and PP (polypropylene). Hence, as shown in Figure 5.4, the process submodel in the sorting facility produces the sorted PET and PP while in the recycling facility, this sorted plastic is converted into pellets (PET and PP pellets). The process in other agent types remains unchanged.

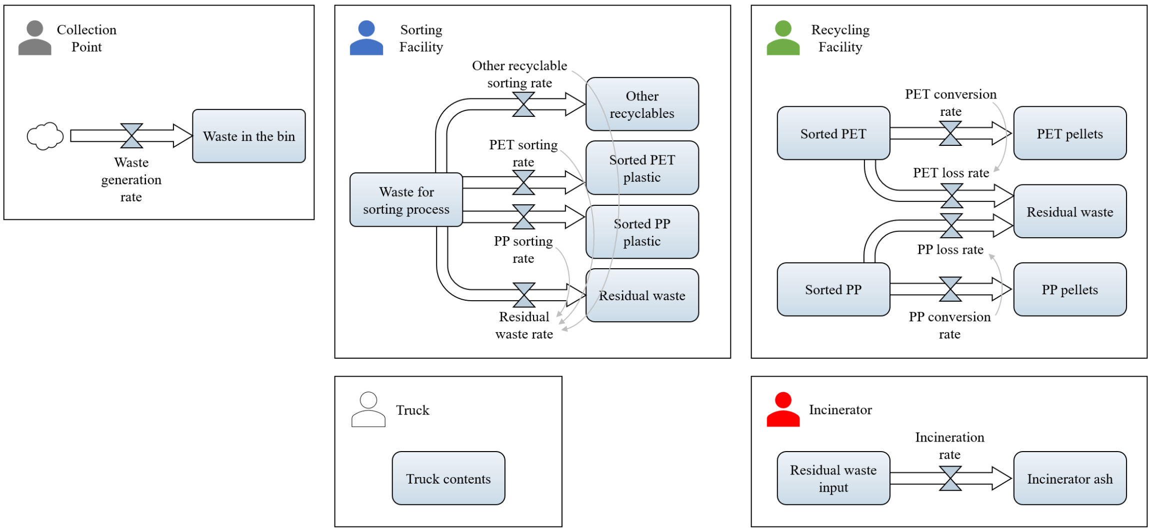


**Figure 5.4** The process submodel is updated based on the materials which are PET and PP.

The next update involves the logistics for the output material which is shown in Figure 5.5. Particularly the criteria to send the material and the end of shift. In this case study, it was assumed that the order is always available. Thus, the material is sent based on whether the inventory is sufficient to fulfil the order. In terms of the shift, it

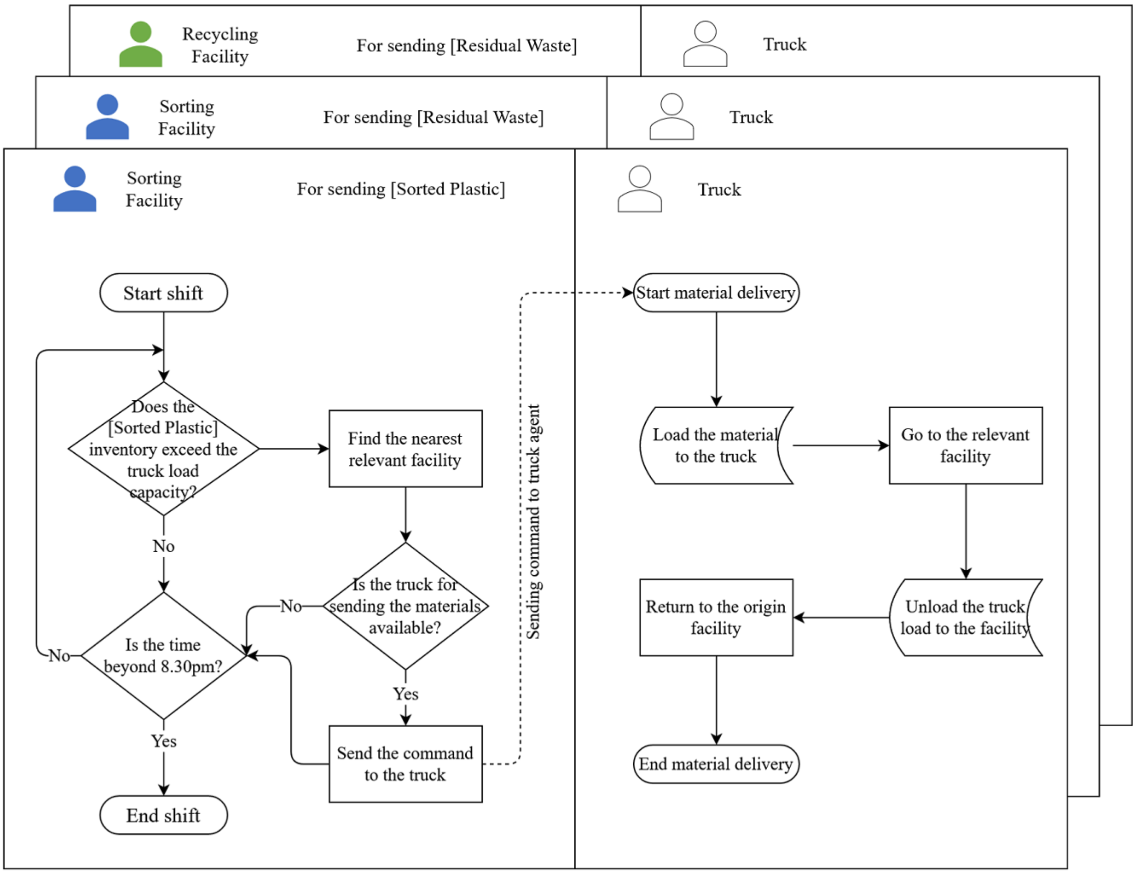


**Figure 5.5** The DES flowchart for output material in Singapore case study.

was assumed that any delivery after 8.30pm will be conducted the next working day (30 minutes before the end of the shift at 9.00pm).

From the start, this case study was intended as a collaboration between simulation modelling and an LCA model. Thus, the system was defined in accordance with LCA methodologies. One particular methodology was the functional unit of the system. Based on the functional unit, this case study was focusing on plastic materials, particularly PET bottles and PP takeaway containers. These materials were selected because plastic was poorly recycled in Singapore. Furthermore, plastic is lightweight which might provide significant transport savings when using distributed systems. Because the main focus and the functional unit was based on PET and PP, the output results were allocated by the weight of the plastic and exclude the other materials.

### 5.1.4 Data input

The data required for the simulation model are outlined in the model parameters in Table 4.1. As shown in the agent-based architecture in Figure 4.1, there are 5 agent types, namely collection point, sorting facility, recycling facility, incinerator, and truck. This section starts with the data for collection point agents because this agent type is the most distinct from the other agent types. The subsequent parts of this section are structured based on the parameter types rather than agent types because of many similarities between the sorting, recycling, and incinerator agent type. Hence, after the collection points data, the next sections cover the facility locations, process, and logistics. The truck agent is explained in the logistics part of the facilities.

#### Collection points location and waste generation

Waste management system for this case study was based on the National Recycling Programme (NRP) administered by National Environment Agency (n.d.*b*). Under the NRP, Singapore was divided into 6 regions which were handled by 4 Public Waste Collectors (PWCs) as shown in Figure 5.6. In 2018, the 4 centralized sorting facilities in the business-as-usual scenario were based on the 4 PWCs, namely 800 Super, Colex, SembWaste, and Veolia. After the case study was finished, there were a few changes in the system such as replacement of Colex with ALBA W&H in April 2020 (National Environment Agency 2020). Since the conclusion would be unaffected by the changes, this study is still using the data from 2018.

There are two types of bins considered in this case study. The first type is the bins from public apartments called Housing Development Board properties (HDBs) and the second type from landed properties. The collection addresses and schedules for HDB and landed properties were publicly available online (800 Super n.d., Colex n.d., SembWaste n.d., Veolia n.d.). All the addresses were converted into latitudes and longitudes with Google Geocoding. Furthermore, the latitudes and longitudes

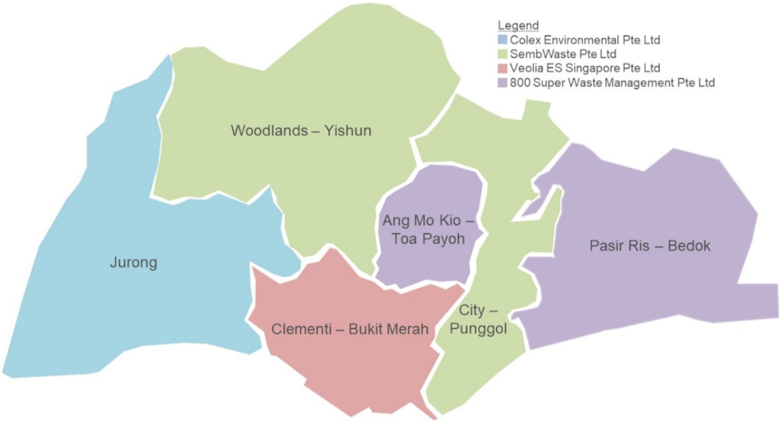


**Figure 5.6** Singapore National Recycling Programme map in 2018 (National Environment Agency n.d.*b*). In April 2020, Colex was replaced by ALBA W&H.

**Figure 5.7** The map of collection points in the simulation model.

were incorporated into the AnyLogic model by using geographic information systems (GIS) as shown in Figure 5.7. The HDB bins are collected typically 3 times a week, either Monday, Wednesday, Friday or Tuesday, Thursday, Saturday, whereas the landed property bins are collected once a week.

The waste generation from each bin was derived by using a top-down approach, from the national statistics. In 2018, the total waste recycled by the NRP was 43,400 tonnes (The Straits Times 2019). By assuming a recycling rate of 60% (Ministry of Sustainability and the Environment 2019), the total waste input from the recycling bins was estimated to be 72,333 tonnes. The distribution of waste throughout Singapore

**Table 5.2** Population data of each recycling region (Department of Statistics 2019).

| Recycling region | Waste collection company | Population of Singaporean resident living in various property types (persons) | | | | Population distribution |
|---|---|---|---|---|---|---|
| | | HDB[1] | Condo[2] | Landed | Others | |
| Ang Mo Kio - Toa Payoh | 800 Super | 373,385 | 66,965 | 71,350 | 4,785 | 30.73% |
| Pasir Ris - Bedok | | 519,935 | 124,105 | 61,025 | 5,970 | |
| Jurong | Colex | 430,970 | 49,100 | 10,100 | 2,850 | 12.35% |
| Woodlands - Yishun | SembWaste | 791,610 | 73,880 | 17,080 | 3,570 | 42.73% |
| City Center - Punggol | | 662,810 | 112,650 | 36,160 | 9,070 | |
| Clementi - Bukit Merah | Veolia | 370,570 | 135,550 | 52,535 | 8,045 | 14.19% |

[1] HDB = Housing Development Board property or public apartment

[2] Condo = condominium or private apartment

was assumed to follow the population distribution. Hence, the population data from Department of Statistics (2019) was matched with the recycling regions and summarised in Table 5.2.

The data presented in Table 5.2 is the population of residents which consist of Singapore citizens and permanent residents. The non-residents comprise of foreigners who are working, studying, or living in Singapore without permanent residency. Since the detailed non-resident population was unavailable, an assumption was made that the non-residents are proportional to the residents. Thus, the population distribution remained the same after including the non-residents.

As mentioned earlier, two types of bins considered were HDB bins and landed property bins. Due to data limitations, the waste from condominiums was assumed to go to the HDB bins whereas the waste from other property types to landed property bins. Thus, the proportion of waste from the HDB bins ranges between 85-97% depending on the region.

The daily waste generation per bin was calculated by using the population distribution in Table 5.2 and the number of bins in the area. The waste was assumed to be uniformly generated every day across the region. By using the average value for waste generation, it is easier to compare the simulation results across different scenarios. The uncertainties were difficult to determine due to lack of data, but discussed further in the chapter.

The number of HDB bins from each region was estimated differently due to the data availability. Two out of four PWCs provided a complete list of the addresses along with the serial number of each bin in the collection schedules (800 Super n.d., Veolia n.d.). These schedules also show that each address consists of multiple buildings and each building has one recycling bin. Therefore, it is suitable to model each address as a collection point agent with multiple bins. The other two PWCs only provided the addresses without specifying the bins (Colex n.d., SembWaste n.d.). From these schedules, the addresses were matched with HDB property information (Housing Development Board 2020) to calculate the number of HDB buildings from each address as the number of bins. Hence, the daily waste per bin from HDBs was estimated to be around 17 to 21 kg as shown in Table 5.3. Based on discussions with industrial stakeholders, the HDB bins are full at around 50 - 80 kg. Thus, with waste collection occurring every 2 or 3 days, the estimated daily waste generation per bin matches closely with what currently happens in Singapore.

Estimating the number of bins for landed properties was more challenging than the HDB bins due to the lack of data. All PWCs only provided the lists of landed property addresses without the details of the bins. Because the waste from landed properties was small compared to the waste from HDB, the daily recyclable waste was assumed to be equally distributed among the landed property addresses in the region. Based on this assumption, the number of bins was irrelevant with regards to the waste

**Table 5.3** Waste generation data for the simulation model. Assuming that the waste distribution follows the population distribution.

| Type of bins | Data type | Name of public waste collector | | | |
|---|---|---|---|---|---|
| | | 800 Super | Colex | SembWaste | Veolia |
| HDB | Waste input (tonnes per year) | 19,638 | 8,697 | 29,716 | 9,165 |
| | Collection per week | 3 times | 2 times | 3 times | 3 times |
| | Number of bins | 2,994 | 1,398 | 4,294 | 1,193 |
| | Waste per bin (kg/day) | 17.97 | 17.04 | 18.96 | 21.05 |
| Landed property | Waste input (tonnes per year) | 2,592 | 235 | 1,193 | 1,097 |
| | Collection per week | 1 time | 1 time | 2 times | 1 time |
| | Number of bins | 2,364 | 273 | 1,458 | 1,344 |
| | Waste per bin (kg/day) | 3.00 | 2.36 | 2.24 | 2.24 |
| Total waste input (tonnes per year) | | 22,230 | 8,932 | 30,909 | 10,262 |
| Waste Composition | | 12.20% PET, 11.12% PP, and 76.68% Others | | | |

amount but was useful for calculating the time to collect the waste from each address. Therefore, the number of bins per address was assumed to be 3. With all the data preparation work outlined in this part, each collection point was assigned with the location, schedule, number of bins, and daily waste generation amount. As mentioned earlier, these collection points remained unchanged in all five scenarios in this study. The complete data for collection points are provided in SI-B of the published paper (Kerdlap et al. 2021*a*).

The waste composition was assumed to be equally distributed across Singapore. In 2018, it was estimated that the entire population of Singapore used 467 million PET bottles and 473 million PP takeaway containers (SEC and Deloitte 2018). Assuming that all PET bottles and PP containers were disposed in the recycling bins, this was equivalent to 8,826 tonnes of PET and 8,041 tonnes of PP which was used as the functional unit of this study. Since the total waste from recycling bins was 72,333 tonnes, the composition of PET and PP were 12.20% and 11.12%, respectively. This study excluded other plastic types and only considered PET bottles and PP containers because these waste streams are desirable by plastic recyclers and can be easily converted into pellets. Furthermore, reliable data for other plastic types in Singapore was unavailable.

### Facility location

Facility location data is fundamental for the simulation model. For scenario A1, the locations of the sorting facilities were taken from the 4 public waste collectors in Singapore (National Environment Agency n.d.*b*). The recycling facility was based on a plastic recycling facility in Johor Bahru, Malaysia. The incinerator was based on Tuas South incineration plant and the landfill in Malaysia was based on Seelong sanitary landfill. Scenario A2 had a similar configuration except for the recycling facility which was based on Singapore's plan on the integrated waste management facility (National Environment Agency n.d.*a*).

The facility location data for the small-scale facilities in scenarios B, C1, and C2 was unavailable since these scenarios are constructed as what-if scenarios. Hence, the approximation method in Section 4.3 was utilised to determine the facility locations. The sorting and recycling facilities were placed in a GIS map as shown in Figure 5.8. The complete data of facility locations can be found in SI-B of the published paper (Kerdlap et al. 2021*a*).

In terms of number of facilities, increasing the number would reduce the distance to collection points, but could lead to underutilisation of machineries and resources.

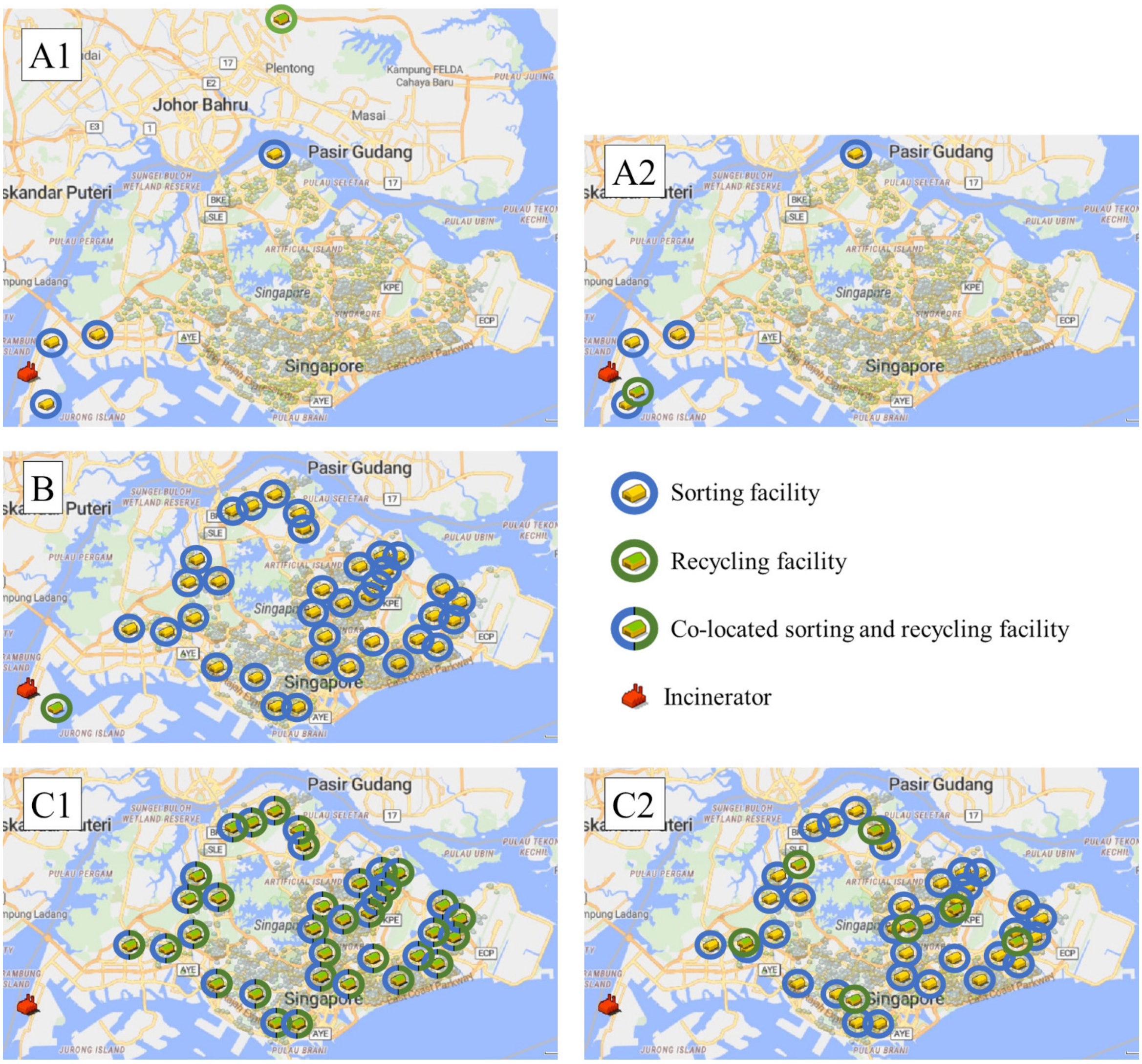


**Figure 5.8** The map of facility locations in all 5 scenarios.

Hence, the number of small-scale sorting facilities for scenario B was determined based on the total number of collection trucks used in scenario A1. This ensures that the number of small-scale facilities could sufficiently cover Singapore. Furthermore, with each facility having one collection truck, the number of collection trucks remained constant in all scenarios which reduces the possibility of underutilisation. The total number of trucks was estimated to be 35 through an iterative process as the minimum number of trucks to complete waste collection each day. The truck estimation is explained further in the facility logistics section. As shown in Table 5.1, the sorting facilities in scenario B was the same as in scenario C1 and C2.

The recycling facility in scenario B was the same as in scenario A2. In scenario C1, the recycling facility is co-located with the sorting facility and thus the number of small recycling facilities were 35. For scenario C2, the number of recycling facilities was determined to be 7 to evenly and thoroughly cover the 35 small-scale sorting facilities.

### Facility process

In this case study, the processes in the facility were simplified as converting input into output. This was done because the 1-year simulation time frame was too high to simulate the dynamics of the process. To incorporate more mechanisms into the process, a more suitable time frame would either be daily or weekly. However, the 1-year time frame was more appropriate for this research since the objective is system design and planning. Hence, the analysis on a different time frame could be conducted in future research.

Based on Table 4.1, the parameters for the sorting facilities are input composition, sorting throughput, and process efficiency. The composition of the incoming waste is consistent for all the scenarios as shown in Table 5.3, namely 12.20% PET, 11.12% PP, and 76.68% other recyclables. All other parameters are summarised in Table 5.4.

For the large-scale sorting facilities (scenario A1 and A2), the sorting throughput of each facility was obtained from the annual waste input for each PWC as shown in Table 5.3. The process efficiency was described by using the recovery rate for each material. In the sorting process, the recovery rate of both PET and PP was 75% (Perugini et al. 2005). By assuming that 40% of sorting facility output is residual waste (Ministry of Sustainability and the Environment 2019), the recovery rate for the other recyclables was calculated to be 55.44%.

**Table 5.4** Process details of all scenarios in this case study.

| Data type | Scenario A1: Centralised BAU | Scenario A2: Centralised Singapore | Scenario B: Semi-Distributed | Scenario C1: Distributed co-located | Scenario C2: Distributed clustered |
|---|---|---|---|---|---|
| *Sorting facility* | | | | | |
| Location | Singapore | Singapore | Singapore | Singapore | Singapore |
| Number of facilities | 4 | 4 | 35 | 35 | 35 |
| Capacity range of each facility (tonnes/year) | 8,932 - 30,909 | 8,932 - 30,909 | 1,768 - 3,071 | 1,768 - 3,071 | 1,768 - 3,071 |
| Plastic recovery rate | 75% | 75% | 80% | 80% | 80% |
| *Recycling facility* | | | | | |
| Location | Malaysia | Singapore | Singapore | Singapore | Singapore |
| Number of facilities | 1 | 1 | 1 | 35 | 7 |
| Capacity range of each facility (tonnes/year) | PET 6,628<br>PP 6,038 | PET 6,628<br>PP 6,038 | PET 7,070<br>PP 6,441 | PET 172 - 229<br>PP 157 - 273 | PET 752 - 1,487<br>PP 685 - 1,335 |
| Plastic conversion rate | 76% | 76% | 76% | 76% | 76% |

For the small-scale sorting facilities (scenario B, C1, and C2), the sorting throughput was acquired from the expected daily waste as described in the facility location section. The PET and PP recovery rate was 80% by assuming that the sorting in a small-scale facility is slightly better than the large-scale facility (Rigamonti et al. 2014). Since the other recyclables are sorted in the large-scale facility, the recovery rate of other recyclables remained the same.

The recycling facility throughput was estimated similarly to the sorting facility, by calculating the expected plastic input from the sorting facilities. Since similar types of machinery were used in all scenarios, the conversion rate was 76% (Perugini et al. 2005). In other words, 76% of the incoming sorted PET or PP becomes pellets while the remaining 24% becomes residual waste. Since the incinerator in all scenarios was based on Tuas South Incineration Plant, the incineration rate was 3,000 tonnes per day (National Environment Agency n.d.*c*).

### Facility logistics

The logistics in the case study was mainly concerned with materials transportation by the sorting and recycling facilities. Hence, the parameters refer to the trucks, namely the transportation route and type, number, and maximum load of trucks. There are 4 types of transportation routes in this system which are collection points to sorting facility, sorting facility to recycling facility, sorting facility to incinerator, and recycling facility to incinerator (or landfill). The transportation of other recyclables and plastic pellets are outside of the system boundary. The summary of the truck details can be found in Table 5.5.

Both centralised scenarios (A1 and A2) have the same truck configurations. The waste collection uses a rear-loader truck and the total number of trucks from all 4 large-scale sorting facilities was 35. This number was estimated as the minimum number of trucks required to complete waste collection before 9pm on a working day. The estimation process was performed iteratively, by running the model with different number of trucks and measuring the time for the waste collection to be finished for each facility. The maximum load of the waste collection truck was estimated to be 5 tonnes based on interviews with waste management companies in Singapore.

To send the sorted plastic from sorting to a recycling facility, the truck was assumed to have a shipping container. Since each facility owns 1 truck, the total number of shipping trucks was 4. The maximum load of the truck for recycling was estimated based on the volume of a shipping container with a dimension of 6.1m × 2.44m × 2.59m (DSV n.d.). With a PET bale dimension of 1.52m × 0.76m × 1.22m, the container could carry 24 bales which are equivalent to 9.21 tonnes of PET (Association of Plastic

**Table 5.5** Summary of the trucks for the 4 transportation routes in all scenarios.

<table>
<tr><th rowspan="2">Scenarios</th><th rowspan="2">Truck data type</th><th colspan="4">Transport route</th></tr>
<tr><th>Collection points to sorters</th><th>Sorters to recyclers</th><th>Sorters to incinerator</th><th>Recyclers to incinerator</th></tr>
<tr><td rowspan="3">Centralised<br>A1: BAU<br>A2: Singapore</td><td>Type</td><td>Waste collection truck</td><td>Large shipping truck</td><td>Medium lorry</td><td>Medium lorry</td></tr>
<tr><td>Total number</td><td>35</td><td>4</td><td>4</td><td>1</td></tr>
<tr><td>Max load (tonnes)</td><td>5</td><td>PET 9.21 or PP 6.31</td><td>5</td><td>5</td></tr>
<tr><td rowspan="3">B: Semi-Distributed</td><td>Type</td><td>Commercial van</td><td colspan="2">Commercial van</td><td>Medium lorry</td></tr>
<tr><td>Total number</td><td>35</td><td colspan="2">35</td><td>1</td></tr>
<tr><td>Max load (tonnes)</td><td>3</td><td>PET 2.12 or PP 1.45</td><td>3</td><td>5</td></tr>
<tr><td rowspan="3">C1: Distributed co-located</td><td>Type</td><td>Commercial van</td><td rowspan="3">None (sorters and recyclers are co-located)</td><td colspan="2">Commercial van</td></tr>
<tr><td>Total number</td><td>35</td><td colspan="2">35</td></tr>
<tr><td>Max load (tonnes)</td><td>3</td><td colspan="2">3</td></tr>
<tr><td rowspan="3">C2: Distributed clusters</td><td>Type</td><td>Commercial van</td><td colspan="2">Commercial van</td><td>Commercial van</td></tr>
<tr><td>Total number</td><td>35</td><td colspan="2">35</td><td>7</td></tr>
<tr><td>Max load (tonnes)</td><td>3</td><td>PET 2.12 or PP 1.45</td><td>3</td><td>3</td></tr>
</table>

Recyclers n.d.). To estimate the maximum load of PP bales, the PET and PP bale density was assumed to be proportional to the material density. The ratio of PET and PP density is 1.38:0.946 (Bai et al. 2003, IFA n.d.) and thus the same volume of the shipping container could haul 6.31 tonnes of PP bales.

The transportation to incinerator from both sorting and recycling facility use the same type of truck which is a medium lorry. Each facility owns 1 truck with a maximum load of 5 tonnes, assuming that the capacity of the truck is equal to the capacity of waste collection truck.

For scenarios B, C1, and C2, all sorting and recycling facilities were small except for the recycling facility in scenario B. Thus, the transport from recycling facility to incinerator in scenario B uses a medium lorry whereas all other transportation was using commercial vans. For waste collection, there was 1 commercial van per facility which makes the total number of vans in the system to be 35. Subsequently, there was 1 additional commercial van per facility which was allocated for the other routes. In scenarios B and C2, this van was employed by the sorting facility to send sorted plastic to the recycling facility and residual waste to the incinerator. In scenario C1, the van was loaded with residual waste from both the sorting and recycling process in the co-located facility. The commercial vans were assumed to have a different maximum load when carrying different materials, namely 3 tonnes for mixed waste and residuals, 2.12 tonnes for PET bales, or 1.45 tonnes for PP bales. The sorted plastic load capacity was estimated by using a similar method for the large shipping truck.

### 5.1.5 Results and discussion

#### Simulation modelling

The simulation was run for one year period and produced material and logistics data. The material data represents the material output of sorting and recycling facilities which can be seen in Table 5.6. The waste input of all scenarios is the same because the waste collections were set to be constant across all scenarios. Furthermore, the simulation was conducted in a deterministic way. This provides a reliable comparison and verification of the output data between the scenarios. The stochastic part of the model is discussed further in this section.

Since the process was assumed to be linear, the annual material output is relatively straightforward. The minor difference between centralised scenarios (A1 and A2) and distributed scenarios (B, C1, and C2) is attributed to the plastic recovery rate. The distributed scenarios have a slightly higher plastic recovery rate which increases the

**Table 5.6** Material output data in tonnes from sorting and recycling facilities in the system.

| Annual output (tonnes) | Centralised scenarios: A1 and A2 | Distributed scenarios: B, C1, and C2 |
|---|---|---|
| *Sorting facility* | | |
| Incoming waste | 72,422 | 72,422 |
| Sorted PET | 6,628 | 7,070 |
| Sorted PP | 6,038 | 6,441 |
| Other Recyclables | 30,787 | 30,787 |
| Residuals | 28,969 | 28,124 |
| *Recycling facility* | | |
| PET Pellets | 5,037 | 5,373 |
| PP Pellets | 4,589 | 4,895 |
| Residuals | 3,040 | 3,243 |

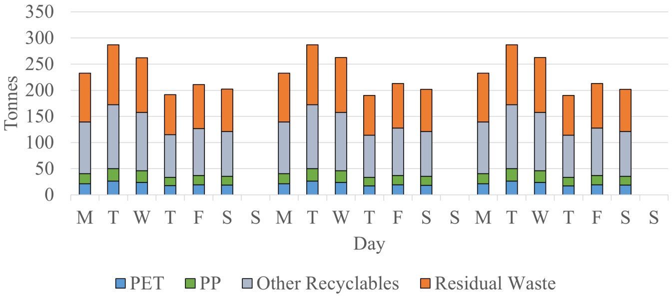


**Figure 5.9** The daily output of the large-scale sorting facilities over a 3-week period. Similar trends occur at the small-scale sorting facilities.

recycled plastic and reduces the residual waste. A lower simulation time frame might be more suitable to represent the dynamics of the process

Despite the simplified process, the incoming waste varies each day due to the non-linearity of the logistics. The daily output of the sorting facility is shown in Figure 5.9. The daily variation arises because of the collection schedule which involves different sets of collection points to be collected each day. The schedule repeats every week which produces the same cycle each week. Similar trends can be observed for the

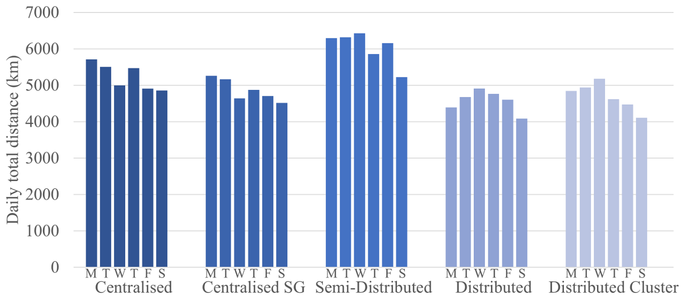
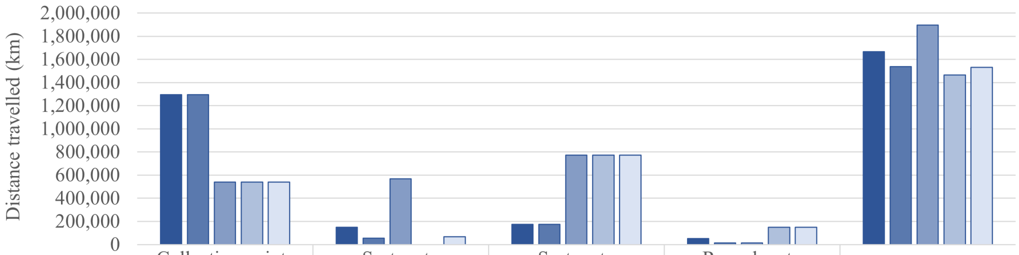


**Figure 5.10** The daily total distance of each scenario over a 6-working-day period.

output of the recycling facilities and small-scale sorting facilities. The schedule also creates some variations in the total distance travelled each day. Figure 5.10 shows the daily total distance in each scenario over a 6-working-day period. The total distance includes all 4 transportation routes in Table 5.5. Each week, the total distance slightly changes due to the availability of sorted PET and PP for delivery.

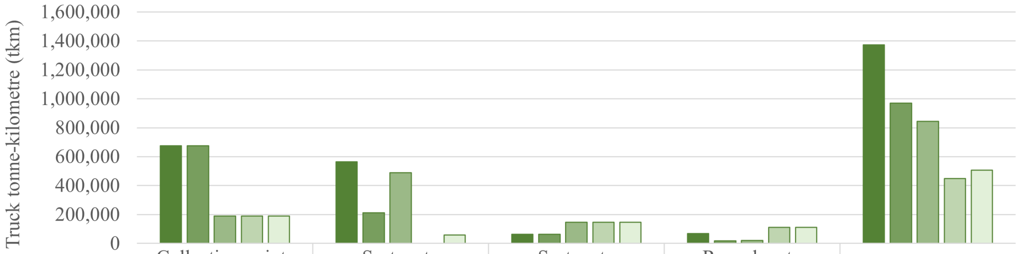
The total distance travelled and tonne-kilometer (tkm) in one year are shown in Figure 5.11 and 5.12, respectively. As mentioned in Section 5.1.3, this case study is focusing on PET and PP because plastic is poorly recycled in Singapore and lightweight which could yield a significant benefit in distributed systems. By following LCA methodology, weight allocation of PET and PP was implemented based on the percentage of PET and PP in the load. For waste collection, PET and PP accounted for 23% of the waste collected. In the sorting to incinerator route, the residual PET and PP was 15% of total residual waste. For the other routes (sorter to recycler and recycler to incinerator), PET and PP is 100% of the truck load. Because of this, the tkm only represents plastic and other materials are excluded from the tkm calculation in Figure 5.12.

In the collection points to sorters route, distributed scenarios (B, C1, and C2) could reduce the distance travelled by 58% compared to the centralised scenarios (A1 and A2). Consequently, this also reduces the tkm by 72%. This result is expected because the small-scale sorting facilities are much closer to the waste sources and thus significantly reduces the transportation distance.



| | Collection points to sorters | Sorters to recyclers | Sorters to incinerator | Recyclers to incinerator | Total of all routes |
|---|---|---|---|---|---|
| ■ A1: Centralised BAU | 1,294,124 | 148,037 | 173,621 | 50,857 | 1,666,639 |
| ■ A2: Centralised SG | 1,294,128 | 55,663 | 173,621 | 14,394 | 1,537,805 |
| ■ B: Semi-Distributed | 540,819 | 566,939 | 773,590 | 15,351 | 1,896,699 |
| ■ C1: Distributed co-located | 540,819 | 0 | 773,590 | 149,901 | 1,464,310 |
| □ C2: Distributed clustered | 540,819 | 66,953 | 773,590 | 149,131 | 1,530,493 |

**Figure 5.11** The total distance travelled of each scenario in one year.



| | Collection points to sorters | Sorters to recyclers | Sorters to incinerator | Recyclers to incinerator | Total of all routes |
|---|---|---|---|---|---|
| ■ A1: Centralised BAU | 675,327 | 565,183 | 63,532 | 69,931 | 1,373,974 |
| ■ A2: Centralised SG | 675,331 | 211,627 | 63,532 | 18,677 | 969,168 |
| ■ B: Semi-Distributed | 190,625 | 488,903 | 145,806 | 19,922 | 845,257 |
| ■ C1: Distributed co-located | 190,625 | 0 | 145,806 | 111,640 | 448,071 |
| □ C2: Distributed clustered | 190,625 | 59,091 | 145,806 | 112,237 | 507,760 |

**Figure 5.12** The total tkm of each scenario in one year. The tkm is allocated for plastic, meaning that only the transport of plastic is included while other recyclables are excluded.

In the sorters to recyclers route, the distance travelled and tkm has more variations across the scenarios compared to other routes. By moving the recycling facility from Malaysia in scenario A1 to Singapore in scenario A2, both the distance travelled and tkm were reduced by around 62% because the recycling facility is much closer. For scenario B, the distance travelled in this route had a 10-fold increase compared to scenario A2. This is a trade-off where the small sorting facilities were closer to the waste sources but further away from the large-scale recycling facility. In addition, the truck in scenario B was smaller which requires additional trips to transport the same load. The tkm is more concerned with the amount of materials transported rather than the number of trips. Because of that, despite a 10-fold increase in distance travelled, the tkm only increases by two-fold compared to scenario A2 and still lower than the tkm in scenario A1. In scenario C1, there is no transportation in this route because the sorting and recycling facilities are co-located. In scenario C2, the small recycling facilities are designed to be near the small sorting facilities. Thus, the distance travelled is comparable with scenario A2 but with 72% less tkm because of the smaller trucks.

In the sorters to incinerator route, distributed scenarios (B, C1, and C2) had a much higher distance travelled and tkm than centralised scenarios (A1 and A2). This is similar to the sharp increase in the sorters to recyclers route of scenario B. The small sorting facilities were further from the incinerator compared to the large sorting facilities. The total distance was inflated due to the smaller trucks being used, but the tkm was relatively reasonable.

The recyclers to incinerator route had a similar trend to the sorters to incinerator route. The small recycling facilities in both scenario C1 and C2 requires more distance and tkm. Since scenario B involves a large recycling facility in scenario A2, the distance and tkm follows scenario A2.

The total distances from all the routes vary across the scenarios as shown in Figure 5.11. Scenario B had the highest total distance despite closer to the waste source because the transportation to large-scale recycling facility and incinerator far outweighs the reduction in waste collection. However, this is partly due to the smaller trucks involved in scenario B which increases the number of trips required by around 2 to 3 times. This was corrected by analysing the tkm which accounts for the load per trip. In Figure 5.12, scenarios C1 and C2 show a remarkable reduction of tkm, around 50% from scenario A2 and 65% from scenario A1. The tkm was then used to calculate the environmental impact and fuel costs of transportation in the system.

### LCA and LCC model

The material and logistics data presented in Table 5.6 and Figure 5.11 and 5.12 were used as lifecycle inventory data for both LCA (lifecycle analysis) and LCC (lifecycle costing) model in collaboration with Piya Kerdlap from National University of Singapore. This shows the viability of the simulation model to be combined with other models. The integration consists of processing the simulation results into the input for the LCA and LCC model. This section highlights some of the important findings and the full results of the environmental impact can be found in the published paper (Kerdlap et al. 2021*a*). At the time of writing, the paper which contains the LCC model is submitted for publication (Kerdlap et al. 2021*b*).

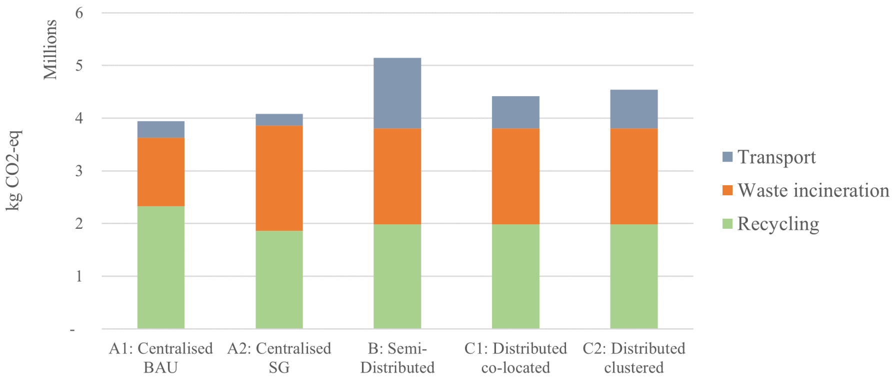


**Figure 5.13** The global warming potential of the process and transportation of each scenario.

One of the environmental impact categories is the global warming potential which measures the greenhouse gas emissions in terms of kg of $CO_2$ equivalent. As shown in Figure 5.13, the largest emissions came from the recycling process because of the high energy usage of the extruder. The second highest emissions came from waste incineration because of the by-product of this process which is $CO_2$. From these two processes, scenario A1 had the most unique composition compared to the other scenarios, specifically the emissions from recycling were higher whereas that from waste incineration was lower. This is because the recycling facility was operating in Malaysia which had a different emission factor for the electricity generation than Singapore.

Furthermore, the residual waste from recycling process was landfilled instead of being incinerated. Compared to scenario A2, the distributed scenarios (B, C1, and C2) have a slightly higher emissions from recycling and lower from incineration. This can be attributed to the marginally higher plastic recovery rate which means that more plastic was recycled which required more electricity, but less waste was incinerated.

The carbon emissions of transportation represented the third largest emissions in Figure 5.13. This result has a correlation with the tkm results in Figure 5.12. Despite the significant reduction of tkm, the carbon emissions from transportation of distributed scenarios (B, C1, and C2) are between two to six times higher than the centralised scenarios (A1 and A2). This is because of the emission factor of the small trucks is larger by a factor of eight than the large trucks. In other words, the tkm from the smaller trucks requires a reduction of almost 90% to equalise this significant disparity. The disparity in the emission factor arises because the large trucks could carry a substantially higher load with only a slightly higher fuel consumption compared to the small trucks. Thus, the fuel consumption per load for small trucks is worse than for large trucks as reflected in the emission factor. Hence, using electric vehicles has the potential to reduce the emission factor and thus overall global warming potential.

The global warming potential of the manual sorting process was less than 1% of the total (not shown in Figure 5.13). This was due to the small electricity consumption of conveyor belts since the sorting was done by using manual labour.

The net present value (NPV) of the system for all scenarios are shown in Figure 5.14. The NPV was highly dependent on the price of the recycled plastic pellets which were determined to be SGD 240 and 360 per tonne of PET and PP pellets, respectively. This allows all but scenario C1 to reach profitability at the end of 7 years. The period of 7 years was selected as the contract period awarded to a public waste collector by National Environment Agency (n.d.*e*) in Singapore. Scenario A1, B, and C2 reached the breakeven point at year 2 while scenario A2 at year 3. After 7 years, the centralised scenarios A1 and A2 had a better NPV compared to the distributed scenarios B, C1,

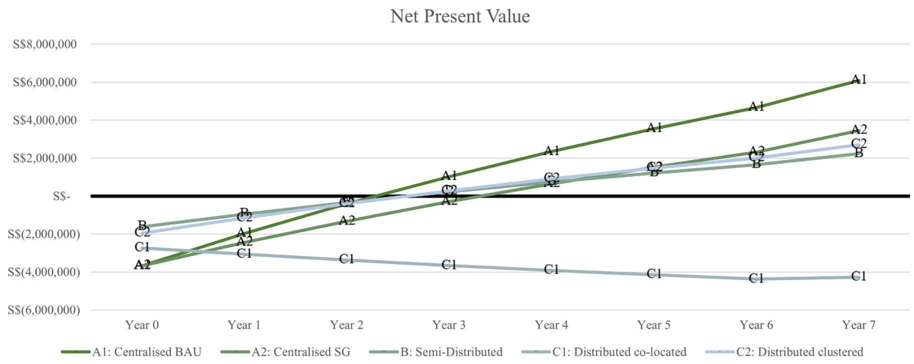


**Figure 5.14** The NPV of the system in each scenario. The recycled plastic pellets are priced at SGD 240/tonne and SGD 360/tonne for PET and PP, respectively.

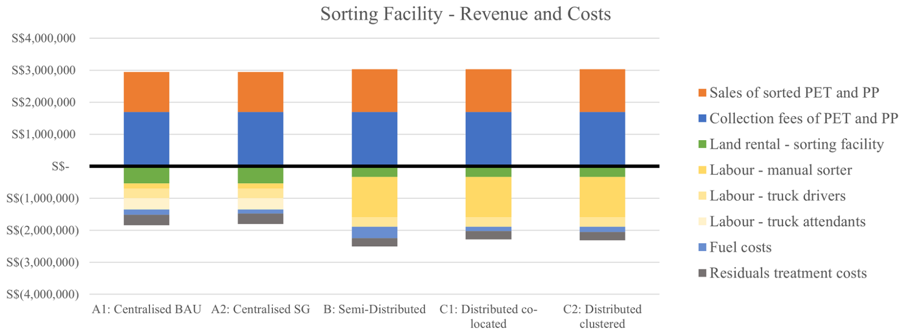


**Figure 5.15** Sorting facility annual revenue and costs of each scenario.

and C2 despite having a higher initial investment. In other words, the profitability of centralised scenarios A1 and A2 were better.

The revenue and costs of all sorting facilities in the system are shown in Figure 5.15. As mentioned earlier, the revenue and costs were allocated to plastic which excluded all other materials. The annual net profit of the centralised scenarios A1 and A2 was around SGD 1,100,000 with a profit margin of 38% while the distributed scenarios B, C1, and C2 was SGD 500,000 - 700,000 with a profit margin of 17 - 24%. The revenue was obtained from the collection fees (allocated to PET and PP) and sales of the sorted PET and PP. The sales of sorted PET and PP was assumed to be SGD 80 and SGD 120 per tonne, respectively.

In Figure 5.15, it is apparent that labour was the most significant cost, especially for the distributed scenarios. This is because the sorting process used manual sorting and thus relied heavily on labour. The distributed scenarios had more total workers (70 workers in 35 small-scale facilities) compared to the centralised scenarios (40 workers in 4 large-scale facilities). Furthermore, the labour in the distributed scenarios was 100% allocated to plastic because the facilities are purpose-built for sorting out plastic. This is in contrast to the centralised scenarios where only 23% of labour costs were allocated to plastic while the rest for other materials. The allocation was made based on the weight composition of plastic in the waste stream.

Similar to the environmental impact, the fuel cost was a small part of the costs. The fuel cost represented between 6 - 14% of the operational costs of sorting facilities. Despite being closer to the waste sources, distributed scenarios had a higher fuel cost because of using trucks with higher fuel consumption. Thus, fuel efficiency is important to consider in addition to the distance travelled and tkm.

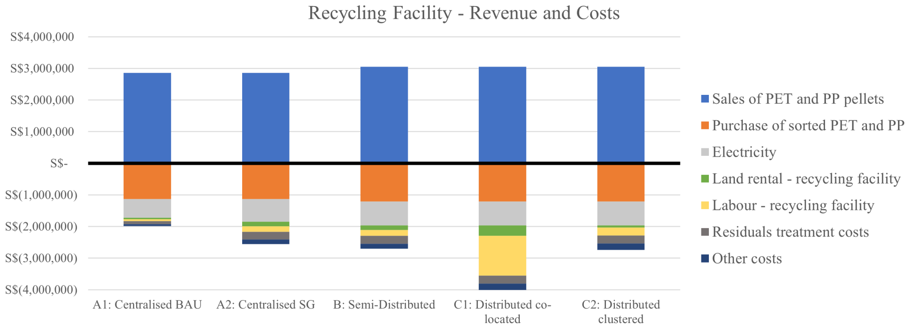


**Figure 5.16** Recycling facility annual revenue and costs of each scenario. The other costs include water, soda, fuel, and wastewater treatment cost.

For the recycling facilities, the revenue and costs are shown in Figure 5.16. The revenue of recycling facilities comes from sales of plastic pellets at a price of SGD 240 per tonne of PET and SGD 360 per tonne of PP. This equates to an annual profit of SGD 750,000 and a profit margin of 26% in scenario A1 and around SGD 180,000 - 220,000 with a profit margin of 6% in scenario A2, B, and C2. The higher profit in scenario A1 is mainly because the recycling was done in Malaysia where the land rental, labour, and residual waste treatment costs are much cheaper than in Singapore. The highest cost came from the purchase of raw materials from the sorting facility. The next major cost was from the electricity, particularly from the extruder which used a high amount of electricity. Since some machineries were involved, the labour costs in recycling facilities were relatively small. However, in the semi-distributed scenario C1, the labour was extremely high due to the excessive number of recycling facilities.

Since labour for the sorting facility is a significant cost, it might be advantageous to use automated sorting technologies. In the distributed scenarios (B, C1, and C2), the labour for the manual sorting process was 2 workers per facility. By reducing the labour from 2 to 1 worker per facility, the NPV could be increased by SGD 91,000. Hence, the potential savings could be allocated as an investment for some sorting technologies. Since the facility was purpose-built for plastic, the labour costs for distributed scenarios were fully allocated to plastic. Hence, it might be reasonable for the facility to sort other materials especially with sorting technologies.

The number of facilities was determined based on the total number of collection trucks in the system. Given that the labour cost for manual sorting is substantial, an additional analysis on the appropriate number of facilities would be important for future research. In this analysis, the relationship between the number of facilities and workers would need to be established.

In both sorting and recycling facilities, the profitability depends highly on the sales of the materials. In this model, it was assumed that the sales were immediate as soon as the materials were ready. In reality, the sales process might require more effort such as sales and marketing team and budget. Furthermore, the unsold material might give rise to a cash flow challenge and generate additional difficulty when the storage area is filled up. The sales process involves numerous human elements which would require significant effort and time to clearly define for the model. Thus, this is outside of the scope of this research, but could be implemented for future research.

With regards to the system boundary, the end product of this system is plastic pellets. The pellets are likely to be sent to a large-scale processing facility and subsequently converted into usable plastic products. Due to the diverse possibilities of processing facilities and products, these parts were excluded from the system boundary. However, it is an interesting area to explore especially for scenario C1, i.e. distributed system with co-located sorting and recycling facilities. By involving a processing facility and selling the end products directly to local consumers, the value of the recycled plastic can be increased which would positively affects the revenue and profit. Potentially, since the waste is processed in a local way, there could be more awareness in the waste system which could drive better waste separation. The difficulty in this area includes the product design and predicting customer demand which can be explored in future research.

### Sensitivity analysis

The sensitivity analysis was conducted to investigate the effect of various parameters. Based on the model parameters in Table 4.1 and the available data in this case study, there are seven input parameters as shown in Table 5.7.

**Table 5.7** Input parameters for the system and the average values.

| No | Input parameters | Average value |
|---|---|---|
| 1. | Waste generation amount | 72,422 tonnes per year |
| 2. | Input composition | 12.20% PET and 11.12% PP |
| 3. | Sorting loss rate | 25% for PET and PP |
| 4. | Recycling loss rate | 24% for PET and PP |
| 5. | Truck capacity for waste collection | 5 tonnes |
| 6. | Truck capacity for residual waste transport | 5 tonnes |
| 7. | Truck capacity for recycled plastic transport | 9.21 tonnes for PET or<br>6.31 tonnes for PP |

For the sensitivity analysis, the average values of the parameters in Table 5.7 were changed by ± 50%. The effects from the parameters were measured against the changes in the output results, namely material and logistics data. The first four parameters from Table 5.7 affect both material data and logistics data, whereas the other three parameters for truck capacity only affect the logistics data.

As shown in Table 5.8, the waste generation parameter affected all material data significantly. The linear relationship was obtained because of the assumption that the process was simplified as converting input into output which depends on the input composition and loss rate. This simplification was justified because the simulation time frame was suitable for system design, but too large to capture the dynamics of the process. Since the input composition and loss rate remained constant, the material data was proportional to the waste generation.

For the logistics data, the waste collection distance and tkm was affected in a non-linear way as shown in Figure 5.17 because waste collection requires multiple stops per trip and other logistics decisions. However, all the other routes were linearly correlated with the waste generation. Potentially because each delivery was a simple return trip and thus the amount of material directly influenced the number of trips. From these results, it is critical for the waste generation data to be accurate because of the high correlation to the modelling results.

The input composition parameter can also highly affect the output. The composition of both plastic types was changed simultaneously and the other recyclables made up for the rest of the composition. Thus, the analysis was done by varying the composition from 6.10% PET and 5.56% PP to 18.30% PET and 16.68% PP. As shown in Table 5.8, this parameter affects some results in a linear way. However, the amount of incoming waste and consequently the waste collection logistics were unaffected. By increasing the plastic composition, the residual waste from the sorting process was less and thus showing an inverse linear relationship. The final two parameters, sorting and recycling

**Table 5.8** Sensitivity analysis of input parameters excluding the truck capacity based on scenario A1. Showing the output range when the average value of input parameters was varied by ± 50%.

| | | **1. Waste generation** | | **2. Input composition** | | **3. Sorting loss rate** | | **4. Recycling loss rate** | |
|---|---|---|---|---|---|---|---|---|---|
| | | -50% | +50% | -50% | +50% | -50% | +50% | -50% | +50% |
| *Material data of sorting facility* | | | | | | | | | |
| Incoming waste | | -50% | +50% | 0% | 0% | 0% | 0% | 0% | 0% |
| Sorted PET | | -50% | +50% | -50% | +50% | +17% | -17% | 0% | 0% |
| Sorted PP | | -50% | +50% | -50% | +50% | +17% | -17% | 0% | 0% |
| Residuals | | -50% | +50% | +6% | -6% | -7% | +7% | 0% | 0% |
| *Material data of recycling facility* | | | | | | | | | |
| PET Pellets | | -50% | +50% | -50% | +50% | +17% | -17% | +16% | -16% |
| PP Pellets | | -50% | +50% | -50% | +50% | +17% | -17% | +16% | -16% |
| Residuals | | -50% | +50% | -50% | +50% | +17% | -17% | -50% | +50% |
| *Logistics data* | | | | | | | | | |
| Waste collection | distance | -3% | +17% | 0% | 0% | 0% | 0% | 0% | 0% |
| | tkm | -48% | +38% | 0% | 0% | 0% | 0% | 0% | 0% |
| Sorter to recycler | distance | -50% | +50% | -50% | +50% | +17% | -17% | 0% | 0% |
| | tkm | -50% | +50% | -50% | +50% | +17% | -17% | 0% | 0% |
| Sorter to incinerator | distance | -50% | +50% | +6% | -6% | -7% | +7% | 0% | 0% |
| | tkm | -50% | +50% | +6% | -6% | -7% | +7% | 0% | 0% |
| Recycler to incinerator | distance | -50% | +50% | -50% | +50% | +17% | -17% | -50% | +50% |
| | tkm | -50% | +50% | -50% | +50% | +17% | -17% | -50% | +50% |

loss rate, were inversely proportional to the plastic material data. The effect from these parameters were also smaller than the first two parameters.

As shown in Figure 5.17, most of the results were linear except for the waste collection. This is because the process was simplified as converting input into output. Furthermore, deterministic modelling was applied which means that the daily conversion rate was constant. Hence, applying randomness in the model could reflect a more realistic process which is explored in the next section.

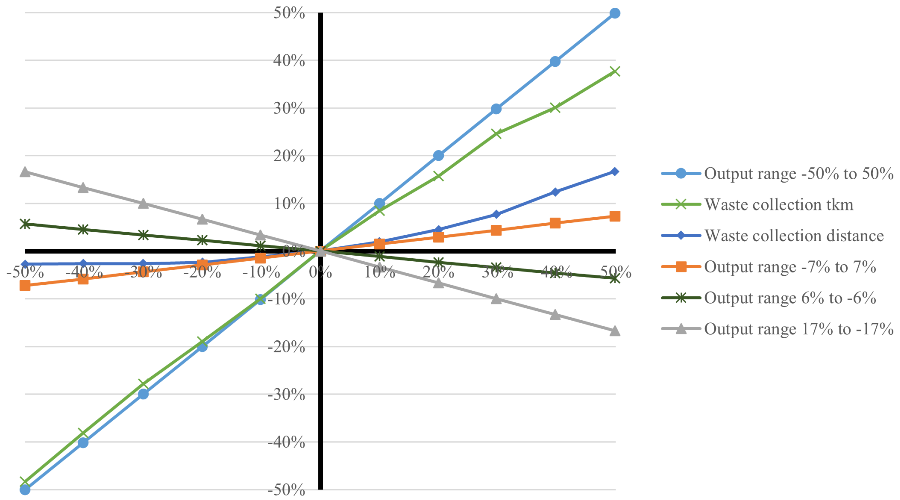


**Figure 5.17** Sensitivity analysis trend of various output ranges from Table 5.8. X-axis shows the deviation of input parameter from the average value whereas the Y-axis the deviation of output results.

The parameters for truck capacity only affect the logistics data as shown in Table 5.9. By increasing the truck capacity regardless of the routes, the distance was reduced because fewer trips were required. As shown in Figure 5.18, changes in the logistics data were non-linear with a higher rate of change at lower truck capacity. For waste collection, the distance reaches a minimum of -3% despite the increase of truck capacity because the truck needs to visit all the collection points. The tkm for waste collection has a reverse trend where the tkm increases with the truck capacity to a maximum of +3% from the average result. The inverse relationship between tkm and distance results is because the load per trip increment outweighed the reduction of the distance travelled.

Other than the waste collection route, the truck capacity influenced the distance travelled for other routes in a large way. Despite of that, the tkm remained constant. This is because of a simplification where each delivery consists of a return trip and the destination is always the same. As a result of this simplification, the relationship between distance and change in truck capacity can be derived. The tkm can be calculated in two ways. The first is by multiplying the total load and distance per trip.

**Table 5.9** Sensitivity analysis of the truck capacity based on scenario A1. Showing the output range when the average value of input parameters were varied by ± 50%.

| | | **Truck capacity for** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **5. waste collection** | | **6. recycled plastic** | | **7. residual waste** | |
| | | -50% | +50% | -50% | +50% | -50% | +50% |
| *Logistics data* | | | | | | | |
| Waste collection | distance | +39% | -3% | 0% | 0% | 0% | 0% |
| | tkm | -15% | +3% | 0% | 0% | 0% | 0% |
| Sorter to recycler | distance | 0% | 0% | +100% | -33% | 0% | 0% |
| | tkm | 0% | 0% | 0% | 0% | 0% | 0% |
| Sorter to incinerator | distance | 0% | 0% | 0% | 0% | +100% | -33% |
| | tkm | 0% | 0% | 0% | 0% | 0% | 0% |
| Recycler to incinerator | distance | 0% | 0% | 0% | 0% | +100% | -33% |
| | tkm | 0% | 0% | 0% | 0% | 0% | 0% |

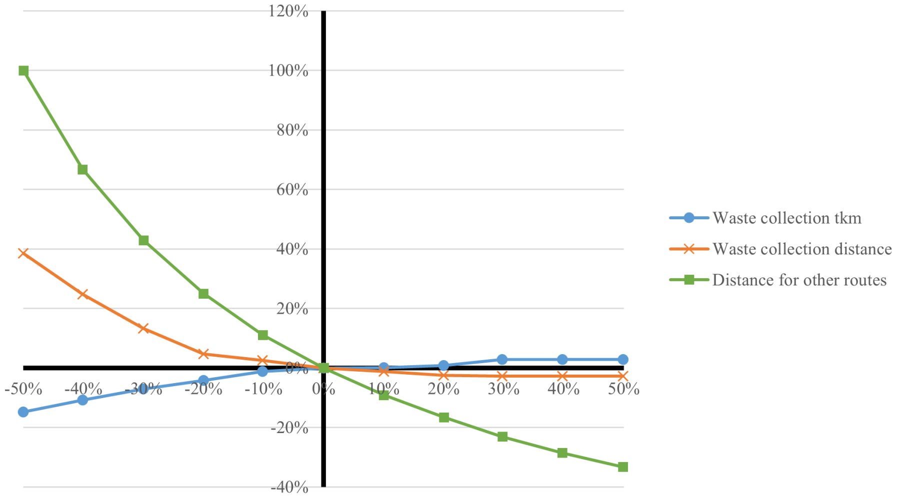


**Figure 5.18** Sensitivity analysis trend of the truck capacity from Table 5.9. X-axis shows the deviation of input parameter from the average value whereas the Y-axis the deviation of output results.

In this way, it is apparent that changing the truck capacity has no effect on the tkm. The second is by multiplying average load per trip (or truck capacity) and the total distance travelled. Since the tkm is constant, the percentage distance change ($\%\Delta D$) can then be expressed as:

$$\%\Delta D = \frac{1}{1 + \%\Delta T} - 1$$

where, $\%\Delta T$ is the percentage change of truck capacity. With this relationship, varying the truck capacity from -50% to +50% would yield the percentage of distance change of +100% and -33%, respectively.

This is the relationship as observed in Table 5.9 and Figure 5.18 between truck capacity and distance for other routes (for sending recycled plastic and residual waste). In both LCA and LCC results, the calculation was conducted based on the tkm instead of distance travelled. Thus, the uncertainty in truck capacity for these routes had little influence on the results. However, this could be important for future research when the distance is used for the calculation.

Based on this sensitivity analysis, there are some insights into improving the system. In the LCC results, the revenue depends on the amount of waste in the collection, sorting, and recycling. In other words, increasing the waste generation could increase the revenue from both collection fees and sales of recyclable materials. Since the waste in this case study refers to the waste from recycling bins, it is desirable to increase the waste generation. However, it would be undesirable if the waste included general waste for incineration.

Another promising aspect to improve is the input composition. This refers to increasing the quality of the waste in the recycling bins which can be done by increasing awareness and education on waste sustainability. With a cleaner recyclable waste in the recycling bins, a larger revenue can be produced from the sales of sorted and recycled materials.

The process loss rates can be reduced by improving process efficiency. This could lead to increasing the overall profitability of the facility. The efficiency could be significantly increased by using better automation technologies. Moreover, the technologies could also improve the throughput and thus the range of target materials can potentially be expanded.

### Stochastic modelling

A natural next step after deterministic modelling is to apply randomness into the model. Particularly because waste management system has many uncertainties which could be addressed by using stochastic modelling. Each parameter in Table 5.7 was converted into a probability distribution function. Due to data limitation, it was assumed that all parameters follow the normal distribution as the most common probability distribution function (Wolfram Mathworld n.d.). The average values for the normal distribution were taken from Table 5.7, but the standard deviations were difficult to determine. As a result, the stochastic modelling was used to investigate the effect of parameter randomness to the modelling results.

Similar to the sensitivity analysis, each parameter was modified with a normal distribution function while the other parameters remain deterministic. The parameter with the normal distribution obtained new values each day and the standard deviations were assumed to be 30% of the average value. This was selected as a large, but still reasonable standard deviation value. This means that there is a 95% probability that the value is within ± 60% from the average value. The model was then run for 50 replications and the percentage standard deviation were measured as shown in Table 5.10.

The results in Table 5.10 showed some of the trends from the sensitivity analysis in Table 5.8 and 5.9. However, the effect on output values was much lower than expected for the first four parameters. This is potentially because large data were generated

**Table 5.10** The standard deviation in terms of percentage of output results when the input parameter follows a normal distribution with standard deviation of 30%.

| | | **Input parameter no*** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| *Material data of sorting facility* | | | | | | | | |
| Incoming waste | | 0.09% | 0% | 0% | 0% | 0% | 0% | 0% |
| Sorted PET | | 0.09% | 1.56% | 0.58% | 0% | 0% | 0% | 0% |
| Sorted PP | | 0.09% | 1.70% | 0.56% | 0% | 0% | 0% | 0% |
| Residuals | | 0.09% | 1.30% | 1.46% | 0% | 0% | 0% | 0% |
| *Material data of recycling facility* | | | | | | | | |
| PET Pellets | | 0.28% | 1.60% | 0.58% | 0.96% | 0% | 0% | 0% |
| PP Pellets | | 0.09% | 1.70% | 0.56% | 0.76% | 0% | 0% | 0% |
| Residuals | | 0.17% | 1.25% | 0.39% | 1.72% | 0% | 0% | 0% |
| *Logistics data* | | | | | | | | |
| Waste collection | distance | 0.11% | 0% | 0% | 0% | 12.04% | 0% | 0% |
| | tkm | 0.19% | 0% | 0% | 0% | 11.02% | 0% | 0% |
| Sorter to recycler | distance | 0.18% | 1.25% | 0.46% | 0% | 0% | 34.58% | 0% |
| | tkm | 0.09% | 1.24% | 0.39% | 0% | 0% | 0% | 0% |
| Sorter to incinerator | distance | 0.10% | 1.30% | 1.46% | 0% | 0% | 0% | 39.87% |
| | tkm | 0.09% | 1.30% | 1.46% | 0% | 0% | 0% | 0% |
| Recycler to incinerator | distance | 0.16% | 1.27% | 0.44% | 1.73% | 0% | 0% | 39.82% |
| | tkm | 0.17% | 1.25% | 0.39% | 1.72% | 0% | 0% | 0% |

*The numbering is based on Table 5.7, namely 1. Waste generation, 2. Input composition, 3. Sorting loss rate, 4. Recycling loss rate, 5. Truck capacity for waste collection, 6. Truck capacity for recycled plastic, and 7. Truck capacity for residual waste.

throughout the simulation, e.g. 15,318 recycling bins generated waste daily for one year period. By summing up all the values, the result converged towards the average value and thus yielded a small percentage in the output standard deviation. This reaffirms the sensitivity analysis results that the accuracy of the average value is very important for this model.

For the truck capacity parameters (number 5 to 7), the randomness has a more significant effect. First is because these parameters had a large influence on the results as shown in the sensitivity analysis in Table 5.9. Second is possibly because a smaller set of data were generated such as a few trips per day. Since the LCA and LCC results were calculated by using the tkm, the results would be unaffected by the randomness of the truck capacity for recycled plastic and residual waste.

### 5.1.6 Conclusion

Distributed recycling has some potential to reduce the transportation of materials and making recycling closer to the consumers. However, limited studies were conducted in the quantitative aspect of distributed recycling. The Waste Network Model developed in this research allows experimentation into distributed recycling systems. Thus, the model could address the research gap in distributed recycling (additional to the research gaps in Section 2.4).

There were 5 scenarios created for this case study to compare some configurations of centralised and distributed systems. Most of the data in this case study came from publicly available information, such as addresses of recycling bins and national statistics. When the data was unavailable, reasonable assumptions and estimates were made based on resources, such as literature and interviews.

The model runs for one year period and the results were material and logistics data. Since the changes in the process were minimal between centralised and distributed scenarios, the material output data were similar. As expected, distributed scenarios have the potential to significantly lower the transportation tkm by more than 50%. However, using smaller trucks in distributed scenarios increases the environmental impact to a larger value than the centralised scenarios. Furthermore, the environmental impact from transportation was small compared to the recycling process due to the high electricity usage of extruders.

The profitability of distributed scenarios was smaller than the centralised scenarios due to the high operational costs. The largest cost was found to be labour because the sorting process heavily relied on manual sorting. Hence, it could be promising for distributed systems to employ automated sorting technology. This could also increase the revenue since more waste could be sorted and subsequently recycled.

The uncertainties of the model were analysed by using sensitivity analysis and stochastic modelling. Most of the output, especially the material data, was linearly correlated with the input parameters because the process was simplified due to the high simulation time frame. The waste generation and input composition parameter showed a large effect on the simulation results and thus the accuracy of these parameters is crucial. In the stochastic modelling, the parameters were assumed to follow a normal distribution. However, the data for standard deviation of all parameters were unavailable and thus the modelling was used to investigate the significance of adding randomness to each parameter. When analysing a one-year simulation period, most of the output results converged to the average values despite the large standard deviation of the input parameters. From the uncertainty analysis, the deterministic modelling could be valid when it comes to comparison between scenarios. However, the numerical results should be used with caution because there are some uncertainties regarding the data which can have a large effect on the results.

This case study provided an excellent opportunity to test the model in experimenting with new systems. The results of this experiment show that distributed systems must be carefully designed in order to perform better in terms of environmental and economic aspects. An important analysis which needs to be conducted is to determine the appropriate number of facilities for the system. Since labour was a significant cost, the relationship between number of facilities and workers would also be important. Hence, this analysis was explored in the next case study.

## 5.2 New Waste Management Infrastructure in Indonesia

Indonesia is one of the biggest sources of ocean plastic due to the large coastal area and a high proportion of mismanaged waste (Jambeck et al. 2015). In addition to ocean plastic, the mismanagement of waste and open dump landfills can cause serious health problems such as respiratory illnesses, skin irritation, and gastrointestinal diseases (De and Debnath 2016, Etea et al. 2021, Singh et al. 2021). The issue arises from the lack of proper waste management system in small cities and rural areas. As a result, 76% of the mismanaged waste that leaks to the environment originates from small cities and rural areas (NPAP 2020). To tackle this problem, SYSTEMIQ (2017) launched project STOP (Stop Ocean Plastic) to build low-cost and scalable waste management systems in Indonesia.

This case study is a collaboration with SYSTEMIQ in developing a new waste management infrastructure in Indonesia. There are four levels of administrative divisions in Indonesia, namely provinces, regencies, districts, and villages. The current trial facility serves at a district level which consists of around 10 to 15 villages. SYSTEMIQ has a target to scale up the facilities to a regency level which could serve more than a million people. In this collaboration, SYSTEMIQ provides data and expert opinions from their trial facilities. The data and experience were utilised into the Waste Network Model to design and assess various what-if scenarios.

### 5.2.1 Scenarios

The system boundary for this case study is shown in Figure 5.19. At the collection points, the waste is separated into organic and inorganic waste. In the sorting facilities, the organic waste is converted into compost while the inorganic waste is sorted into recyclable materials. The compost and recyclables are then sold to local recyclers.

Since the main focus of this system is waste collection and the data for local recyclers were unavailable, the local recyclers were considered as the market. The residual waste from the sorting facilities is sent to a locally managed landfill.

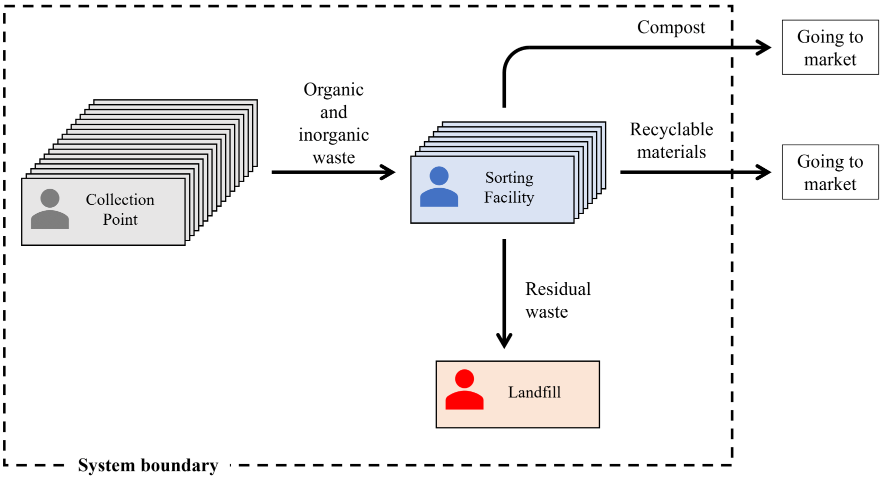


**Figure 5.19** The system boundary for Indonesia case study.

In this case study, two groups of scenarios are evaluated. The first scenario group covers the current operations by SYSTEMIQ in three cities, namely Pasuruan, Jembrana, and Muncar district (Project STOP n.d.). The purposes of modelling these operations are to adjust the model with the available input data and measure the output accuracy against the current operations.

The second group includes what-if scenarios of future systems which cover the waste from a larger population than the current operations. The scenarios in this group focus on a regency in Indonesia which encompasses more than 600,000 households across more than 200 villages. There are three analyses conducted in this regency, namely A. Scale analysis, B. Network transfer stations, and C. Automated sorting process.

Analysis A was done by varying the number of facilities to serve the whole regency from 1 to 26 facilities. Each facility operates both the logistics and manual sorting process. The system was measured based on the economic performance of the entire system which would indicate the appropriate scale and number of facilities for the regency.

Analysis B investigates the use of network transfer stations. In this analysis, the logistics and manual sorting process of the facility are separated. Hence, the system could be designed to achieve a desirable logistics configuration with a suitable processing scale.

In analysis C, the manual sorting is replaced with automated sorting technologies. This has the potential to reduce labour costs and improve materials recovery rate and revenue. Due to a substantial capital investment for automated process, different shift schedules are explored to maximise equipment utilisation. Analysis C1 explores the facility with a single shift, C2 double shifts, and C3 the facility runs for 24/7. Network transfer stations are implemented in this analysis to enable desirable logistics arrangements.

### 5.2.2 Case study specific submodel updates

There are some updates in this case study for both the process and logistics submodels. In the process submodel as shown in Figure 5.20, the materials processed by the sorting facility agents are organic and inorganic waste. The organic waste is converted into compost while the inorganic waste is sorted into recyclable materials. The details of the processing steps are discussed further in the chapter.

In terms of the logistics submodel, the only output material that require logistics in the model is the residual waste. This is because the compost and recyclable materials are considered sold to market. Hence, the logistics for residual waste is similar to the logistics in Singapore case study in Figure 5.5. The only difference is the time for the shift to end which is 4.30pm, 30 minutes before the end of the shift at 5.00pm.

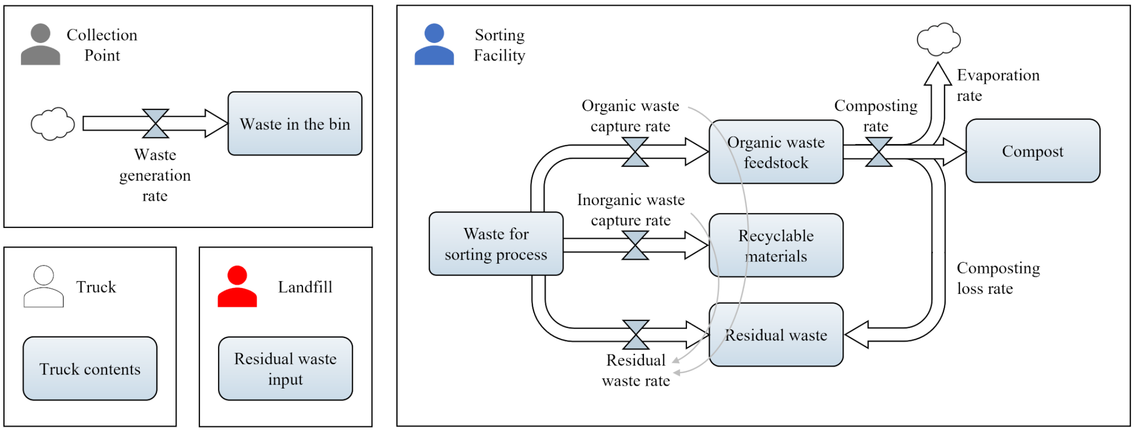


**Figure 5.20** The process submodel is updated based on the processed materials.

A major change in the logistics submodel is the route planning part. This is largely driven by the available data. Since the locations of individual households were unavailable, the households within a village are clustered together in the location of the respective village office. The average number of households per village is around 3,000, but the number can range from 700 to 10,000.

With this assumption, there are three parts of the route. The first part is the journey from the facility to a village office, the second part is waste collection from a certain number of households, and the third part is the return journey back to the facility. The schematic of this route is shown in Figure 5.21. By assuming that the time is the limiting factor for waste collection and one worker can only cover one route, the total work shift time ($t_s$) can be expressed as:

$$t_s = t_r + n \times t_l + (n - 1) \times t_h + t_u$$

where $t_r$ is the time for return trip between the facility and the village office, $n$ the number of households per route, $t_l$ the time required for loading the household waste to the collection vehicle, $t_h$ the travel time between household, and $t_u$ is the unloading time at the facility after the vehicle returns from the route. This also assumed that the vehicle would be able to take all the waste from the route.

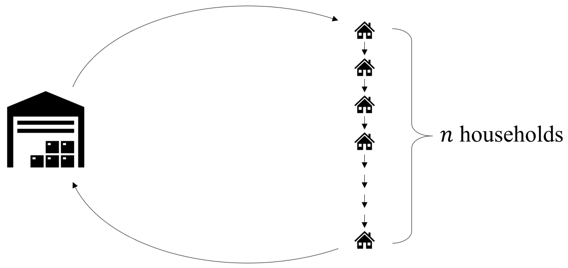


**Figure 5.21** The schematic of the route for collecting $n$ number of households.

In this case study, work shift time $t_s$ was assumed to be 7 hours. The return trip time $t_r$ was obtained by dividing the return trip distance with an average travelling speed of 20 kmph. The loading time at each household $t_l$ was assumed to be 0.8 minutes which was tested to yield reasonable results. The travel time between household $t_h$ was calculated from the average distance between household which can be estimated by using the household density (household per km$^2$). Finally, the unloading time at facility $t_u$ was assumed to be 15 minutes.

To calculate $t_h$, an assumption was made that the households are equally distributed throughout the area and located at the centre of a square. For example, if a village has 4 households per km$^2$, then the household are arranged as shown in Figure 5.22. Hence, the distance between household can be obtained from the square root of the inverse of household density, $\sqrt{1/4} = 0.5$ km. The average speed between household was assumed to be 10 kmph, slower than the travelling speed from the facility to take into account a poorer road infrastructure. Finally, $t_h$ can be estimated by dividing the distance with the average speed.

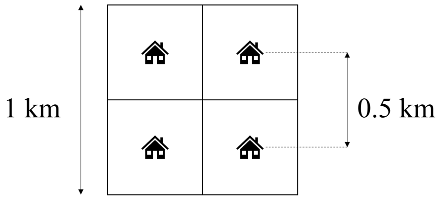


**Figure 5.22** The assumption on the household density to calculate the average distance between household. In this example, the household density is 4 households per km$^2$ and the average distance between household is 0.5 km.

Hence, the maximum number of households per route can be obtained as:

$$n = \frac{t_s - t_r + t_h - t_u}{t_l + t_h}$$

As a result, the required number of routes for each village can be obtained by dividing the total number of households in a village with $n$. The number of routes is rounded up by using a ceiling function and can be used to estimate the waste collection vehicles for the system.

### 5.2.3 Data input

#### Collection points

In the current operations, the collection point data were obtained based on the available information of the district. SYSTEMIQ covers in total of five districts as shown in Table 5.11, namely Lekok and Nguling in Pasuruan (Project STOP 2020), Negara and Jembrana in Bali (Project STOP 2019), and Muncar in Banyuwangi (Project STOP 2018). The information on population and household for all villages within the relevant districts was obtained from Indonesian Government Statistics Agency (BPS 2019*a*,*b*, 2020*a*,*b*,*c*).

As mentioned previously, the households within a village are clustered together in the location of the village office because the individual household data were unavailable. The locations of all village offices were obtained from Google Maps and converted into latitudes and longitudes with Google Geocoding.

The waste generation and composition data for each district were provided by SYSTEMIQ. The waste amount per district ranges between 17 and 40 tonnes per day with a composition of organic waste around 70 - 80%. The waste of each village was

**Table 5.11** Collection points data of the current operations in five districts.

| Regency, Province | No | District | Total household | Household per village | Household density (household/km$^2$) |
|---|---|---|---|---|---|
| Pasuruan, East Java | 1 | Lekok | 19,599 in 11 villages | 799 - 3,150 | 194 - 1,406 |
| | 2 | Nguling | 16,393 in 15 villages | 360 - 2,053 | 121 - 1,513 |
| Jembrana, Bali | 3 | Negara | 28,851 in 12 villages | 1,441 - 4,037 | 45 - 986 |
| | 4 | Jembrana | 18,700 in 10 villages | 560 - 3,322 | 59 - 1,088 |
| Banyuwangi, East Java | 5 | Muncar | 48,668 in 10 villages | 2,210 - 10,734 | 147 - 992 |

assumed to be proportional to the population. Then, the waste was distributed equally among the households within the village.

For the what-if scenarios, a waste management system was designed to serve a regency of more than 20 districts which covers 200+ villages and 600,000+ households. The information on this regency is hidden for confidentiality purposes. The data for the what-if scenarios were organised similar to the current operations. The household data for all villages in the regency were compiled from Indonesian Government Statistics Agency.

The waste generation was assumed to be around 850 tonnes per day. The composition was obtained from waste characterisation studies in multiple districts by SYSTEMIQ. Around 75% of the waste is organic and 22% was made of paper, cardboard, and various types of plastics, and the other 3% was other waste including metals.

### Sorting facility

The data input for sorting facility can be categorised as location, logistics, and process. The logistics data consists of the number and types of vehicles, fuel consumption, residual waste destination, and waste collection route. The process data includes the number of workers, processing equipment, and material recovery rate. The worker salary used in this study is GBP 1,080 per year.

In the current operations, all the data required for the model were provided by SYSTEMIQ except for the waste collection route. This is because of the lack of data on the collection points. Hence, the collection routes were estimated by using the method outlined in section 5.2.2. With that, the vehicle required for waste collection could also be estimated and compared against the operational data. The vehicle used for waste collection was a tricycle with a compartment as shown in Figure 5.23.

**Figure 5.23** The vehicle used for waste collection.

There are two sources of revenue, namely collection fees from the households and sales of compost and recyclables. For the collection fees, it can be assumed that each household was charged IDR 15,000 (GBP 0.75) per month and only 60% of the households were willing to pay the fee. Since this fee was collected manually, the collectors were given 10% commission. Despite of the suboptimal payment rate, this fee was the largest revenue stream for the operations.

The organic waste is converted into compost which generates additional income. However, there is a significant loss during the process. In this case study, it can be assumed that 25% of the organic waste were removed from the source for home composting. From the collected organic waste, 50% was considered as residual waste. During the composting process another 50% of the weight was lost due to water evaporation and other decomposition process. Finally, the compost was sold locally at around IDR 250 per kg (GBP 0.0125).

The inorganic waste can contribute a considerable revenue. It was assumed that waste pickers took some of the recyclables from the bins. For high value materials (plastic bottles, cardboards, and aluminium cans), the waste pickers were assumed to remove 60%. For the other recyclable materials, the waste pickers were assumed to remove 15%. After the waste is collected, 10% of the materials was assumed to be residual waste. Then, the recyclable materials have a recovery rate of 70% when using manual sorting. The material price data were provided by SYSTEMIQ and thus applied accordingly. The sales of compost and recyclables were assumed to be immediate whenever the material was available. The costs of sales were assumed to be 10% for packaging and other expenses.

For the what-if scenarios, the facility locations were estimated by using the approximation method in section 4.3. In this way, the facilities are distributed evenly throughout the region. The number of facilities ranges from 1 to 26 but only some configurations are shown in Figure 5.24 for illustration purposes.

The number of manual sorters was estimated by using the data from SYSTEMIQ. The data on number of sorters vs facility throughput can be fitted with both linear and logarithmic line as shown in Figure 5.25a. From both functions, the number of sorters in the system (when using between 1 to 26 sorting facilities) can be estimated in Figure 5.25b. Since the process involves manual sorting, the linear function might be more suitable in describing the improved labour efficiency due to the economy of scale. This is because the logarithmic function shows a significant improvement which

**Figure 5.24** Showing the locations of facilities for the what-if scenarios. For illustration purposes, only 6 out of 26 configurations are shown. These 6 configurations are the system with number of facilities of: 1, 5, 10, 15, 20, and 25.

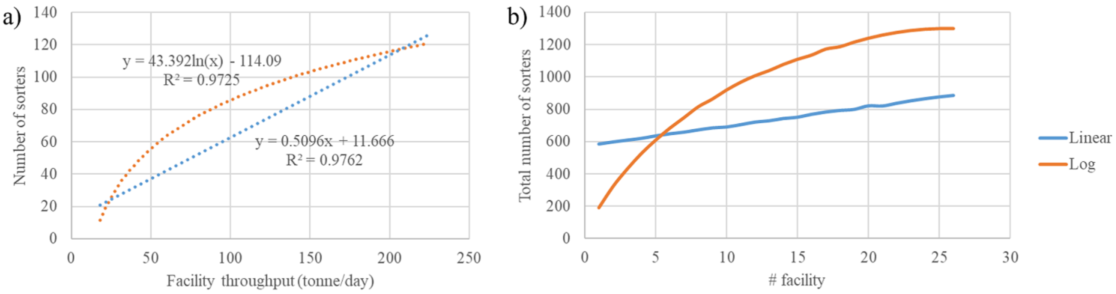


**Figure 5.25** a) The linear and logarithmic line between number of sorters and facility throughput. b) The total number of sorters in the system from 1 to 26 facilities.

would be difficult to achieve without scaling up the machineries. Due to the small data samples, there is a large degree of uncertainty of these functions.

For network transfer stations, additional trucks would be necessary to transfer the waste to the centralised sorting facilities. The truck has a capacity of $15m^3$ with a price of around GBP 18,200 (Blibli n.d.). It was assumed that the truck can carry either 5.85 tonnes of organic waste or 2.93 tonnes of inorganic waste. The truck would require one driver and one attendant. This type of truck is also used to transport residual waste from the sorting facilities to a locally managed landfill. For residual waste, the maximum load of the truck was assumed to be 4.68 tonnes. It was assumed that each truck can do two trips per day.

For the automated sorting process, the process flow was designed as shown in Figure 5.26. The necessary data for the automated process were gathered and summarised in Table 5.12. The throughput of these system was assumed to be 10 tonnes per hour which requires 20 workers and the maintenance costs per year were 5% of the capital costs (WRAP 2009). The electricity price was set as IDR 1,444.70 (GBP 0.072) and diesel price IDR 9,4000 (GBP 0.47). By using automated system, the recovery rate was assumed to be 90%.

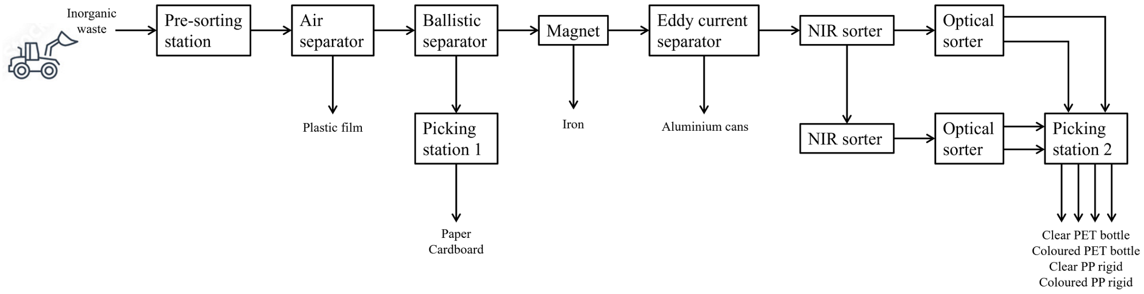


**Figure 5.26** The process flow for automated sorting process.

**Table 5.12** Summary of equipment for automated sorting process. The prices from 2009 were adjusted to 2021 by +50% and assuming 1 USD = 0.73 GBP.

| Equipment | Amount | Unit price (GBP) | Resource usage per unit | Source |
|---|---|---|---|---|
| *Machineries* | | | *Electricity (kW)* | |
| Conveyor and feeder system | 1 | 225,000 | 20 | WRAP (2009) |
| Air separator | 1 | 73,000 | 66 | Alibaba (n.d.*f*) |
| Ballistic separator | 1 | 90,000 | 7.5 | WRAP (2009) |
| Overband magnet | 1 | 2,920 | 3 | Alibaba (n.d.*c*) |
| Eddy current separator | 1 | 13,870 | 15 | Alibaba (n.d.*d*) |
| NIR sorter | 2 | 150,000 | 15.5 | WRAP (2009) |
| Optical sorter | 2 | 150,000 | 15.5 | WRAP (2009) |
| Baler | 4 | 17,520 | 11.74 | Alibaba (n.d.*e*) |
| Picking station | 3 | 15,000 | - | WRAP (2009) |
| *Vehicles* | | | *Diesel (L/h)* | |
| Feeder truck | 1 | 8,760 | 23 | Alibaba (n.d.*a*) |
| Forklift | 2 | 5,840 | 13 | Alibaba (n.d.*b*) |

### 5.2.4 Results and discussion

#### Current operations

The simulation of the current operations was valuable in the data preparation. Furthermore, the results of the simulation can be cross-checked with the operational data.

The route and vehicle were estimated by using the method described in Section 5.2.2. In order to calculate the routes, $t_r$ (the time for return trip between the facility and village office) can be estimated from the return trip distance. This was achieved by using the road infrastructures in geographical information system (GIS) which is a feature in AnyLogic software. The calculation of routes in Lekok district is shown in Table 5.13. By assuming that the average speed of 20 kmph, the distance can be converted into $t_r$. The maximum number of households for each route was calculated and subsequently the number of routes for each village.

The total number of routes can be used to estimate the number of vehicles required. An assumption was that all collection points are collected twice a week and one vehicle can take only one route per day. Thus, in Lekok district from Table 5.13, the number of vehicles can be estimated as 61 total collection routes $\times$ 2 collection per week $\div$ 6 working days per week $\approx$ 21 vehicles. The same calculation was applied to other districts in Table 5.11.

The accuracy of this estimation can be measured against the data provided by SYSTEMIQ. The comparison with the data is summarised in Table 5.14. Starting with the estimation value, the operational data can be obtained within the deviation percentages. Hence, the suitable number of vehicles on average is within 14% deviation from the estimation. The method however was compared against a limited sample size.

A large part of the inaccuracy comes from clustering the households in the location of the village office. On average, each village office consists of 3,000 households. This

**Table 5.13** The calculation for number of routes of each village in Lekok district. The return trip distance was calculated between the facility to each village office. $t_r$ is the return trip time.

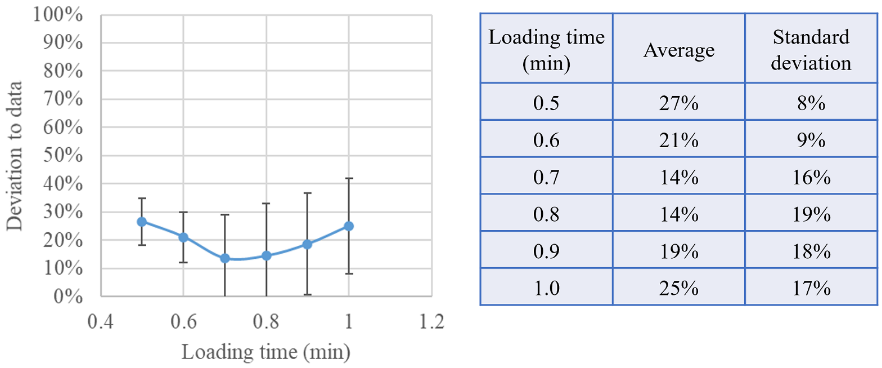
| No | Village name | Return trip distance (km) | $t_r$ (minutes) | Max household per route | Total household | Number of routes |
|---|---|---|---|---|---|---|
| 1 | Rowogempol | 6.78 | 20.33 | 376 | 2,338 | 7 |
| 2 | Gejugjati | 10.64 | 31.91 | 345 | 1,655 | 5 |
| 3 | Alastlogo | 11.30 | 33.90 | 311 | 1,268 | 5 |
| 4 | Balunganyar | 3.52 | 10.57 | 357 | 1,929 | 6 |
| 5 | Branang | 4.98 | 14.95 | 387 | 1,300 | 4 |
| 6 | Tampung | 3.34 | 10.02 | 376 | 1,059 | 3 |
| 7 | Tambaklekok | 4.46 | 13.38 | 333 | 1,525 | 5 |
| 8 | Jatirejo | 4.64 | 13.92 | 408 | 3,150 | 8 |
| 9 | Pasinan | 3.85 | 11.56 | 347 | 2,613 | 8 |
| 10 | Wates | 8.03 | 24.09 | 327 | 1,963 | 7 |
| 11 | Semedusari | 15.74 | 47.23 | 292 | 799 | 3 |

was done because of the data limitations on household locations. It would be possible to refine the data by reducing the household per cluster and distribute the cluster across the village area. However, this data refining process would require a significant amount of time without much contribution to the model development. Due to the time constraint of this research, the data can be refined as a future research agenda.

In the vehicle estimation method in Section 5.2.2, one of the variables is $t_l$, the time required for loading the household waste to the collection vehicle. The appropriate loading time was tested from 0.5 to 1.0 minute as shown in Figure 5.27. The $t_l$ value of 0.7 and 0.8 min yields the smallest average error of 14%. However, 0.8 min was selected as the value for the case study since it is more reasonable based on the real operations in the field.

**Table 5.14** The comparison between estimated vehicle with operational data. Measuring the accuracy of the estimated value.

| District | Estimated vehicles | Deviation to the data |
|---|---|---|
| Lekok | 21 | ± 5% |
| Nguling | 19 | ± 42% |
| Negara and Jembrana | 57 | ± 9% |
| Muncar | 49 | ± 2% |
| Average | | 14% |
| Standard deviation | | 19% |



| Loading time (min) | Average | Standard deviation |
|---|---|---|
| 0.5 | 27% | 8% |
| 0.6 | 21% | 9% |
| 0.7 | 14% | 16% |
| 0.8 | 14% | 19% |
| 0.9 | 19% | 18% |
| 1.0 | 25% | 17% |

**Figure 5.27** The average error of vehicle estimation in relation to the loading time $t_l$. The loading time $t_l$ for 0.7 and 0.8 min shows the lowest average error. Based on the real operations, 0.8 min is more reasonable.

The result from the simulation generates logistics data, in particular distance travelled for waste collection. This can be converted into fuel consumption and subsequently fuel costs. The information regarding fuel efficiency of the vehicle was found to be unreliable (25 km/L of fuel) and thus the fuel efficiency was estimated with a similar method as Figure 5.27. The fuel efficiency was varied from 10 to 25 km/L and lowest average error came from 15 km/L consumption. At 15 km/L, the average error was 27% while the standard deviation was 32%. As mentioned earlier, the large percentage error was likely to be generated from the assumption on household clustering at the village office. This will need to be addressed in future research.

### What-if scenarios

The waste collection route and the number of vehicles were estimated by using the same calculation method as in Section 5.2.2. Similarly, all collection points were assumed to be collected twice a week. The calculations were repeated for each facility configurations, from 1 to 26 sorting facilities. From the calculation, the number of vehicles can be estimated as shown in Figure 5.28a. By varying the number of facilities, the only variable that changes is the average distance between facilities and the village offices. When the system has more than 5 facilities, the average distance decreases gradually, on average by 4%. Hence, this trend was reflected on the number of vehicles in Figure 5.28a.

The number of waste collection drivers can be assumed to be the same as the vehicles which has an average uncertainty of 14%. Additionally, coordinators were required to manage a certain number of drivers. The number of residual truck drivers were estimated by using the amount of residual waste and number of trips required. Thus, the total number of employees for the logistics in the system is shown in Figure 5.28b.

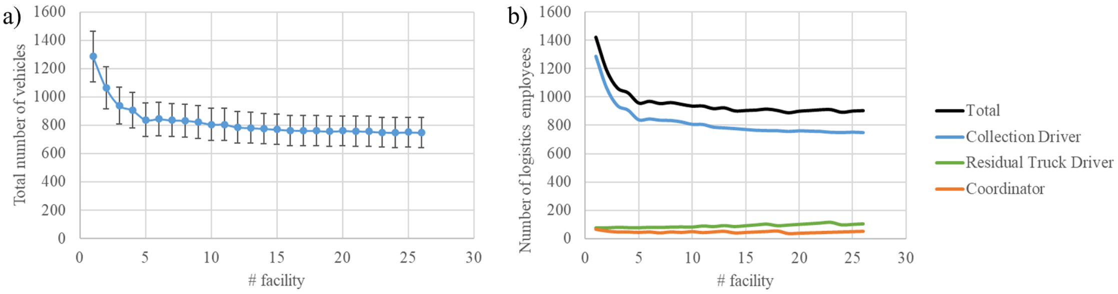


**Figure 5.28** The total number of a) vehicles and b) logistics employees in the system from 1 to 26 facilities.

For analysis A (scale analysis), the operational costs of the system are shown in Figure 5.29. The labour costs for sorting and logistics were obtained from Figure 5.25b and 5.28b, respectively. The number of sorters was estimated by using the linear function since it is more appropriate when scaling up a labour-intensive system. The

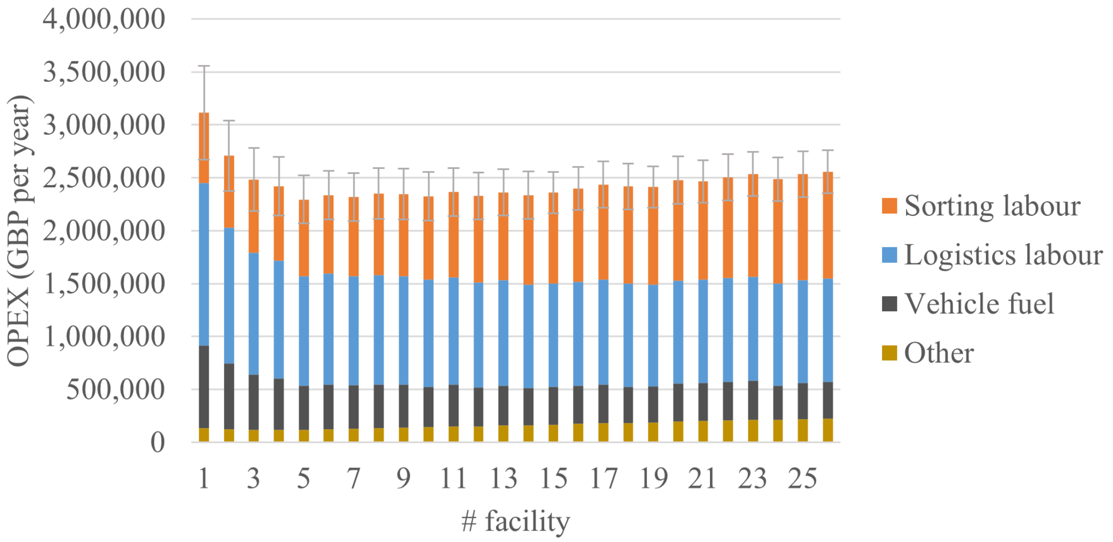


**Figure 5.29** The operational costs of the system when using various facility numbers. If the OPEX when using 5 facilities is considered as 100%, almost all configurations are within +10%. The system with 1 and 2 facilities are higher by 36% and 18%, respectively. Other costs include management team and vehicle maintenance.

fuel costs were obtained from simulating the waste collection process and sending residual waste into a landfill. Based on the Singapore case study, electricity costs are minor when using a manual sorting process and thus neglected in the calculation.

In terms of logistics labour and fuel costs, the system leans towards a greater number of facilities because the average distance to the collection points and fuel consumption are reduced. On the contrary, the sorting process is more inclined towards fewer facilities due to the economy of scale. In total, the least OPEX can be achieved by using 5 facilities to serve the whole regency. However, nearly all other configurations are higher by 1 - 10%.

The uncertainties in the vehicle estimation and fuel consumption were included in Figure 5.29. These numbers were assumed to follow a normal distribution curve. The standard deviation however follows another normal distribution curve with an average and standard deviation value from comparison with operational data, i.e. 14% and 19% for vehicle estimation and 27% and 32% for fuel consumption. By using Monte

Carlo Simulation, the model was run for 1000 iterations and the percentage standard deviation of the OPEX was 8 - 14%. By comparing the uncertainties, the system would have a similar OPEX when using between 3 to 26 facilities.

As mentioned earlier, two sources of revenue came from the collection fees from the households and sales of compost and recyclables. These revenue sources are dependent on the number of households and the amount of waste collected. Therefore, the revenue of the system remained constant regardless of the number of facilities. The total revenue was more than GBP 5.9 million per year which yields 62% profit margin when using 5 facilities. The collection fees accounted for 52% of the revenue while the sales of composts 8% and recyclables 40%. When considering OPEX uncertainty, the profit margin ranged between 58 to 65%. With such a large profit margin, the payback period for the collection vehicles was less than a year. The high profit margin could be resulted from low worker salary and good prices for the recyclables.

The uncertainties in material prices were investigated. Based on price data from SYSTEMIQ, the average prices and standard deviations of various materials were obtained. The material prices were assumed to follow a normal distribution curve and the price changed every month. After 1000 iterations, the percentage standard deviation was found to be only 3%. Hence, this uncertainty only affects the profit margin by around 2%. There are however other unquantifiable uncertainties which could affect the profitability such as missed fee payments, unsold materials, and human errors.

In analysis B (network transfer stations), there are two types of facility, namely sorting facility and network transfer station. The logistics of waste collection were done at both sorting facilities and transfer stations. However, only the sorting facilities that do the sorting process and transport residual waste to landfill. In addition, the sorting facilities managed the trucks to collect the waste from network transfer stations.

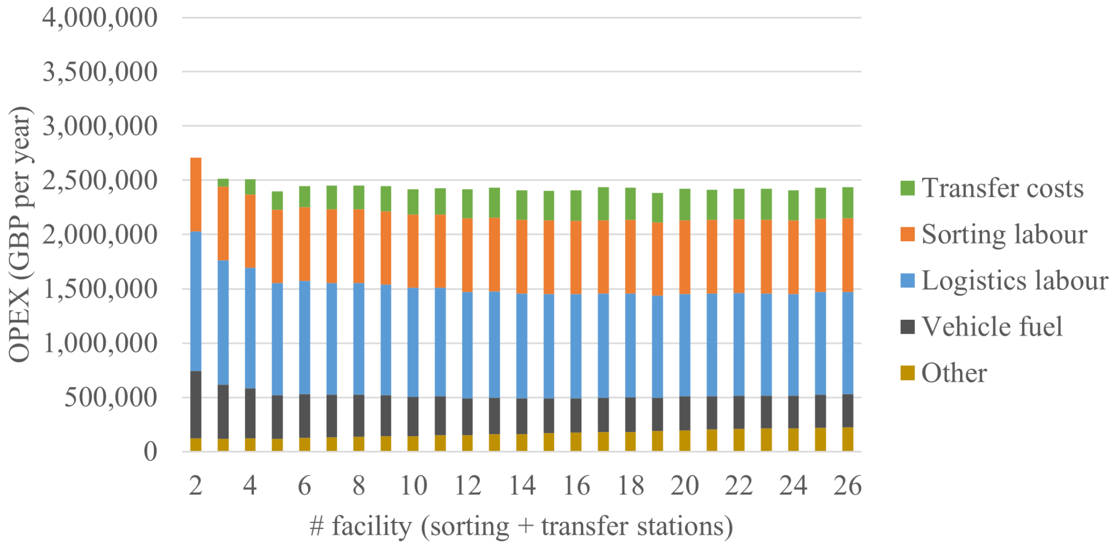


**Figure 5.30** The operational costs of the system when using 2 sorting facilities and various numbers of network transfer stations (from 0 to 24). Transfer costs include the costs of drivers and fuel from network transfer stations to the sorting facility. Other costs include management team and vehicle maintenance.

The number of sorting facilities was analysed between 1, 2, and 3. It was found the OPEX of nearly all configurations are +1 to +6% from the lowest OPEX which can be achieved when using 2 sorting facilities. To determine the locations of the 2 sorting facilities, all facilities were clustered into two groups. The sorting facilities are then the closest facility to the centre of each cluster.

The OPEX of using 2 sorting facilities and various network transfer stations (from 0 to 24) are shown in Figure 5.30. The logistics labour and fuel costs were the similar to analysis A since the waste collection logistics were the same. The sorting labour also used the sorting labour of 2 facilities from analysis A. In this analysis however, there is an additional cost to transport the waste from transfer stations to the sorting facilities. This cost was estimated from the required number of trucks and drivers and the fuel for all the trips.

The lowest OPEX was attained when using 19 facilities (2 sorting facilities and 17 network transfer stations). However, there was barely any cost difference, only between 1 to 6% higher in other configurations in Figure 5.30. The transfer costs were noticeable that the overall OPEX is 4% higher than the lowest OPEX in analysis A. Despite of that, there are potentially some social benefits of using network transfer stations, such as better hygiene and odour control and reducing worker fatigue. Due to the high profit margin, the additional investment for the trucks can be paid back in less than four months.

In analysis C, the manual sorting was replaced with automated sorting technologies. Three scenarios on the shift schedules were investigated, namely C1 single shift, C2 double shifts, and C3 24/7 operations. With a throughput of 10 tonnes per hour, the number of sorting facilities for C1, C2, and C3 were 3, 2, and 1, respectively. The logistics were carried out by using network transfer stations to allow a more centralised process. From analysis B, total number of facilities with the lowest OPEX was 19. Hence, the number of transfer stations for C1, C2, and C3 were 16, 17, and 18, respectively.

The OPEX and CAPEX for all the analysis are shown in Figure 5.31, this includes the lowest OPEX from analysis A and B. When using automated sorting technologies, there are additional operational costs such as electricity, fuel, and maintenance. However, due to the large reduction in sorting labour, the overall OPEX were still lower, between 2 - 5% from analysis A and 6 - 8% from analysis B. This benefit can be more significant when the worker salary is high. For instance, if the current salary was doubled to GBP 2,160 per year, the overall OPEX saving could reach 20%.

Between the different shifts (C1, C2, and C3), the operational costs varied slightly, but the significant difference lies in the CAPEX of the facilities. Since only 1 facility was required in C3, the capital cost was lower compared to C1 and C2 but still higher than using manual sorting in A and B which used conveyor systems. The CAPEX excluded land and building costs because it would require a significant data gathering from many different geographical regions. Due to the limited time for this research, the land and building cost analysis could be conducted in future research.

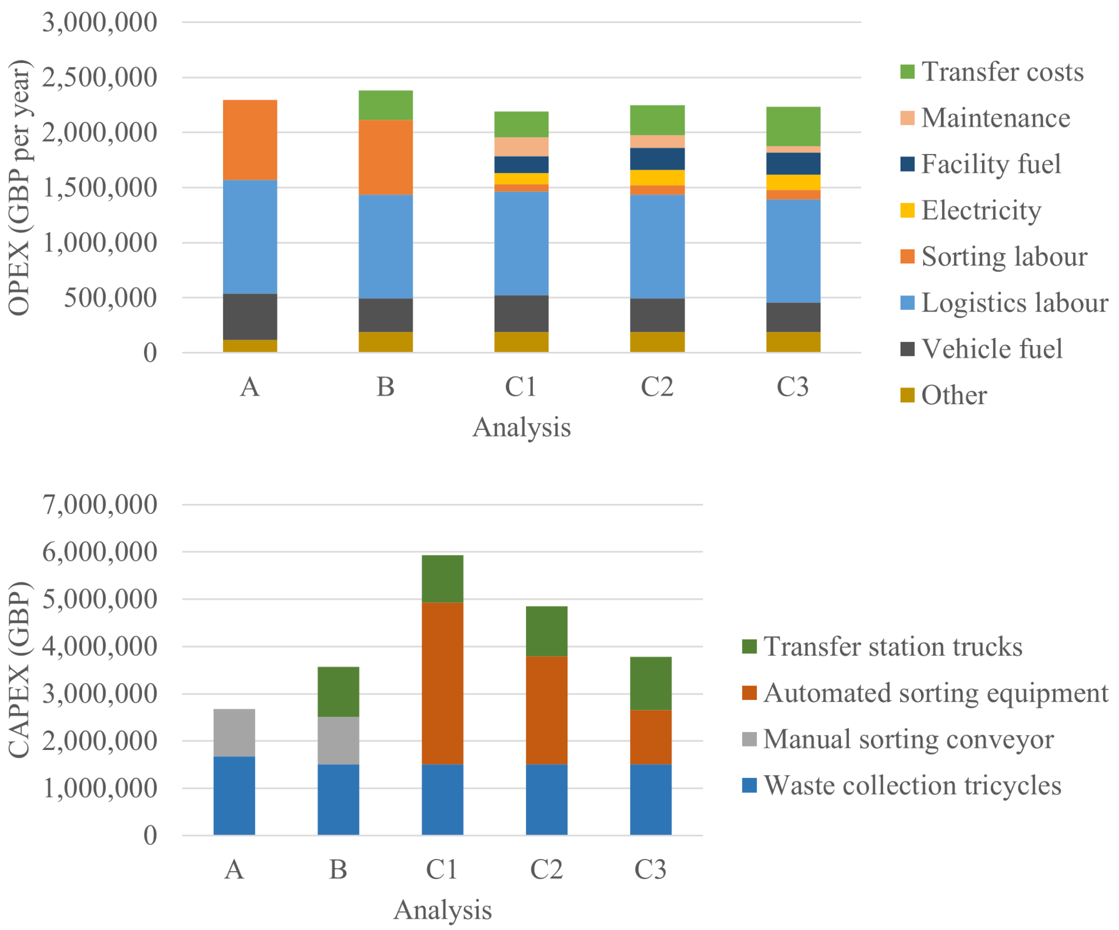


**Figure 5.31** The operational (top) and capital costs (bottom) of the system analysed in this study. The capital costs exclude land and building. Analysis A: manual sorting with 5 facilities, B: 2 manual sorting facilties and 17 network transfer stations, C: automated sorting facilities with transfer stations (C1 = single shift, C2 = double shift, C3 = 24/7).

Due to the increase of materials recovery rate, there is an 11% increase in revenue. From both cost reduction and additional revenue, the profit margin can be increased by 4%. Due to the high profit margin, the payback period for the automated equipment and vehicles was less than a year in C3 and more than a year in C1 and C2. This made it more attractive to invest in automated sorting process.

As apparent in Figure 5.31, the manual sorting system in analysis A had the lowest CAPEX. This would be the easiest to set up and could be good in the short term, especially in Indonesia where the salary is low. However, the profitability of the automated sorting system in analysis C is better than the manual system due to the large reduction of labour and better materials recovery. By having less reliance on labour, the process can have a higher throughput, consistency and safety. Furthermore, an increase of materials recovery is more sustainable since it reduces the amount of waste to landfill. Hence, the system in analysis C is preferable in the long term.

### Limitations and future research

In the current research, some limitations were dealt with reasonable assumptions due to time constraint. Hence, the limitations could be addressed in future research.

The first limitation was related to the data input, especially for collection points. In this research, a large number of collection points were clustered in one location. As a result, a large uncertainty was generated in terms of time and distance travelled. This limitation could be addressed by further refining the collection point data. Potentially, the cluster size could be reduced to a much smaller number and the locations of the clusters can be uniformly distributed across the area. The collection points were also assumed to be one type whereas in the real operation, the urban and rural areas should be distinguished. Some of the differences between urban and rural areas could be in terms of different waste amount, compositions, average speed between households, etc.

The limited data on collection points contributed to a limitation in the vehicle estimation method. The estimation was done based on a large cluster of households in addition to some route planning assumptions. When using smaller clusters with better locations, the route planning and vehicle estimation could be done more accurately.

In terms of manual labour, the estimation was done by using a limited data size. However, it can be challenging to obtain a decent sample size because this would require interviewing a substantial number of companies. This limitation can be considered minor when using automated sorting technologies since the use of manual labour was minimal.

There are a few areas that could be explored in the future. The first area is composting technology. Due to the large amount of organic waste, it would be necessary to consider utilising better technologies. Some potential advantages include better compost price, higher throughput, fewer wastage, and better compost quality which improves soil health. Additionally, the use of anaerobic digestion should be evaluated to generate more revenue.

The second area is the recycling technology for inorganic material. An in-house recycling could be worth considering especially for the inorganic material with a large volume. While the technology would require additional investment, the potential revenue from this recycling process should be investigated, especially for simple processes such as shredding and cleaning.

Finally, the land and building costs should be examined. Due to the time constraint, this analysis was excluded from the CAPEX despite being a substantial investment cost. The calculation for land and building should be relatively straightforward, but the data gathering would take a considerable amount of time. This analysis would be essential to assess the viability of the system.

### 5.2.5 Conclusion

The waste management infrastructure in Indonesia should be improved to reduce mismanagement of waste. This problem is prevalent especially in small cities and rural areas. Hence, this case study was conducted in collaboration with SYSTEMIQ to improve waste management in Indonesia.

In this case study, the current operations were used to adapt the model with the available data and measure model accuracy with the existing operational data. After that, several what-if scenarios were conducted to investigate various waste management systems to cover a regency of more than 600,000 households. The first analysis was assessing the scale of facilities. Subsequently, network transfer stations were introduced into the system. Finally, automated sorting process was used to replace the manual sorting process.

A route planning method was developed for this case study to estimate the route and vehicles required for the system. This method was predominantly driven by the available collection points data. Since the data were limited, the households within a village were assumed to be clustered at the village office location. It would be possible to refine the data, but it would require a significant amount of time which could be done in future research.

The operational costs of various waste management systems with different facilities were estimated. The largest cost came from the labour from the waste collection and sorting process. When a system uses more facilities, the average distance to the waste sources was reduced and thus the logistics costs. However, more workers were needed for the sorting process.

By using network transfer stations, the distance to the waste sources can be reduced while the sorting process can be done at centralised facilities. Some cost savings could be achieved when the manual sorting was replaced with the automated sorting process. Despite additional electricity, fuel, and maintenance costs, there is an overall costs reduction due to the substantial labour reduction. In addition, the higher recovery rate of automated process could increase the revenue from the sales of recyclables. The use of automation system would require a higher capital investment for the equipment. However, considering the high profit margin and low payback period, it would be worth to consider using automated sorting process.

The data, particularly for collection points, should be refined further in order to improve the accuracy of the model. Furthermore, composting technology and anaerobic digestion would be necessary due to the high volume of organic waste. In terms of recycling inorganic waste, it would be better to use recycling technology, but further analysis is essential.

This case study demonstrates the model capability to experiment with new waste management systems. The results offered some insights into the performance of various waste management systems. The model provided an additional dimension to the feasibility studies and contributes to the recommendations. Therefore, the model can support the decision-making process and improvement of the waste management infrastructures.

# Chapter 6

# Discussion

This chapter begins with comparing the two case studies in Chapter 5. The research findings are then derived from this comparison. In the second section, the Waste Network Model developed in this research is analysed against the criteria defined in Chapter 2. Finally, the third section revisits and answers the research questions in Section 1.2.

## 6.1 Cross Case Studies Analysis and Findings

This section compares the two case studies in Chapter 5. The first and second case studies are referred to as Singapore and Indonesia case study, respectively. The comparison between these case studies covers the overview, scenarios, modelling updates, data input, and finally results and discussion.

The motivation for the Singapore case study is to investigate the potential benefits of distributed systems. On the other hand, the Indonesia case study was conducted to explore new waste systems for a new region. Although the motivations were different, the underlying idea was the same whereby hypothetical systems were evaluated.

The approach for both case study was different because the case studies were conducted at different stages of model development. The Singapore case study was carried out while the model was being developed. Thus, the first case study had a limited number of scenarios and focused on exploring the model capabilities, parameters, transportation aspect of distributed systems. The Indonesia case study was conducted after the model was finished. As a result, the aim of the case study was to apply the model for deeper insights into the system. Furthermore, the learning from the Singapore case study was utilised for the Indonesia case study. For instance, since labour was found to be a major operational cost, more emphasis was placed on the relationship between distributed systems and labour. Some parts of the model were also upgraded to improve modelling efficiency.

Both case studies have a similar system boundary which involves waste sources and sorting facilities. The Singapore case study took into account the recycling facilities, but the recycling facilities in the Indonesia case study were considered as the market. The business-as-usual case in the Singapore case study was used as a performance benchmark because the what-if scenarios were within the same area. In Indonesia case study, the current operations were used to measure the model accuracy because the what-if scenarios were in a different region.

In terms of the modelling updates for the case study, Indonesia case study had a large update in the route planning logic. This large update was largely driven by the available collection point data. A significant time would be required to refine the data and due to time constraint, the collection points were clustered at a village level (on average 3,000 households per cluster). On the contrary, the addresses of public recycling bins in Singapore were publicly available. Hence, the submodels in Singapore case study had only a minor update.

Different waste types were considered in the case studies. In the Singapore case study, the waste only comes from the recycling bins. Hence, despite a significantly larger population, the amount of waste in the system was smaller. In the Indonesia case study however, all waste streams were considered and thus having a higher waste volume. Despite of having a smaller population, the case study in Indonesia covered a much larger area, more than 8 times of Singapore land area.

Based on the model development and case study results, the research findings are:

- The model provides more insight into the logistics than the process of the system. This is partly because the logistics was more complex and unpredictable since more decisions were involved, especially the waste collection. Another reason is because the time frame of the simulation was one year. This time frame is suitable for system planning, design, and the weekly collection schedule, but potentially too large for dynamics of the process. The more appropriate time frame for the processes would be either daily or weekly. Thus, the processes were simplified as converting input into output for this research.
- Labour is the most significant operational cost. As apparent in both case studies, labour represents a large part of the OPEX since the waste collection requires a large number of drivers. Surprisingly, fuel cost was minor relative to the labour cost even though waste collection heavily requires transportation. The labour cost was even more substantial when the sorting was done by using manual labourers. This is despite of the much smaller salary in Indonesia (≈ GBP 1,080 per year) than Singapore (≈ GBP 10,000 per year). A large labour reduction can be achieved by using automated sorting equipment. This can be translated to a significant cost saving, especially when worker salary is high. Although a larger capital investment would be necessary, the equipment could considerably increase the process throughput, recovery rate, consistency, and worker health and safety.
- The economic performance of centralised systems was more favourable than distributed systems. This was because the economy of scale in centralised systems outweighed the benefits in logistics of distributed systems. Furthermore,

the logistics can be improved by using network transfer stations. However, this was obtained based on the system where the output was sold to the market. In order to favour distributed systems, the system would require more local aspects such as, local raw materials, labour, and demand. Despite of that, the scale and revenue of the system must be large enough to be profitable. More system analysis and other performance metrics would be necessary in order to uncover the favourable conditions for distributed systems. The model developed in this research can assist in this investigation but would require additional improvements.

- Data limitation is a prevalent issue in modelling. This issue is even more common in this study because it involves designing new systems. In a more developed countries like Singapore, some of the data are publicly available. Despite of that, some data would need to be filled with reasonable estimates and assumptions. Thus, it is imperative to have industrial experts to provide data and insights into the model while simultaneously validating the model and results.

## 6.2 Modelling Criteria Evaluation

The objective of this study is to support waste and recycling infrastructures by developing a model that can assist in experimentation of new systems. Thus, the ideal model would have a set of characteristics as discussed in Section 2.3. The characteristics are multiscale modelling, uncertainty analysis, flexibility, and validation.

As described in Chapter 4, the model has an agent-based architecture which consists of three submodels, namely process, logistics, and communication. Hence, the model can represent both operations and supply chain and can be considered as a multiscale model. However, due to the time frame of the simulation, more emphasis was given on the complexity of the supply chain. Since the model is multiscale, the process and communication submodel can be improved to incorporate more sophisticated mechanisms without affecting the logistics submodel.

For both case studies in Chapter 5, uncertainty analysis was conducted. The stochastic modelling was done by substituting variables as normal distribution functions and using Monte Carlo Simulation for multiple iterations. The sensitivity analysis was performed in the first case study to investigate the effect of output results with the input parameters.

In terms of flexibility, the model was designed with a general model (agent-based architecture) and submodels (process, logistics, and communication). The general model remained constant for both case studies, but the submodels were updated accordingly. The first case study required a minimal update whereas the second case study required a major update due to the differences in the data availability. Despite the significant update, other parts of the model were unaffected by the change. This demonstrates the flexibility of the model when changes are required to simulate various new scenarios of different systems. Furthermore, the model can be improved to simulate more complex behaviours without a major disruption.

For model validation, expert validation was utilised in two key areas of the research, namely model framework and case study results. The model framework was validated by gathering feedback from a few academics in the field of operations research. When publishing the first case study (Kerdlap et al. 2021*a*), the model framework received a major revision based on the feedback from the reviewers. As a result, the framework was changed from a DES-like framework to an agent-based architecture.

Regarding the case studies, local experts in Singapore and Indonesia were involved through multiple interviews. At the beginning of the case study, the experts provided valuable data and insights into the current systems and local conditions. The data were then used for the model to generate the results. Multiple rounds of interviews were conducted to gather feedback on model calculations and ensure that the results are reasonable.

In addition to expert validation, there were some sanity checks to ensure the results are within an acceptable range. For instance, manually estimating the mass of facility output and transportation distance and compare them with the results. Moreover, the GIS map during the simulation was used to ensure that the trucks arrive at the correct destinations and schedules.

Based on this assessment, the Waste Network Model developed in this research fulfilled the criteria of an ideal model defined in Section 2.3. There are some areas that could be improved such as better analysis on the operations, engaging more experts for validation, and testing model accuracy with more known systems. Despite of that, the model can be utilised to achieve the objective of this research.

## 6.3 Answers to Research Questions

As described in Section 1.2, there are two research questions proposed in this research.

**Research question 1:** *How to develop a model which can simulate new waste management and recycling systems?*

This question is answered in three parts. The first part is defining the characteristics of an ideal model. This was achieved from the literature review in Chapter 2, namely multiscale modelling, uncertainty analysis, flexibility, and validation. These criteria can act as guidelines for future models that can enable experimentations of new systems. The second part is the dataflow framework in Chapter 3 which provides an overall dataflow structure when developing a model.

The third part is the model development framework in Chapter 4. As shown in Figure 6.1, the framework consists of an agent-based architecture with three submodels

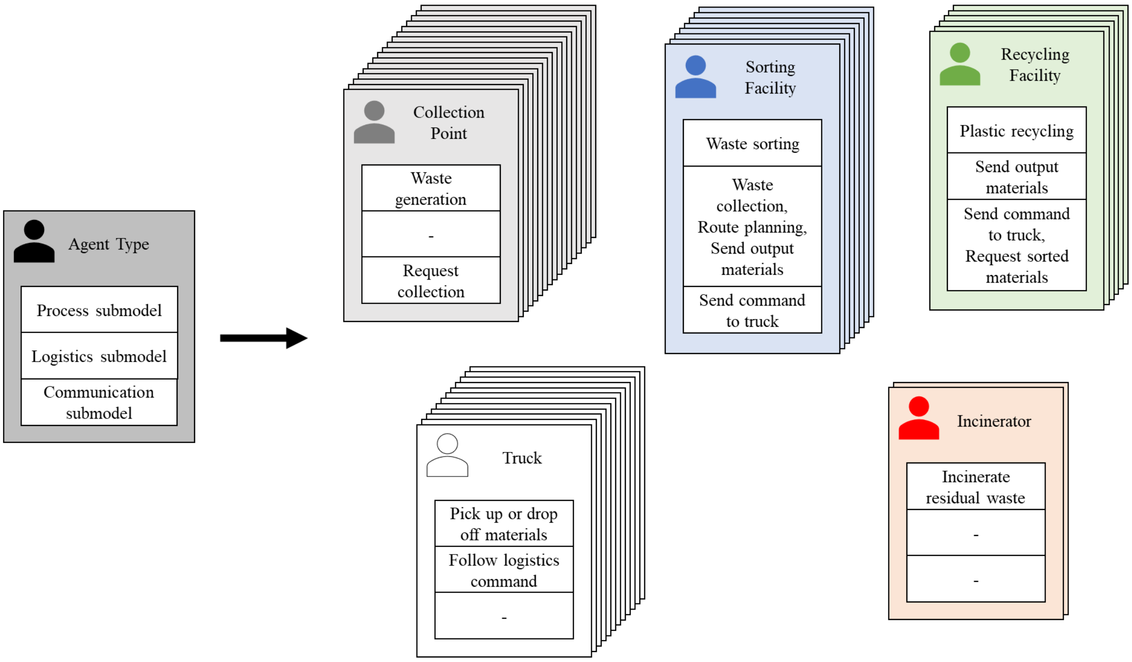


**Figure 6.1** The agent-based architecture developed in this research, taken from Figure 4.1.

for each agent type. The model is developed by using hybrid simulation modelling method. Hence, the process, logistics, and communication submodels were modelled by using system dynamics, discrete-event simulation, and agent based modelling, respectively. In a typical waste management system, there are 5 agent types namely collection point, sorting facility, recycling facility, incinerator, and truck.

There are two purposes of the submodels. The first one is to provide the accuracy and details of the agent's behaviours when modelling case studies. The second is to contribute flexibility and thus any part of the submodel can be updated without affecting other parts of the model. Overall, the agent-based architecture developed in this research provides a new approach of using hybrid simulation modelling.

The model capabilities were demonstrated in Chapter 5 where the two case studies were located in different countries. In each case study, multiple what-if scenarios were simulated to generate insights to compare centralised and distributed systems. Additionally, the model and results are validated with the experts.

**Research question 2:** *What are the important factors to be considered for the development of recycling infrastructures?*

Based on the case studies, the research question can be answered in terms of economic and environmental aspects. For the economic performance, the most important cost is labour for both logistics and facility process. In terms of labour, a more centralised system requires fewer labour for processing the materials. On the other hand, a more distributed system reduces the labour and fuel costs for material logistics. Thus, one important consideration between centralised and distributed systems is the labour reduction of the whole system.

A promising path is to significantly reduce the labour cost is process automation. This can produce a net savings despite increasing the costs for other resources such as electricity and fuel. The net savings can be substantial in countries with a high worker salary. Other than labour, the operational costs to consider are fuel, electricity, land rental, and residual treatment costs.

The revenue of the system comes mainly from waste collection fee and sales of recyclable materials. The former is relatively certain, but the latter requires more effort to maximise. Process automation not only reduces the operational costs, but also increases the revenue via better throughput and recovery rate.

In terms of the environmental aspect, particularly global warming potential, the main sources are electricity usage, waste incineration, fuel consumption, and landfill gas. Therefore, an overall reduction in any of the main sources would be desirable for the environment. This could be achieved through better technology, such as a more resource efficient machineries and vehicles.

The economic and environmental aspects of the system is critical when developing new recycling infrastructures. In addition, the trade-off between various decisions should be carefully investigated. The model developed in this research could support in the analysis and thus contribute to the overall decision-making process.

# Chapter 7

# Conclusion

This final chapter concludes this research. The first section provides the summary of the research. This is followed by the second section which presents the research contributions. The final section discusses some limitations and potential future research directions.

## 7.1 Research Summary

This research begins with identifying the problems in Chapter 1. Due to many years of using the linear economy, the amount of waste generated is becoming a huge problem. Hence, a shift towards the circular economy could mitigate some of the challenges.

This research is focusing on recycling since it has the potential to convert a large amount of waste into valuable resources. However, there is a lack of recycling infrastructures in many developed countries and thus some material recycling relies on waste export. As more countries are beginning to refuse waste from other countries, the need for recycling infrastructures is becoming more urgent.

Therefore, this research aims to support the development of waste management and recycling infrastructures. This is achieved by developing a model to experiment with new systems. Thus, contributing to a more robust system planning. The model utilises simulation modelling due to the flexibility to model various systems in real time. The research questions are then formulated to develop and utilise this model.

A set of literature reviews in Chapter 2 were conducted to support this research. The first literature review was performed to provide a background knowledge on typical waste management systems and the available technologies. The second review explores the suitable simulation modelling method for the research. The hybrid simulation modelling was found to be the most suitable due to the accuracy and flexibility from the method. Finally, the third review assessed the existing simulation modelling research beyond the waste management context. The third review yields a set of modelling criteria which is important in developing a model that can enable experimentation of new systems. The criteria were multiscale modelling, uncertainty analysis, flexibility, and validation. From the literature reviews, there is a lack of a model that can evaluate new systems, especially in the waste management context.

The methodology of this research is described in Chapter 3. The dataflow framework is built as an overview of the dataflow around the model. There are three main steps in the framework. First is input data processing which is mostly done manually due to the large variability of available data. Second is modelling the system with the Waste Network Model which I had developed in this research. The third step is output data processing which yields simulation results, measures system performance, and generates insights to the system.

The development of the Waste Network Model is discussed in Chapter 4. The model was developed by using an agent-based architecture because of the numerous entities in the system. In the agent-based architecture, there are five agent types in the system, namely collection point, sorting facility, recycling facility, incinerator, and truck. Each agent has three submodels which are the process, logistics, and communication. The process submodel takes into account the material processing, the logistics submodel considers the transport of materials, while the communication submodel involves the interactions between agents. These submodels however require data from a case study.

Since the model requires facility locations especially for new systems, an approximation method was developed to determine facility locations. The idea behind this method is to distribute the facilities uniformly across the region. The facility location approximation method is based on a heuristic approach which consists of 3 parts, namely making the initial guess, matching with the closest facility, and equalising daily waste input.

The Waste Network Model was applied to two case studies in Chapter 5. The first case study analysed the waste management systems in Singapore to compare the performance of centralised and distributed systems. Prior to the case study, a literature review was conducted on distributed manufacturing and recycling to assess the advantages, disadvantages, and research gaps in the topic. It was found that there is a lack of a quantitative model that evaluate distributed systems.

A total of 5 scenarios were examined, namely two centralised, one semi-distributed, and two distributed scenarios. The differences between the scenarios lie in the different configurations of sorting and recycling facilities. The model had some minor updates in the process and logistics submodels based on the case study. In terms of data, some were publicly available while some other were estimated by using reasonable assumptions.

As expected, the distributed scenarios provide some benefits in terms of transport reduction. However, because small trucks were used in the distributed systems, the environmental impact was worse than the centralised scenarios. This is because the small trucks consume more fuel than the larger trucks in the centralised system. Hence, the fuel efficiency of the truck needs to be carefully considered.

In terms of the net present value after seven years, the centralised scenarios performed slightly better than the distributed scenarios. This is because of the better profitability in the centralised scenarios. The main reason is because more workers were required in the distributed scenarios which significantly increases the labour cost. It was found that the transport fuel cost was relatively minor compared to the labour cost.

The effect of input parameters was investigated with sensitivity analysis. The waste generation and composition parameter were found to be significant to the modelling results. Thus, the accuracy of both parameters is crucial. Due to data limitations, the stochastic modelling was used to analyse the effect of randomness from each parameter. The randomness produces only a little effect on the output results. This confirms the sensitivity analysis whereby the accuracy of the average values is necessary.

Some of the learning from this case study was used for the next case study. In particular, the need to assess the labour requirement and the appropriate number of facilities.

The second case study investigated new waste management infrastructures in Indonesia. This is important because a large portion of the waste from rural areas in Indonesia is mismanaged. As a result, the waste leaks to the environment and cause a range of problems. Hence, this case study aims to support the development of new infrastructures as a solution to reduce the mismanagement of waste.

There are two groups of scenarios analysed. The first group is the current operations of the industrial partner. This is important to adapt the model for the case study and also measure the model accuracy against real operational data. The second group investigates the what-if scenarios for the new infrastructures. There are 3 analyses in this scenario group. The first is the appropriate scale and number of facilities. The second is the use of network transfer stations in the system. Finally, the third is replacing the manual sorting process with the automated sorting process.

Due to the data limitations on the collection points, a new route planning method was developed. An assumption was made that the households are clustered at the location of the village office (on average, 3,000 households per cluster). By assuming that time is the limiting factor, the number of households per route can be determined. This in turn can be used to estimate the number of vehicles and drivers required by the facility.

Most of the data were obtained from the existing operations of the industrial partner. Some data can also be used to measure the accuracy of the route planning and vehicle estimation method. Based on this assessment, the method provides reasonable estimations for this case study.

By simulating the what-if scenarios, the operational costs of different facility numbers can be obtained. This confirms the results from the first case study where the process favours a more centralised system due to the economy of scale. However, the logistics in terms of distance travelled leans towards a distributed system. By using network transfer stations, a more centralised process can be utilised while providing sufficient coverage for the logistics. However, there was a slight increase in cost when using transfer stations.

A significant benefit can be achieved by replacing the manual sorting with an automated sorting process. This significantly reduces the requirement for manual labour and increases the material recovery rate. The network transfer stations enable a more favourable logistics configuration while using the automation technologies.

The two case studies in this research demonstrate the applicability of the model to simulate different countries and experiment with new systems. Some of the findings from these case studies are summarised in Chapter 6. The 1-year simulation time frame was suitable for system design and the logistics but was too large for the dynamics of the process. The labour is the most significant cost due to the requirement for drivers and sorters. Automated sorting equipment is a promising avenue to significantly reduce the labour requirement and recover more recyclable materials. The process is more suitable in a centralised system while the logistics is better with a distributed system. The balance between these dynamics can be analysed by using the model developed in this research.

The Waste Network Model was evaluated against the modelling criteria from Chapter 2. Since the model can simulate process and logistics simultaneously, the model is considered as multiscale. The uncertainty analysis and flexibility of the model were demonstrated in the case studies. Some validation steps were taken such as engaging experts, publishing in a peer-reviewed journal, and other manual calculations as sanity checks. Therefore, the model fulfils the criteria defined in this research.

The research questions are answered by the frameworks and case studies in this research. The modelling criteria, dataflow framework, and model development framework can be used as guidelines for the development of future tools and models. The model capabilities are demonstrated by the two case studies in different geographic locations. The model developed in this research could generate insights which supports decision-making and system planning of waste management and recycling infrastructures. Thus, the work in this thesis answers the research questions.

## 7.2 Research Contributions

The contributions of this research can be summarised as follows:

- **The criteria and frameworks for evaluating new systems.** The first is the modelling criteria which were derived from literature review of existing simulation modelling research. The second is the dataflow framework which acts as the overall dataflow structure of the model. However, most data processing and result analysis would still need to be done manually. The dataflow framework leads to the third framework for model development. The model development framework demonstrates the use of an agent-based architecture and submodels. Hybrid simulation modelling was suitable since the submodels have the flexibility to use other simulation modelling methods. The criteria and frameworks from this research can then be used as guidelines when developing other models to support experimentation of new systems in the future. Furthermore, the model developed in this research is a unique way of using simulation modelling.

- **Insights for new waste management systems.** The case study analysis in this research provides insights for developing future waste management systems and models. Labour estimation is a critical factor in assessing the economic performance. Better electricity and fuel efficiency and higher recovery rate are desirable in the environmental aspect. The use of better technology could then improve the overall system performance. This research could therefore be beneficial for future industrial projects and academic research.

- **Quantitative analysis of distributed systems.** Most literature on distributed manufacturing assessed the system based on qualitative aspects. Hence, this research provides the much-needed quantitative analysis on this topic. Both case studies in this research analysed a wide range of distributed systems in two different countries. Overall, the economy of scale in the process opposes the better logistics configurations of distributed systems. More case studies would be needed to evaluate the more favourable conditions for distributed systems. Nevertheless, the model developed in this research could provide some contribution in this area.

- **Developing a model for new recycling infrastructures.** The model developed in this research can be used to analyse future recycling systems in various regions. The model can offer insights into the performance of the system to assist the decision-making process. As more case studies are conducted, the model would be constantly improved to capture all the necessary details of the system.

## 7.3 Limitations and Future Research

Although an extensive effort has been made to cover all the important aspects, there are some limitations and further investigations that can be addressed in the future to improve this research.

The first area is on data limitations. The model was developed to be flexible for various case studies. Because of that however, the model is heavily reliant on case studies and data. In most cases, the data can be difficult to obtain due to confidentiality reasons. Hence, assumptions and estimations are necessary to fill the unavailable data. By analysing more case studies in the future, the data and learning could be utilised to improve the model and data accuracy for the subsequent case studies. The data format in different systems can also vary significantly. As a result, the data processing step and model updates require a lot of manual input into the model. This depends heavily on the expertise of the developer and thus increases the importance of involving experts for their insights and validation.

The second area is the improvement in modelling logic and submodels. There are three submodels in the model, namely process, logistics, and communication. In this research however, the process submodel was simplified as a conversion process from input to output. This is largely because the 1-year simulation time frame was too large to show the dynamics of the process despite having multiple process steps. Thus, the process would require a different time frame analysis. For instance, 1-week time frame to analyse the process hour-by-hour. In terms of logistics submodel, there are some possible improvements such as better route planning and driver estimation logic. The estimation for workers was found to be important since the labour is a significant part of the costs. For both process and logistics submodels, other mechanisms could be implemented such as downtime due to breakdown or maintenance, workforce availability, and other uncertainties. The communication submodel could also give rise to some interesting dynamics such as sales of material, collaboration between entities, and measurement of social metrics. Those mechanisms need to be clearly defined in order to be implemented into the model. Additionally, the user interface to update the submodels could be implemented to increase the model usability.

The third area is the improvement in determining the facility locations. This is a large research area because determining facility locations is a fundamental decision for system design and planning. However, selecting the appropriate method for this research requires an extensive literature review. Due to time constraint, an approximation method was developed to distribute the facilities uniformly across a region of collection points. As demonstrated in the case studies, this method was sufficient in providing acceptable results and analysis. For the future, this method can either be improved or replaced with a better method from the large body of literature.

The fourth area is to conduct more case study analysis. This adds an additional validation to the model developed in this research for two reasons. First, the results demonstrate the model capabilities to experiment with new systems. Second, more experts would be engaged and thus further scrutinise the model. In addition to the model validation, more databases, results, insights, and learning would be generated which can be used improve the model for subsequent case studies. Other than environment and economic analysis, social and community aspects of the system should be explored.

While there is room for improvement, the work in this thesis provides a model to support the development of waste management and recycling infrastructures. The criteria and frameworks from this research can be used as guidelines for future model development. The case study analysis provided insights into various waste management systems and could be utilised as a reference to design better infrastructures. The work in this research can then contribute to a more robust design and planning process and potentially lead to more investment in waste management and recycling infrastructures.

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