Calculation model for energy and fuel consumption of waste transports in Sweden

Master's thesis in Supply Chain Management

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SUMMARY

Although the high-quality tools used for environmental impact measurement of transport are well developed and widely used nowadays, there are fewer academic studies which focus on waste transport. This thesis aims to develop a data collection and analysis model for energy and fuel use of waste transports in Swedish municipalities. The framework was inspired by the calculation process of the NTM model (The Network for Transport Measures), which mainly studied two parts. The first part introduced the input factors which impact the energy and fuel usage in waste transportation, while the second one analysed how each factor in the model quantitatively impacts the energy and fuel consumption. Based on the analysis, the calculation model was developed.

In order to analyse the different input parameters, a literature study was performed, where relevant information was extracted and compiled. In addition, one interview and two workshops were conducted with project managers in order to gain further knowledge about the subject. As for the model development, the Microsoft Excel and the Excel VBA are used for the theoretical framework visualisation. The testing of the model was conducted together with Chalmers Industriteknik using the data provided by municipalities in Sweden. Since the model development is still in the initial stage of the project, which means there are some improvements that should be done in further studies, some recommendations were provided at the end of the report.

Keywords: calculation model, energy and fuel consumption, sustainability, waste transportation, input parameters, standardized system

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1 Introduction

This chapter starts with a research background, which briefly described this thesis and the shortage of current research in waste logistics. Then the aim of the thesis is introduced, followed with three research questions which used to fulfill the aim. The next section is the scope of this thesis. As for the last section, the thesis framework is given which shows the overall structure of this master thesis.

1.1 Research background

Logistics service is an essential part of the supply chain which helps to deliver goods according to planned routes. However, many companies or organizations overemphasize the importance of forward logistics but pay less attention to reverse logistics (Cullinane et al., 2019), especially the waste logistics. Nowadays, waste logistics has already become a serious challenge towards sustainability in many large municipalities or regions (Bing et al., 2014; Monnot et al., 2014). Every second, there are more than 60 tons of household wastes generated globally, which means only 2 hours are needed to fill the world's largest container ship with household waste (The World Counts, 2020). The amount of waste is increasing every year, which is expected to double by 2030 (Cullinane et al., 2019). All of the household waste should be collected and sent to the recycling system. In Sweden, most household waste has been collected and put into the recycling system (Avfall Sverige, 2020).

Avfall Sverige, the Swedish waste management and recycling association, always works for preventing the waste generation and saving the earth's resources (Avfall Sverige, 2020). According to its yearly statistic, the overall goal of waste management is to *"develop more tools that will support the municipalities in their work to increase reuse and prevent waste"* (Avfall Sverige, 2020). In order to achieve this goal, a large amount of waste transports is generated, since all of the waste must be transported from the places that are generated to various facilities for reuse, recycling, incineration, and landfill. During waste transportation processes, there are many serious environmental impacts as well as health risks caused by greenhouse gases (GHG) emissions. According to the report 'Global EV Outlook 2020' (IEA, 2020), electric vehicles play a huge role in the reduction of local air pollution and to address climate change. However, only switching to electric vehicles is not enough to reduce the environmental impact, a comprehensive approach is needed to decarbonize transportation.

It is difficult to get an overview of waste transports in a municipality or region when they start to link waste transport to regional environmental goals. Not only because the regional waste plans refer in different ways to waste transports, which makes the calculation of energy usage more complex, but also missing tools to measure and follow up on waste transports across different municipalities or regions. Hence, it is not possible to compare the municipalities energy usage of waste transports by a standard tool right now.

In order to create a more sustainable environment for people living in Sweden, Chalmers Industriteknik, Gothenburg Region and City of Gothenburg build this project, financed by Avfall Sverige, in order to create a uniform and standardized data collection and analysis model for energy and fuel use of waste transports which will be used for calculating the environmental impacts in municipalities throughout Sweden.

The model should support municipalities when they calculate energy and fuel use of waste transports and make it possible to compare energy and fuel use between municipalities.

In addition, municipalities can get reference when purchasing transport vehicles based on the fuel consumption of each vehicle type.

1.2 Aim and research questions

The aim of the project is to develop a data collection and analysis model for energy and fuel use of waste transports in Swedish municipalities, in order to find out how to decrease the negative environmental impacts. The following three research questions were chosen to fulfill the purpose of the research:

1. *What input parameters impact the energy and fuel usage in waste transportation?*

In order to develop a data collection and analysis model for energy and fuel use of waste transports, it is firstly important to decide the input variables. Since some parameters will influence the energy and fuel use in waste transportation, for instance, the type of transport vehicles, the fuel type, the transport distance and so on. All those parameters will be regarded as inputs. In addition, some parameters are not related to the final result, but are also needed for further analysis, like the number of households, amount of waste, which are also needed.

2. *How does each factor in the model quantitatively impact the energy and fuel consumption?*

After determining all the impact factors, the quantitative relationship between each parameter as well as the energy and fuel consumption in waste transports needs to be calculated. In order to answer this question, not only related data need to be collected, but also the calculation formula should be analyzed.

3. *How can municipalities improve the sustainability in waste transports through the model?*

Through establishing this model, the quantitative relationship between current waste transport and environmental impact will be analyzed in a qualitative discussion, which can support the waste transport planning and improve the sustainability in waste transports.

1.3 Research scope

In order to achieve the research objective and establish the model within the limited time, a research scope is necessary to be set for this master thesis. This project focuses on the development of a structure and analysis model for Swedish municipalities to be able to collect data and metrics, analyze energy and fuel use and present data for decision-making, as well as testing and verification of the model by performing together with Swedish municipalities. Before this model is established, the current situation analysis needs to be done, which includes the data which Swedish municipalities collected for energy use of waste transports nowadays and how this is evaluated and used for decisions on objectives and measures. Moreover, obstacles and challenges for Swedish municipalities regarding the collection and analysis of data for waste transport's energy and fuel use should be identified. The current situation analysis will be investigated in this master thesis together with Chalmers Industriteknik.

After creating this model, the next step should be developing a guide that describes how municipalities should calculate and analyze energy and fuel use of waste transports, which includes the model instruction. The model will also be tested and verified in the Gothenburg region.

In addition, this project is to be carried out during a special period due to the COVID-19, which possibly had an impact on the way of data collection and the dissemination of the final result, and it is therefore a limitation. The project is held mainly online, which might affect the efficiency of the group work.

1.4 Thesis outline

The thesis outline briefly described the content of each chapter, which gives an overall understanding of the thesis for readers.

Chapter 2 Literature review: This chapter lists all academic theories and concepts which are used in this thesis, and also illustrates how those theories contribute to the calculation model.

Chapter 3 Methodology: This chapter presents the framework on how the calculation model is developed.

Chapter 4 Empirical Finding: This chapter describes the current waste transports situation in different municipalities in Sweden.

Chapter 5 Analysis: In this chapter the first two research questions are answered with the help of the literature review and the empirical findings.

Chapter 6 Discussion: This chapter tests and verifies the model, then discusses the practicability and the limitation of the research.

Chapter 7 Conclusion: This chapter gives a summary of the whole report, as well as gives further recommendations to municipality researchers and experts in related fields about how to improve the sustainability in waste transports.

2 Frame of reference

This chapter covers some academic theories that relate to waste transports and energy consumption models. In the first section, the process of waste collection is introduced, which can help to understand the large demands of waste transports. The next section discusses the importance of sustainability in transportation. The third section illustrated the current studies of energy consumption models in transports, from which, some impact factors of the model can be identified. As for the last section, the relationship between energy consumption and greenhouse gases emission is described in order to decide which can be the final output of the calculation model.

2.1 Waste collection and closed loop logistics

Many studies focus on forward supply chains and regard consumers as the last step, for example, many efforts have been put into developing logistics from multi-channels to omni-channels in the forward flow of goods (Mena, 2016). However, environmental concerns are increasing nowadays. How to collect and deal with huge amounts of wastes in efficient and effective ways is still a challenge (Jahre, 1995). There are many countries that have designed waste collection systems which start from end users, especially in north European countries (Bing et al., 2016). Companies may use multiple cycles to increase utilization of resources and reduce the waste and consumption. The value of the reverse supply chain is just like a shrinking pipeline which keeps decreasing with time delays and product downgrading (Blackburn et al., 2004), the main goal of those activities is to help companies to get a higher resource efficiency, higher value creation as well as a tighter financial relationship with their customers. Based on this principle, the first step of the waste hierarchy in Sweden is waste prevention, it also has the priority in other European countries. Then it moves to product reuse, material recycling, other recycling, such as energy recovery, and the final one is the landfill (Avfall Sverige, 2020). Just as the forward supply chain, the waste supply chain is also a complete system, which includes waste generation, collection, and disposal (2010).

2.1.1 Waste generation

As is stated, every second, there are more than 60 tons of household wastes generated globally, which means only 2 hours are needed to fill the largest container ship (The World Counts, 2020). The amount of waste is increasing every year, which is expected to double by 2030 (Cullinane et al., 2019). Population increases and human activities are the main factors to the environmental pollution as well as the waste generation (Karak et al., 2012).

Sustainability has become a widely discussed topic in the world nowadays and reducing the waste generation is an important goal for many countries. He et al. (2020) has shown the higher industrialized degree of countries, the higher ability of waste recycling. In some developed countries, like Sweden, 99% of household waste is recycled as nutrition or materials or recovered as energy (Avfall Sverige, 2020). In England, the total food waste generated in the retail supply chain from 10m tonnes in 2015 and 11.2m in 2007 to 9.5m tonnes in 2018 (The Guardian, 2021). However, the recycling rate of household waste in England only increased from 44.4% in 2015 to 45.1% in 2018. In Malaysia, 70% to 80% of the total generated waste are used in landfills, which are recyclable materials, and only 22% of the waste can be recycled (Moh & Abd Manaf, 2014). As for China, which is the second-largest waste generation country in the world, 55.9% of garbage collected ended up in landfills whereas 39.3% of the garbage was incinerated in 2017 (Han, 2019).

However, many previous studies also showed that there is an inverse U-shaped relationship between economic growth and environmental pollution, like waste gas and solid wastes (Tao et al., 2008).

For example, the Environmental Kuznets curve (EKC) shows the original inverse U-shaped relationship between environmental degradation and income per capita (Tao et al., 2008), see figure 2-1. Increased environmental degradation means serious environmental pollution, waste of resources and biodiversity reduction, all of which are pernicious and undesirable.

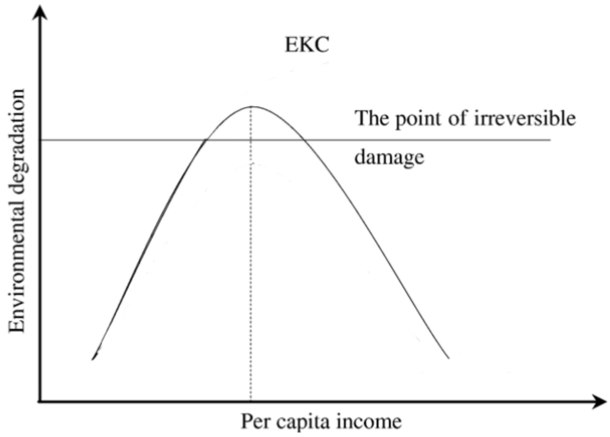

Figure 2-1 The relationship between environmental degradation and income (Tao et al., 2008)

There are many technical tools used for reducing environmental pollution, there are also more energy and resources needed (Gardiner & Hajek, 2020). In the EU, there are many technologies used to deal with the waste generation problem, but none of them are real zero impact technologies (Kuehr, 2007).

2.1.2 Waste collection

The waste collection process can be divided into two parts, one is waste transportation, which delivers waste to process places, and another one is waste sorting, which is an important precondition for efficient and effective waste disposal. Higher sustainability relies on less energy consumption of the waste collection process (Halldórsson et al., 2019).

According to the paper by Amarachukwu et al. (2020), "*Routing is one of the main components of solid waste management. Optimization of the collection route reduces travel distance and time which could reduce disposal cost*", which means the transportation distance and time should be counted into the energy consumption calculation of waste transportation. The main factor which will influence the collection route is the distribution of waste collection points. The report by Wekisa and Majale (2020) described and explained that waste collection points play a critical role in the waste management chain and that they also influence the urban quality of life.

As for the waste sorting, good waste sorting behaviors of residents are responsible for the environment, which is essential for further disposal (Wang et al., 2020). However, clear and reasonable waste sorting instructions are needed for accurate waste sorting. In China, there is a positive relationship between the efforts that local governments made and residents' sorting behavior (Wang & Hao, 2020). In the Nordic countries, the same waste symbols are used in order to reduce the confusion of waste sorting and treatment in different municipalities (Avfall Sverige, 2021).

2.1.3 Waste disposal

According to the waste hierarchy, there are different waste disposal ways at the end-of-use stage, from reusing, recycling to landfill (Halldórsson et al., 2019). The definition of the end-of-use stage of products is in the economical perspective, but there is still some value left if it can be treated as an intermediary, then it is in the first stage of recycling (Anderson & Brodin, 2005).

For example, the products can be repaired and reused, or some components and materials can be used in new products. The model of circle economy clearly illustrated different levels of waste disposal, see figure 2-2. There are six major reverse cycles displayed in this framework, including repair and maintenance, reuse and redistribution, refurbishment and remanufacturing, recycling, cascading, and repurposing, biochemical feedback extractions (Lüdeke-Freund, Gold & Bocken, 2019). This model of circle economy can also help to understand the waste hierarchy in Sweden.

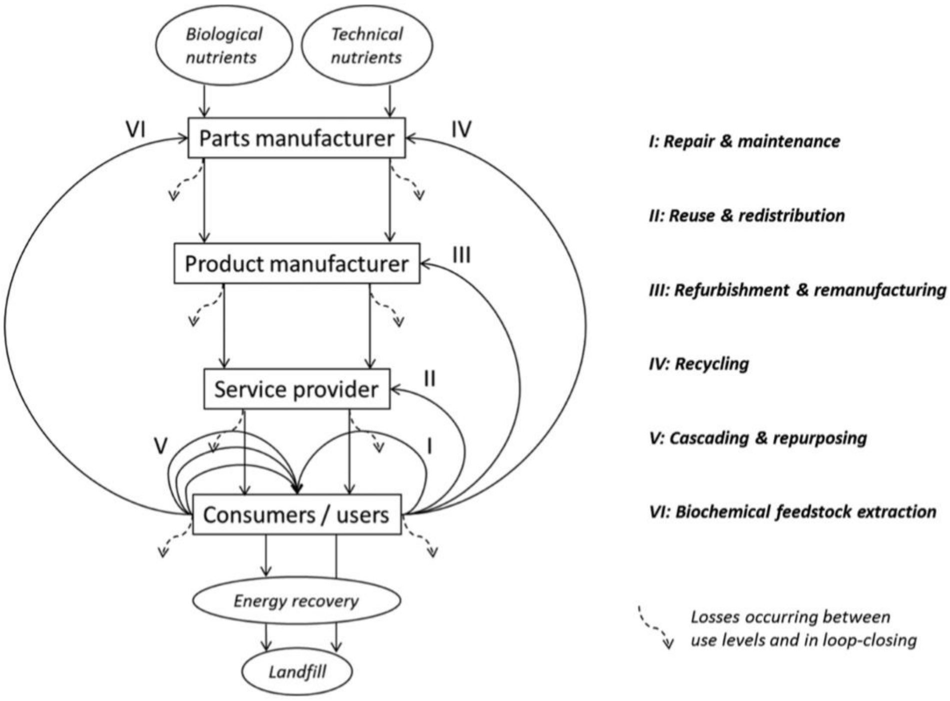

Figure 2-2 Major reverse cycles for the circular economy (Lüdeke - Freund, 2019)

In order to extend the lifetime of products, it is necessary to *repair and maintain* them during the using process (Bocken et al. 2016; Linton and Jayaraman 2005). This cycle asks for the cooperation among users, product companies and professional service providers (Lüdeke-Freund, 2019). If consumers can repair and maintain some products at home, the amount of waste can be reduced. If some people want to sell or discard old products, *reuse and redistribution* operations are needed for secondhand owners to use them again. Although functions of some products need to be enhanced or adjusted, there is less value lost in this cycle. When there are some components broken, *refurbishment and remanufacturing* operations are needed in order to make the product continue to be used (King et al. 2006; Souza 2013). However, refurbished products usually cannot keep the quality level as high as remanufactured products (Harms and Linton 2016). As for those products which cannot be refurbished or remanufactured, *recycling* can be a good choice. Materials of products can be separated, processed, and used for new products (Braungart et al. 2007).

The final two cycles are *cascading and repurposing* and *extraction of biochemical feedstock*, which are closing biological material cycles through the use of biodegradable materials and their eventual return to the environment to feed biological processes (Braungart et al. 2007). Cascading and repurposing means using multiple ways to process biological materials and recover their energy (Lüdeke-Freund, 2019). Repurpose can be regarded as a principle in other cycles, like reusing or remanufacturing. The extraction of biochemical feedstock will finally start a new biorefinery cycle, which happens in the natural environment.

2.2 Importance of sustainability and sustainable transportation

Sustainability is a major topic that has been trending for a while because certain activities that humans have engaged in have led to the destruction of environmental integrity (Sherman., 1990). Sustainability consists of three pillars which are the economic, social, and environmental perspective (Sherman, 1990). The meaning of economic pillar is that businesses or countries should use their resources in a more efficient way so that they can operate in a sustainable way where they can have an operational profit in order to sustain and be competitive in the long term (circular ecology, n.d). The meaning of the environmental pillar is that humans, businesses, or countries should consume natural resources at a more sustainable rate. It is also important to consider the circular economy principles and to consider material scarcity because extraction of some materials damages the environment, i.e., the use of fossil fuels (circular ecology, n.d). The meaning of social pillar is to achieve a good social well-being. (circular ecology, n.d)

Sustainability is concerned with meeting the needs of the present generation without compromising the needs of the future generations. It is important to find a balance between how to meet the needs of the future generations and the use of resources (Kuhlman et al., 2010). According to Lorek et al. (2011) humanity uses about 40 % more natural resources in a year than nature can regenerate within a year. An example of this scenario is that crude oil which is one of the biggest non-renewable natural resources has already reached its peak supply (Lorek et al., 2011). There is also not enough land to produce biofuels and food production because both of the industries are competing in terms of land use (Lorek et al., 2011). Another challenge is how to achieve reduction of GHG emission which is important in order to reduce global warming and target the official goal which is below an increase of 2 degrees Celsius until 2015 (Lorek et al., 2011).

Currently, transportation is one of the largest sources of air pollution and GHG that affects global warming negatively. Although, the air pollution has declined in the two past decades and still continues to decrease (EEA, 2015), transportation made up for a share of 72.1 % of all GHG emissions in Europe in 2010 and had a share of 31.6 % in energy consumption in the EU in 2015 (Eurostat, 2015). Transportation is also the only sector where the GHG has increased since 1990 (EEA, 2015). There are also other unsustainable impacts as a result of the increased transportation. High noise level is a result of the high transportation that occurs within Europe, 25 % of the population are exposed to the high noise level from road traffic (EEA, 2015). Congestion is another problem that occurs due to high road traffic which results in increased travel time and increased operating costs. According to the EU Commission (2011) the congestion costs are projected to increase by 50 % before 2050.

In order to minimize unsustainable transportation, there are options that could make the transportation more sustainable. One of the solutions is the use of technology options such as fuels and powertrain. Biofuels emits less emissions than fossil fuel, especially as it has a lower impact on GHG emissions, but it depends on how the biomass is converted into transport fuels, heat or electricity and also what kind of fossil fuels are replaced (IEA, 2011).

Electrification of powertrains has improved and made transportation more sustainable. Electric vehicles were almost introduced a decade ago, since then it has become a highly popular vehicle option to use for transportation because it is emission free, however the negative side effects of producing electric vehicles should be considered (Nordelöf et al., 2014).

According to Nordelöf et al. (2014) an electric vehicle compared to the size of a Volkswagen Golf in both size and power demand around 120 GJ for one Battery electric vehicle (BEV) and one internal combustion engine vehicle (ICEV) demands 94 GJ during the whole lifetime. If the car drives 150 000 km this results in 46 CO2-eq./km and 35 CO2-eq./km respectively (Nordelöf et al., 2014). According to Nordelöf et al. (2014) the base of the BEV accounts for 54 % of the emission which excludes the powertrain, 20 % of the emissions emitted from the powertrain and lastly the remainder 26 % of the emissions are emitted from the battery. The main reasons for the high emissions when producing electric vehicles can be related to the high energy use of electricity which is based on high carbon intensive average grid mix (Nordelöf et al., 2014).

Hydrogen Fuel Cell Vehicle (HFCV) is another option that is emission free, but currently there are no infrastructures for the use of hydrogen, but it could be a good option that could make transportation more sustainable in the future if the infrastructure is provided and also if the high costs for hydrogen are reduced in order to be more affordable for the public (Veziroglu et al., 2011).

2.3 Current energy consumption and CO2 emission models

Many studies have been carried out to assess and evaluate the environmental impacts of transportation, especially in two aspects: energy consumption and greenhouse gases emissions (Bose, 1996; He et al., 2005; Shabbir and Ahmad, 2010; Yan and Crookes, 2010; Mraihi et al., 2013; Solís and Sheinbaum, 2013; Chavez-Baeza and Sheinbaum-Pardo, 2014). In the paper by Mraihi et al. (2013), several driving factors of road transport-related energy consumption were listed, like variation of road energy consumption, effect of vehicles fuel intensity, effect of vehicles intensity, effect of economic activity, effect of urbanized kilometers and effect of national road network. Only listing all the influences is not enough, using models or tools to reduce the environmental impacts of transportation is more important.

Bose (1996) developed a model which can help to optimize the energy consumption and GHG emissions in the urban transportation sector. A software called Long Range Energy Alternatives Planning (LEAP) and the associated Environmental Database (EDB) model are used, which help to collect basic data, including "*passenger travel demand, mode (rail/road), type of vehicle and occupancy (persons per vehicle)*", as well as fuel consumption for different vehicle types (Bose, 1996). The LEAP software was also used by Shabbir and Ahmad (2010) to monitor urban transport air pollution and energy demand in Rawalpindi and Islamabad, Pakistan. This model cannot only be used for passenger transports but also be applied into goods transportation.

In the paper by He et al. (2005), a bottom-up model was developed to estimate the oil consumption and CO_2 emissions of Chinese road transportation and forecast the future environmental impacts up to 2030. In its model, "*three important factors — vehicle population, average vehicle mileage traveled, and vehicle fuel economy — determine road transport energy use*" (He et al., 2005). The bottom-up model is an approach which disaggregates total energy demand into end-uses to examine the underlying drivers of energy demand (Maduekwe et al., 2020). The total energy demand can be disaggregated based on transport type, transport mode, vehicle type, and fuel type (Maduekwe et al., 2020). Maduekwe et al. (2020) describes the model with the following words:

"*The energy consumption for each mode of transportation and for each transport type may then be expressed as a multiplicative function of the number of vehicles per vehicle type, the average mileage for each vehicle type, the fuel consumption rate per kilometer for each vehicle type and fuel type, and the average load factor for each vehicle type*".

The GHG emissions calculation is the same as energy consumption. Solís and Sheinbaum (2013) also used a bottom-up model to analyze the fuel consumption and its related CO_2 emissions from passenger and freight road transport in Mexico.

Although there are many literature studies related to the environmental impacts of transportation, the literature in waste transport fields is scarce. In order to create an optimal waste transport route in the University of Abuja main campus, a "MyRouteOnline" software was used to collect and analyze waste data (Amarachukwu et al., 2020). Some of the input parameters included in the model are waste generation and classification, waste disposal location, population distribution. The optimal transportation distance and time can be decided based on those factors, and then the waste transport route map is created.

In order to build a practicable model for waste transports, there are several energy consumption and CO_2 emission models which are widely used nowadays and have been analyzed.

2.3.1 The Network for Transport Measures - NTM

The Network for Transport Measures (NTM) is a non-profit organization aiming at establishing a common and widely accepted method for calculating the environmental performance for different traffic modes, including goods transport and passenger travel, in order to improve and develop the environmental sustainability in the transport sector (NTM, 2021). Based on the calculation method and relevant environmental data provided by NTM, companies can do environmental evaluations towards their own business or suppliers (NTM, 2021).

As is already described, NTM is an environmental assessment model towards transports. After studying the NTM model, several parameters were extracted, which have been further analyzed.

- Type of vehicle, which describes the name of vehicle and their weight/length information.
- Type of fuel, different types of fuel used for vehicles, which is selected by users.
- Fuel quality, which describes the diesel quality and ratio of biomass blend (NTM, 2021).
- Engine emission standard, which describes the emission standard of the vehicle. In NTM Euro VI is used as a standard setting (NTM, 2021).
- Road type since different road types lead to different traffic conditions for vehicles.
- Road gradient since the road topography influences the energy and fuel consumption.
- Load factor weight refers to the actual load weight in vehicles.

2.3.2 Vehicle Energy Consumption Calculation Tool - VECTO

VECTO is a vehicle energy consumption calculation tool which was developed by the European Commission for calculating the environmental impact from different vehicles (European Commission, 2021).

This software has been *"introduced in the European vehicle type-approval regulation in May 2017, as the official tool used in Europe to certify and monitor the fuel consumption and CO2 emissions from Heavy Duty Vehicles (trucks, buses and coaches) with a Gross Vehicle Weight above 3500kg"* (European Commission, 2021).

In order to calculate the energy consumption and air emission of heavy-duty vehicles, the input of VECTO should be characteristic parameters which relate to the power consumption of every relevant vehicle component (European Commission, 2021). In the VECTO simulation, the main inputs are:

- Vehicle category (rigid truck, tractor)
- Axles configuration (i.e., 4x2, 4x4, 6x2 etc.)
- Gross vehicle mass rating (w/o trailer) [kg]
- Vehicle curb mass [kg]
- Tyre characteristics
- Auxiliary specifications (selection from a list of technologies
- Engine characteristics (full load curve, drag curve, fuel map, displacement etc.)
- Gearbox & Final Drive characteristics

2.3.3 COPERT

COPERT is the EU standard vehicle emission calculator, which is used for calculating the air emissions and energy consumption of road transport (EMISIA, 2018). It is a widely used tool especially by many European countries for reporting official emissions data, since it includes all main pollutants: greenhouse gases, air pollutants and toxic species (EMISIA, 2018). The development of COPERT is financed by the Europe Environment Agency (EEA), and the European Commission's Joint Research Centre manages the scientific development of the model (EMISIA, 2018)

COPERT uses many input parameters to calculate the emissions and energy consumption for a specific country or region (EMISIA, 2018), which includes:

- Passenger vehicle approved population.
- Transport mileage
- Driving speed
- Ambient temperature
- Vehicle operation modes

More specifically, when calculating the road transport emissions, there are different road vehicle operation modes are considered, like thermal stabilized engine operation ('hot' emissions); the warming-up phase ('cold start' emissions); non-exhaust emissions (from fuel evaporation, tyre and brake wear emissions) (EMISIA, 2018).

In addition, more than 450 different vehicle types are also included in the model, including passenger cars; light commercial vehicles; heavy duty vehicles (including trucks and buses); L-category vehicles (including mopeds, motorcycles, quads, and mini-cars) (EMISIA, 2018).

This tool is mainly used for calculating air emission but pays less attention to the energy consumption. It covers almost all of the pollutant emissions, not only the GHG emissions, including CO_2, N_2O, CH_4, but also the major air pollutants, including CO, NO_x, VOC, PM, NH_3, SO_2, heavy metals (EMISIA, 2018). The COPERT methodology provides a transparent and standardized tool to help different regions and areas to calculate road transport emissions, so consistent and comparable data collection and emissions reporting procedures are produced (EMISIA, 2018).

2.3.4 EcoTransIT World Calculation

EcoTransIT World (ETW) is the widely used tool worldwide for calculating and analyzing the energy consumption and air emission of freight transport. ETW has considered the whole transport chain across all modes of freight transport, like truck, train, ocean vessel, inland waterways, and aircraft.

There are many input parameters which can be adjusted by users, like the freight weight, origin, and destination as well as mode of transport, so that the complete intermodal transport chain can be calculated. The calculation result can be more accurate if there are more detailed and customer-specific transport information provided. Nowadays, "*several hundred million freight transports are already calculated every year by all customers using the ETW APIs.*" (EcoTransIT, 2021)

After analyzing the calculation process of ETW deeply, the transport details were listed below, which includes the input and output parameters of this tool, as well as the calculation details. The input data is divided into three parts.

- Transport routine

There are different ways provided for users to determine the transport origins, destinations, and waypoints, like postal codes, railway and loading stations, geographic coordinates. By typing that information, the transport routine is determined.

- Transport mode

There are many transport modes listed in EcoTransIT, like all common truck types, all common train types, container, bulk, RoRo ships, in addition, over 250 aircraft types are included.

- Transport vehicle information

Several parameters related to vehicles were analyzed deeply in EcoTransIT, like vehicle types, fuel types, load factor, optional refrigerated cargo, etc.

2.3.5 Comparison among different traffic assessment models

After introducing different calculation models, a comparison among them has been done, which helps authors to get inspiration from their input parameters and calculation process. The advantages and disadvantages of each model are listed below.

1. NTM

The calculation process framework and input factors can be used for reference in waste transports. The model is easy to operate, which gives inspiration for the vision of the model in this thesis. There is also an opened library that provides detailed descriptions of the calculation. In addition, the NTM model provides a comprehensive list of fuel types and calculates fuel consumption according to chosen vehicles which can be overwritten if a more exact number exists. However, as for road transport, it is too general, and more effort is put on transit, so the main problem is to apply it into the waste transports. In addition, the information is not clear about the energy consumption of empty loading.

2. VECTO

In this model, there is enough environmental impact data towards different engines and loads, as well as different operation conditions, but it focuses too much on components of vehicles instead of traffic characteristics. The input parameters are not comprehensive for road transports.

3. COPERT

COPERT cooperates with EEA, the standard in Europe is referenceable for Sweden. The model of COPERT covers almost all of the pollutant emissions, so there is available statistical data for new research. The model not only considers different vehicle types, which includes approximately 450 different vehicle types, but also considers different road vehicle operation modes, including cold start emissions, brake wear emissions etc. However, its calculation is more about the air emission, and less on the fuel consumption.

4. ETW

The model is easy to use and understand and also easy to access. The model is flexible because it allows users to use different modes and can include the intertransports. As for road transport, there are different vehicles and fuels can be chosen as input factors. The loading factor can be changed, which meets the demands of different transport situations. However, the model works for every kind of transportation mode, which means it has not put much effort and makes the road transports more specific and detailed. In addition, there is no open library available for users to study the detailed data and formula of its calculation.

The table below provides a comparison of advantage and drawbacks of the different models.

Table 2-1 The comparison of different calculation models

	Pros	Cons
NTM	• Calculation process and input parameters gives inspiration on how this thesis model can be developed. • Provides a detailed description of the calculation formulas.	• Section about road transport is too general, the main problem is that it is not focused on waste transports. • The information regarding energy consumption of empty loading is not clear.
VECTO	• Provides enough environmental impact data towards different engines and loads, as well as different operation conditions.	• Focus too much on components of vehicles instead of traffic characteristics. • The input parameters are not comprehensive for road transports.
COPERT	• Copert cooperates with EEA. • The model covers almost all of the pollutant emissions. • Consider approximately 450 different vehicle types and different road vehicle operation modes.	• Focus too much on air emission instead of fuel and energy consumption.
ETW	• Easy to use and also accessible. • Flexible because it allows the users to choose different transportation modes. • Fuel type can be chosen as an input parameter. • Loading factor can be changed.	• The model works for every kind of transportation mode, which means that the different transportation modes are too general and specific. • There is no open library available for users to study the detailed data and formula of its calculation.

The table 2.1 highlights the pros and cons of the different models. From the comparison of the different models, all of them have advantages and disadvantages, but the NTM was chosen as an inspiration when building the calculation model for energy and fuel consumption for waste transport in Sweden. The reason for this is not only that it has a suitable calculation process and plenty of available formulas for researchers, but authors have held a seminar with an expert in NTM and got a clear understanding of this model.

2.4 Comparison among different energy sources

There are many unsustainable impacts related to transportation, which are harmful to human health and the environment (Nordelöf, 2020). Because of the large amount of fossil resource depletion in transportation, there is an increased frequency of extreme weather phenomena and alteration of current ecosystems, food productivity, water resources, health issues, etc. More specifically, carbon dioxide, or CO_2, is one of the most commonly discussed greenhouse gases out there when talking about climate change; SOx, NOx, particles, and photochemical smog (ozone) cause asthma, bronchial infections, and some volatile hydrocarbons are carcinogenic; Acidification damages to biodiversity and productivity in lakes and forests (Nordelöf, 2020).

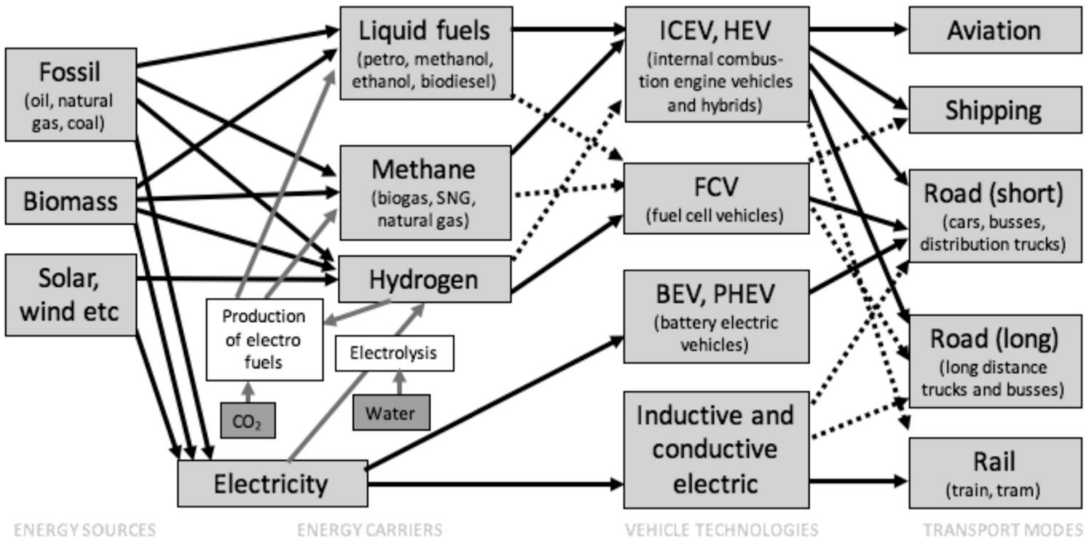

Figure 2-3 Visualize different energy sources, energy carriers, vehicle technologies and transport modes

There are different types of vehicles used for transportation, which rely on different types of energy, see figure 2-3 above (Grahn, 2016). The most common one is fossil fuels, like oil, natural gas, coal, etc, which will produce large amounts of greenhouse gases during energy depletion. In addition, fossil fuels are nonrenewable fuels, with the raw materials being used, dispersed, and lost, human beings will face a large shortage of fuels in the future.

Biofuels are often used as an alternative to fossil fuels (Ball and Wietschel, 2009). As is defined in the report by IEA (2011), *"biofuel refers to liquid and gaseous fuels produced from biomass – organic matter derived from plants or animals"*. The fuel used in some waste transport vehicles is hydrogenated vegetable oil (HVO), which is one type of biofuel.

In the 1990s, the technology in fuel cells had a big breakthrough, which promoted the development of hydrogen (Ball et al., 2009). Hydrogen is a new energy in the transport sector, which has three main advantages, namely almost no air pollution, less CO2 emissions, and higher energy security (Ball et al., 2009). Hydrogen can produce electricity with oxygen through an electrochemical reaction in the fuel cell, resulting in water and heat as the only output. The overall conversion efficiency of fuel cells powered by hydrogen is double that of internal combustion vehicles (Björn, 2020).

Electrification in the transport sector refers to the vehicles that are propelled by electricity to varying degrees. Figure 2-4 shows how Anders et al. (2020) explains the different degrees of electrification, ranging from mild hybrids (typically propelled by electricity combined with other (mainly fossil) sources of energy) to fully electrified vehicles.

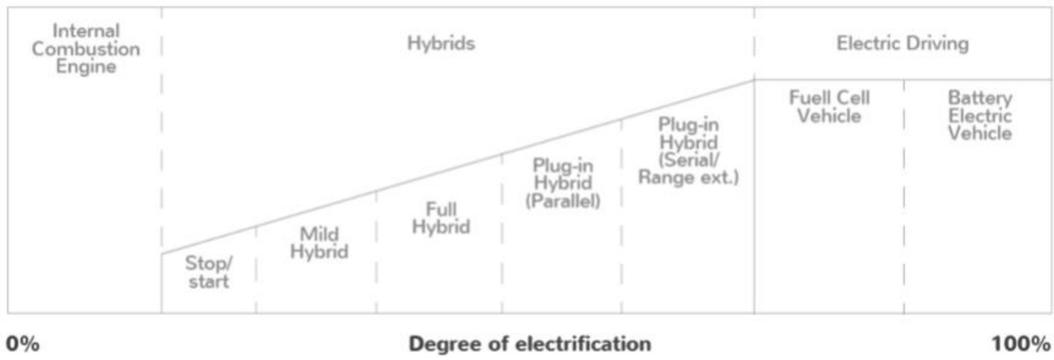

Figure 2-4 Different degrees of electrification (Anders, 2020)

As for the electricity used in vehicles, some electric vehicles are supported by technologies which enable them to produce electricity during the operation process, like fuel cell vehicles. Others are supplied electricity from the general electricity grid. The electricity from the grid is converted from different sources of energy, such as fossil, nuclear, as well as some renewable sources, such as wind and solar (Anders et al., 2013).

Compared with ICEVs, electric vehicles can be superior in some aspects. Firstly, they are 2.5 - 4 times more efficient in their energy conversion than ICEVs (Sten, 2020). Secondly, there is less environmental impact of EVs during the operation, like less CO2 and NOX emissions. However, the environmental impacts are different based on which energy is converted to electricity. If the electricity is converted from fossil fuels, the GHG emission is similar to ICEVs during the well-to-wheel life cycle, but the GHG emissions can be reduced drastically if renewable energy can be used (Sten, 2020). It is therefore necessary to use more renewable sources in the electricity production as well increase the overall level of electrification in vehicles.

3 Methodology

The methodology of the thesis will be described in this chapter. In the first section, the research framework will be demonstrated, which clearly shows how this thesis is conducted. The next section is used for introducing the general calculation process of road transport in the NTM model, which provides an inspiration for research analysis. In the final section, detailed data collection methods will be discussed, which shows the authenticity and reliability of this thesis.

3.1 Research Framework

This research starts with a review that is about sustainable waste transport and different energy and fuel consumption models. After collecting related academic research, the current energy and fuel consumption of waste transports in Sweden is conducted. Then the first two research questions will be analyzed. Based on the analysis of the impact parameters and calculation method, an energy consumption model will be developed, followed by the testing, and verifying work. The final step is proposing further recommendations for improving sustainability in waste transports based on the model. The research framework is shown in figure 3-1.

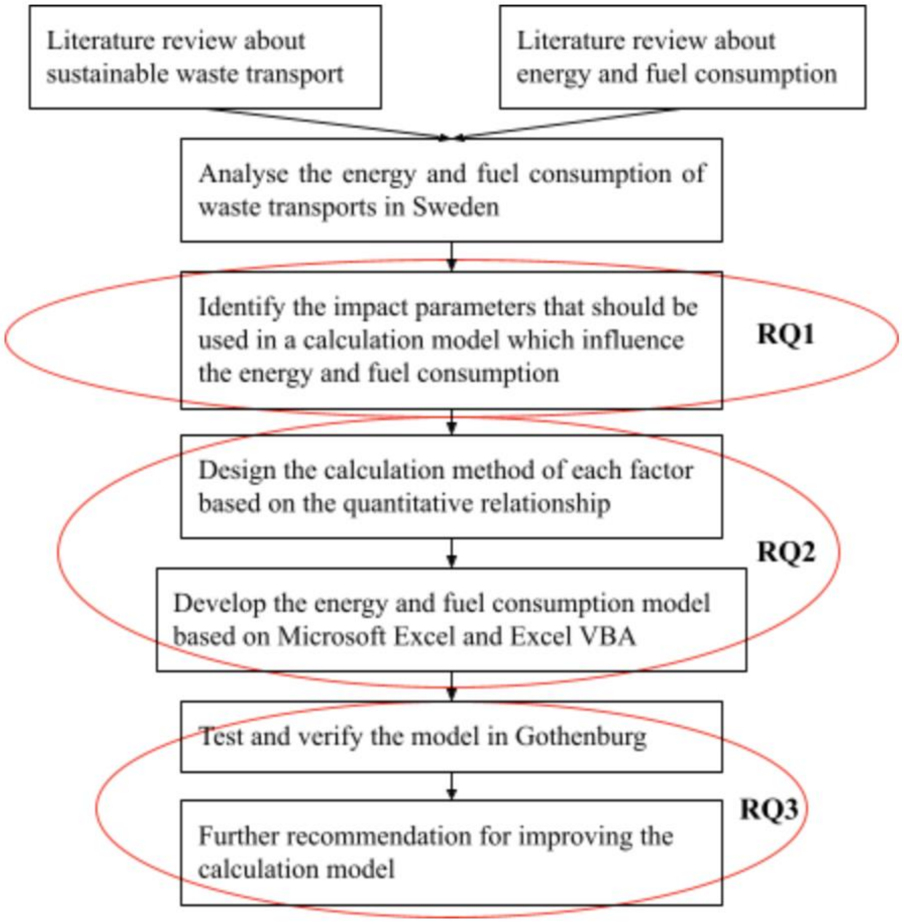

Figure 3-1 Research framework

3.2 Calculation process derived from NTM.

In the calculation method of NTM, different traffic modes are included. The waste transport in Sweden mainly relies on road transport, the general calculation process of road transport in NTM is shown in the figure 3-2, which gives guidance to the model building in this thesis:

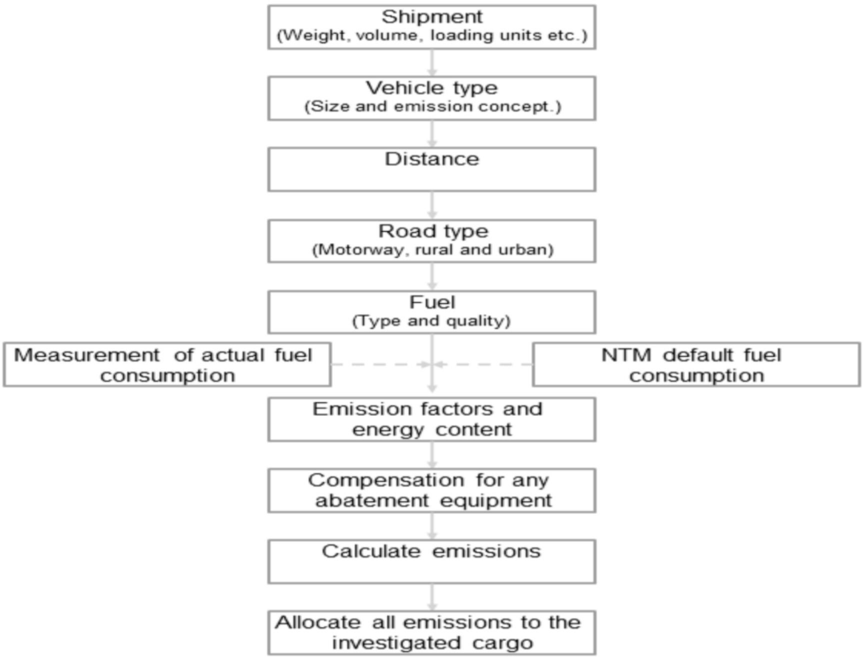

Figure 3-2 General calculation process of road cargo transport in NTM (NTM, 2021)

The figure 3-2 shows the process of calculating the environmental impact of road transports, as well as some related factors. Based on the steps in this figure, the calculation process of waste transport is shown below (NTM, 2021).

1. Collect information about the shipment.

This step needs to collect all the information related to the goods which need to be delivered, like the weight, volume and used cargo holders. In the waste transports, the waste information should be collected.

2. Selection of relevant vehicle type and load capacity **utilization**

NTM collects data for 10 different types of vehicles, which is shown in table 3-1 below. All of those vehicles can be used by different Euro class engines.

Table 3-1 Vehicle information in NTM model

NTM Nomenclature	HBEFA Nomenclature	Max gross weight	Vehicle length	Load capacity			Load Capacity Utilisation			
		tonne	m	tonne	pallets	m3	LCU w%	LCU pallet%	LCU v%	LCU dimw%
Light commersial vehicle - Pick-up	LCV Petrol N1-II/LCV Diesel N1-II	2,5	5,00	0,6	1	6	0,20	0,4	0,25	0,30
Light commersial vehicle - Van	LCV Petrol N1-III/LCV Diesel N1-III	*3,5*	*7,00*	*1,5*	4	*17*	0,20	0,4	0,25	0,30
Rigid Truck <=7.5t	RT <=7,5t	7,5	8	5	14	0	0,40	0,6	0,40	0,50
Rigid Truck 7.5-12t	RT>7,5-12t	12	11	6	20	0	0,40	0,6	0,40	0,50
Rigid Truck 12-14t	RT>12-14t	14	11	9	24	0	0,40	0,6	0,40	0,50
Rigid Truck 14-20t	RT>14-20t	20	12	12	24	0	0,40	0,6	0,40	0,50
Rigid Truck 20-26t	RT>20-26t	26	12	15	24	0	0,40	0,6	0,40	0,50
Truck with Trailer 14-20t	TT/AT > 14-20t	20	12	12	20	0	0,40	0,6	0,40	0,50
Truck with Trailer 20-28t	TT/AT > 20-28t	28	12	16	28	0	0,40	0,6	0,40	0,50
Truck with Trailer 28-34t	TT/AT > 28-34t	34	17	22	36	0	0,50	0,7	0,50	0,60
Truck with Trailer 34-40t	TT/AT > 34-40t	40	19	26	36	0	0,50	0,7	0,50	0,60
Truck with Trailer 40-50t	TT/AT >40-50t	50	16,50	33	33	110	0,50	0,7	0,50	0,60
Truck with Trailer 50-60t	TT/AT >50-60t	60	25,25	40	51	140	0,50	0,7	0,50	0,60

3. Vehicle operation distance and road types

In the NTM calculation model, different road types along the route would influence the final results. There are three categories in the model: Motorway, Rural, Urban (NTM, 2021). The different road types influence the energy consumption and air emission during the road transports.

4. Fuel type and fuel consumption (FC)

There are different fuel types used in road transport, like diesel, electric, biogas and so on. However, no matter which type of fuel the vehicle uses, the fuel consumption increases if the load rises. *"The increase is due to increased rolling resistance and dynamic weight (NTM, 2021)."* There is a formula in NTM which shows the linear relationship between fuel consumption and different vehicle loads, see the formula below.

$$FC_{LCU} = FC_{empty} + \left(FC_{full} - FC_{empty}\right) * LCU_{weight(phys)}$$

$LCU_{weight(phys)}$ = Load Capacity Utilisation, defined as [cargo physical weight/max weight capacity]
FC_{LCU} = Fuel consumption at load capacity utilisation LCU.

All of the steps above are applicable for the calculation model of waste transports. However, the information and data need to be changed to waste transport areas.

3.3 Data collection

The thesis is embedded in a project. The project work includes interviews, workshops, etc. However, the focus of the thesis is on developing the data collection and analysis model. For that, the following is done.

1. Interviews

Chalmers Industriteknik held interviews with 15 municipalities. The 15 municipalities were chosen randomly but at the same time with an even distribution throughout Sweden and an even mix of organization of their waste disposal. Then Avfall Sverige provided contact persons that work in those municipalities. Through the interview, the waste management information in 15 municipalities of Sweden was collected. Then all of the interview data was provided for this master thesis from Chalmers Industriteknik, which has been further introduced in the empirical findings.

2. Workshops

There were three workshops held during the research process. The topic of the first workshop is vehicles used for waste transports in Sweden. Authors invited a strategic adviser who is working in sustainable waste and water which is a department within the city of Gothenburg, as well as a project manager who is working in Chalmers Industriteknik to join the workshop. During this workshop, thirteen different types of vehicles are decided, and the basic vehicle information is collected, including the usage, curb weight, loading capacity, max gross weight, fuel types used for vehicles, energy, and fuel consumption of vehicles.

In order to get more inspiration from NTM, authors held the second workshop and invited a managing director of Network for Transport Measures, as well as two project managers who are working in Chalmers Industriteknik to join the workshop. Many issues related to the calculation model building were discussed during this workshop. For example, which assumption to take in regard to the load factor, how to calculate the impact of road types, etc.

The last workshop was held with Gothenburg Region and Chalmers Industriteknik in order to do the model testing and verifying. During the workshop, the model was tested by using waste transport data of Gothenburg. Then the strength and weakness of the model was identified, and the practicality of the model was analyzed.

In addition, weekly meetings were held between authors and two supervisors in order to do the research in the right direction. Many suggestions and advice were given by supervisors not only in model building issues but also the report writing. Email consultation was also one of main methods for data collection and timely communication in this thesis. There was much secondary data provided by Chalmers Industriteknik, which was sent by email because of the pandemic period.

4 Empirical Finding

This chapter introduced the current waste management situation in Sweden through statistics, which mainly shows the number of different types of waste generated per person as well as different collecting systems used in different municipalities. The second section described the detailed information of vehicles used for waste transports. The final section was used to introduce the waste transports information of each municipality in detail.

4.1 The current waste management in Sweden

The current waste management in Sweden is reflected by the statistics, where good statistics creates credibility and could also be the base for a long-term development of the waste industry. In Sweden there are different types of waste, while household waste (food and residual waste) has the largest share of the amount of waste as visualized in figure 4-1 below.

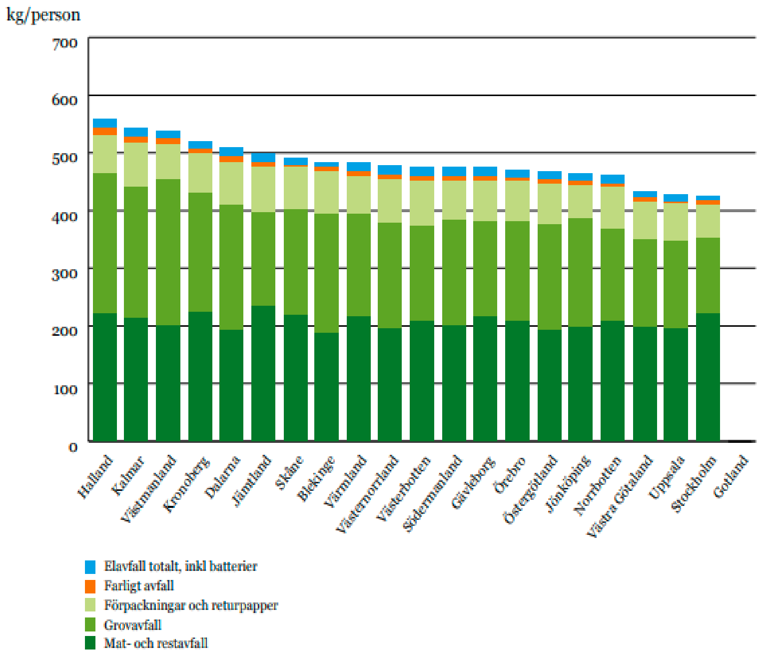

Figure 4-1 The amount of waste per person

Bulky waste is another type of waste that makes up for a large share of waste. Bulky waste is also a type of household waste that is too big to fit into the bins. Examples of bulky waste are broken furniture, frying pans and scrap metal etc.

Packaging and wastepaper make up for the third largest share of waste. Examples of waste in this category are packaging and newspapers etc.

Hazardous waste makes up for the fourth largest share of waste. Hazardous waste is classified as waste that potentially can compose health risks through consuming, touching or if the object has been spread through air or water. Examples of waste in this category are chemicals that are toxic, corrosive, and radioactive etc.

Electrical and electronic waste (includes batteries) makes up for the fifth largest share of waste. Electric waste is classified as household waste that is driven by batteries. Examples of this are hard disks, mobile phones, drilling machines and shavers etc. Other products that are not driven by batteries could also be disposed as an electric waste, for instance an old hairdryer.

There are different types of collecting systems that can be used in order to collect different kinds of waste, but once a municipality has installed a certain system, it is difficult to switch to another one due to high implementation costs. Therefore, once in place the system is installed in a municipality, it will not change for a long time.

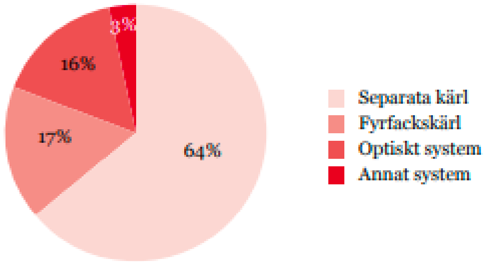

Figure 4-2 Visualize the most popular collecting systems

There are four different types of systems that could be used when collecting waste. A system where the wastes are separated in bins/containers, a system that consists of four different compartments of bins/containers, a system of bags that are in different colors in order to separate the wastes and lastly different collecting systems could also be used. From figure 4-2 it can also be visualized that a system of separated bins/containers is the one that is used most, which accounts for 64 % of the share in total.

4.2 Vehicles that are currently used for waste transports in Sweden.

In order to collect waste, the different municipalities use different types of vehicles. In total 13 different vehicles are used across all of the municipalities throughout Sweden. The vehicles are also operated by different energy sources such as electricity, HVO, diesel and biogas. The load capacity varies also depending on the type of vehicles that are used. Detailed information of vehicles is introduced below:

Smaller, two axle rear loaders. Used for residual-and food waste. This type of vehicle has a load capacity of 6-7 ton and has a max gross weight that is 19,5 ton.	
Bigger, three axle rear load. Used for residual-and food waste. This type of vehicle has a load capacity of 10-11 ton and a gross weight that is 26,5 ton.	

Rear-loading two-compartment truck. Used for both residual-and food waste at the same time, the waste type is divided into compartments. This type of vehicle has a load capacity of 10-11 ton and a gross weight that is 18 ton.	
Cable car. Used in order to empty both bins and containers. This type of vehicle has a load capacity of 10 ton and a gross weight that is 26,5 ton.	
Side loader. Used for residual-and food waste. This type of vehicle has a load capacity of 6-7 ton and a gross weight that is 29 ton.	
Four compartment vehicle. Consists of four waste compartments. This type of vehicle has a load capacity of 6-7 ton and a gross weight that is 26,5 ton.	
Crane truck. Used for underground containers. This type of vehicle has a load capacity of 9 ton and a gross weight of 27 ton.	

Demountable vehicle. Used mostly for containers with operational waste. In terms of household waste, it can be used for bulky waste. This type of vehicle has a gross weight of 29 ton.	
Lift dumper. Used for bulky waste collection. This type of vehicle has a load capacity of 6-7 ton and a gross weight of 19,5 ton.	
Mobile vacuum vehicle. Used for collecting waste. This type of vehicle has a gross weight of 29,5 ton.	
Demountable vehicle with trailers. Used from transshipment stations for incineration or from recycling centers to incineration. This type of vehicle has a load capacity of 50 ton and a gross weight of 22 ton.	
Tractor with trailer. Used primarily to transport slag incineration to landfill. This type of vehicle has a load capacity of 45 ton and a gross weight of 20 ton.	
Front loader. Used mostly for industry waste. This type of vehicle has a load capacity of 11 ton and a gross weight of 35 ton.	

4.3 The current waste transport system

All the information from interviews was used for the current waste management analysis, in order to study the challenges municipalities face. Table 4-1 shows the 15 chosen municipalities and gives an overview of the geographic and demographic information of them. Some municipalities are attractive for tourists, some of them are good places for people to spend summer holidays, so both the number of inhabitants and the adjusted population are collected. In addition, quantities of houses, apartments and summer houses are collected, which can help to calculate the detailed waste generation situations in different municipalities. In the waste transport perspective, the different types of areas would influence the traffic conditions which need to be analyzed in more detail.

Table 4-1 The demographic and geographic information of 15 municipalities

Municipality	Number of Inhabitants	Adjusted Population	Organisation of Waste Disposal	Performer	Share for Renewable Fuels, %	Quantity Household in One and Two-family House	Quantity Household in Apartment Buildings	Quantity Holiday Home	Archipelago/Countryside/Urban Area
Arjeplog	2 794	3 542	Own Management	Entrepreneur (100%)	-	1 111	465	1 300	Countryside
Mullsjö	7 324	7 454	Jointly Owned Company	ET (0%)	-	2 398	896	446	Countryside
Härjedalen	10 147	16 832	Own Management	Entrepreneur (100%)	-	4 534	1 474	8 594	Countryside
Öckerö	12 945	12 836	Own Management	ET (0%)	0	4 350	741	730	Archipelago
Tjörn	15 992	16 740	Own Management	Entrepreneur (100%)	100	5 846	758	4 169	Archipelago/Countryside/Urban Area
Ale	30 926	29 889	Own Management	96% ET / 4% Entrepreneur	100	8 062	4 705	386	Countryside
Lerum	42 137	40 722	Own Management	75% ET / 25% Entrepreneur	-	12 553	3 925	694	Countryside
Karlskrona	66 675	68 764	Own Comany	ET (0%)	-	-	-	-	Archipelago/Urban Area
Mölndal	68 152	69 442	Own Management	ET (0%)	85	13 103	16 406	324	Urban Area
Skellefteå	72 467	75 141	Own Management	60% ET / 40% Entrepreneur	64	18 225	17 772	8 419	Urban Area
Umeå	127 119	130 267	Own Comany	Entrepreneur (100%)	48	21 439	43 650	4 722	Urban Area
Helsingborg	145 415	148 674	Jointly Owned Company	ET (0%)	100	22 056	45 997	718	Urban Area
Örebro	153 367	156 608	Own Management	58% ET / 42% Entrepreneur	100	23 462	49 814	2 835	
Göteborg	571 814	594 270	Joint Committee	Entrepreneur (100%)	99	53 317	222 529	4 429	Urban Area
Stockholm	962 154	1 015 551	Own Comany	Entrepreneur (100%)	100	45 121	427 616	215	Urban Area

In order to understand the current data each municipality collects; each municipality will be discussed separately based on the interview.

1. Gothenburg

Gothenburg is an urban city, which is the second largest city in Sweden, only smaller than Stockholm. There are around 594,270 populations living there. Every year, there are under 100, 000 tons of residual waste and 20-25,000 tons of food waste are generated.

The municipality is always responsible for the collection of residual and food waste but uses a contractor to do this (mostly Renova but Nordisk Återvinning for one area in Gothenburg. There are 100 heavy vehicles used for waste collection. In order to conduct environmental impact analysis of waste transports, some data are collected in Gothenburg, including fuel type used in vehicles, fuel consumption, transport distance, waste weight (kg/km).

As for the energy consumption part, they get the data directly from the contractor through Excel files via email. More specifically, they ask Renova and Nordisk Återvinning how much energy (diesel, electricity) they have consumed per month, then calculated to kWh/ton.

There are some challenges that need to be overcome during the data collection. There are four areas in Gothenburg: Hisingen, northeast (Angered-Kallebäck), southwest (Långedrag-Askim), the center of the archipelago). Nordisk Återvinning collects partly in the northeast and southwest, the rest areas are charged by Renova. It is impossible to get the correct data for every area in Gothenburg since vehicles are used together between the areas.

In summary, the data related to energy consumption is complex and difficult to get correct. The Gothenburg municipality does not collect the data, only the contractor does. Gothenburg municipality gets ready-made figures, but the contractors need to make sure the data are correct.

In the future, Gothenburg municipality wants to increase the proportion of electric vehicles to become fossil-free and to reduce energy consumption in waste transports.

2. Ale

Ale is located in the countryside, which is a 30,926-population municipality. In Ale, the residual and food waste are collected by Renova, which uses different processes to deal with each type of waste. There is a transshipment station for residual waste, everything goes from the bin and then to incineration. Food waste goes to Marieholm directly without transshipment. As for bulky waste, any container goes to the recycling station through a sorting plant. There are 8 vehicles (each vehicle has two compartments and one compartment with a back loader) used for waste collection, all of which meet the standard Euro class 6. Ale has no goal to change fuel soon, they believe Renova is good at improving vehicles.

Compared with Gothenburg, Ale collects the same types of data to do energy consumption analysis, including fuel types, fuel consumption, transport distance, waste weight (kg/km). As for the energy consumption data, Ale gets a summary from Renova (amount of waste, transport mode) once per year. They follow up the energy using condition twice per year and therefore request a little more data from Renova. During the data collection period, Ale collects the fuel data, then sends it to Renova, where all data is added together and then returned to Ale. The Avfalls web is used by Ale to facilitate data analysis. There are challenges especially for the contractor - Renova. For example, if vehicles drive between areas in Ale, then the data of each area is not correct. So Renova must correct it before emailing the data to Ale.

3. Mölndal

Mölndal is an urban municipality, the number of households and size of population are about twice larger than Ale. Unlike Gothenburg, Mölndal handles waste by themselves, including 3000-ton food waste. As for one-family houses, the containers are divided into four compartments, which are used for residual-, food-, paper- and plastic waste. In addition, different bins for each fraction near apartment buildings. The residual waste and food waste are collected only by bins, and always goes through transhipment stations before pre-treatment, since it is easier for waste sorting. Containers are used for collecting bulky waste (big bags used as an alternative). In Mölndal, 12 vehicles are used for food and residual waste and about 1.5 vehicles used for bulky waste.

As for the data on energy use for waste transport, Mölndal collects fuel types, fuel consumption, transport distance, waste weight (kg/km) in Excel files. In order to calculate the energy consumption and how long they drive in waste transports, Mölndal measures how much fuel consumption they have, then puts it in the Avfall web and then it is calculated there, and the kWh/ton is the final number after it has been calculated. Since there is no automated data acquisition equipment in vehicles, all data is collected manually, which is a big challenge for Mölndal to dive deeply in this area. Mölndal has an overall goal to switch to electric vehicles within 5 years. Within the last few years, they already have reached the goal of fossil-free transport (with conversion to HVO and gas)

4. Lerum

Lerum is located in the countryside, like Ale, and 40,722 people are living there. Both food and residual waste in Lerum are collected by Renova, so 4 or 5 vehicles drive across the municipal border, which increases the difficulty to divide the data of different areas. There are different colors of bins used for food (brown bin) and residual waste (green bin), in some apartment buildings, underground containers are also used. In Lerum, residents can choose to not sort out food waste but pay an extra fee. Almost all of the waste goes through a transshipment station in Stenkuller, which can deal with bulky waste.

As for the data collection part, Lerum has an allocation document for Renova where it describes all the data they require. All of the waste data needs to be submitted once a year. In addition, the municipality tries to link all other goals or documents to the waste plan. Lerum collects the same types of data to do energy consumption analysis, including fuel types, fuel consumption, transport distance, waste weight, CO_2 emission (CO_2/ton), share of renewable fuels (% renewable fuels). When collecting the fuel consumption data, Renova calculates how much diesel they use when they refuel cars each month and looks at the kilometers manually.

Lerum faced the same challenge which is similar to Ale. In addition, Lerum has some problems with the previous contractor, and they are still in court today. Since Lerum municipality wants to be a leading environmental municipality in 2025, they focus a lot on transportation. Today, all service workers are already only allowed to drive electric vehicles, Lerum also has demands for fossil free and now everything is already HVO.

5. Öckerö

The geography of Öckerö is an archipelago with only 12,836 people living there. Only bins used for collecting residual and food waste, then go to the same recycling station and transhipment. After everything is put in a container at the recycling center then Renova collects it, drives on the ferry, and goes to incineration in Gothenburg. There are 4 vehicles used for handling the food and residual waste with one extra vehicle for the summer period or other high seasons. As for bulky waste, Öckerö has their own container rent. It is possible to order a container from them.

As for data collection, Öckerö collects fuel type, fuel consumption, transport distance, waste volume (Only to know if everything from an island fits on the vehicle), and fill rate for residual waste (they drive until everything is dull and then they go and empty the vehicle at the recycling station). They do not measure energy consumption in detail today, only fill in little data in Avfallweb.

Öckerö thinks they face no challenge nowadays. Although their vehicles are sometimes used for another municipality, there is no cross-border driving because they are so isolated on the island. The municipality wants to be fossil-free by 2025, so the manager thought they should switch to HVO. But they do not have access to it right now.

6. Tjörn

The geography of Tjörn is complex, which is a mix of archipelago, countryside and urban. The food and residual waste there are collected by Renova and Vebot (contractor to Renova, goes out with some sort of bikes to pick up bags in areas where it is difficult to have a truck). Bins and bags are available for food and residual waste, everything goes through transshipment and then to an incineration or pretreatment facility in Stenungsund. There is no container for bulky waste, the municipality refers to a contractor for this. But it is possible for private persons to go to the recycling station with their waste. There are 3 vehicles used by Renova and some sort of quad bike on some of the islands. Boat used between islands, sack cart, a service car, and a wheel loader at the recycling station. Tjörn collects the information including fuel type, waste weight, but not for each household, they do not calculate energy consumption and only receive Excel files via email from Renova once a year.

As for challenges, waste vehicles only drive across the border when they drive from Stenungsund to the incineration facility. There is no challenge with the data since the islands outside a ferry connection are quite remote and can be regarded as an area of their own area. Tjörn would like to see that they have electric vehicles (from Renova) and then they use their own electricity from solar cells. But it is a little further in the future. They just change the fuel in the wheel loader to HVO during the autumn.

7. Helsingborg

Helsingborg is an urban municipality, which has a population of 145,415. The waste in Helsingborg is handled by the municipality itself. There are 49 trucks for different municipalities and some smaller garbage trucks. For one-family houses and apartment buildings, food and residual waste are collected every week. Every other week, paper, glass, food, and residual waste are collected, and then the other week it is for plastic, glass, newspapers, and metal waste. The residual was collected by bins and underground containers. When bulky waste needs to be collected, households can call for service. The garden waste goes separately.

The fleet management program from Scania collects distance (hard to know which area, it is more a total estimate), fuel consumption (only calculated value), weight (not per household, only total weight of the truck), volume (use this a lot. The bin sets the limit for volume). The data is available, since they collect all the data themselves and make demands on the contractor to send in data, but they do not use it for deep analysis. There are some tools used for data collection, for example, the fleet management plan on waste vehicles of Scania. In addition, route optimization BOM system, Avfallweb for statistics.

8. Skellefteå

Skellefteå is located in the countryside, about 40% of households live in Allmiljö out of town. In 2020, there is 13.192-ton residual waste, 4.594-ton food waste and 5.700-ton bulky waste generated. Residual and food waste are collected by bins and underground containers. For residual waste, everything goes through transshipment before going to incineration (incineration is in Umeå). For food waste, either go direct or through transshipment to biogas facility, the pretreatment facility and gas facility are at the same location, so there is no transport between them. In Skellefteå town, the municipality handles waste transports by themselves, there are five vehicles owned by Skellefteå and three of the contractors.

Skellefteå collects fuel type, vehicle type, distance, weight, fill rate. Here is one advantage in Skellefteå, when the route is finished, the car is always emptied. but the route was optimized, so that the car is full at the end of the route. Although Skellefteå collects data directly through the driving journal in vehicles, the municipality does not calculate the fuel consumption.

Nowadays, Skellefteå just started to analyze the data in a four-field matrix, and the data is already collected today, like distance from each vehicle per day, from 14 different routes, consumption, and collected waste's weight. It is an internal development project (business development).

9. Mullsjö

There are only 7324 people living in Mullsjö. The wastes there are divided into 8 fractions, including food, residual, newspapers, plastic packaging, paper packaging, transparent glass, stained glass, and metal waste. All of the waste is collected by Juneavfall. The residual waste is collected by bins and underground containers and goes directly to incineration. The food waste goes directly to the biogas facility. There are eleven recycling stations for bulky waste, probably no containers for it. Incineration and biogas facilities are located in Jönköping. One of the recycling stations is located in Mullsjö, but most are in Jönköping. There are 37 garbage trucks used for waste collection, 15 of them are biogas, others are diesel.

Mullsjö collects data including fuel type, vehicle type, fuel consumption (sum for all vehicles), distance (a driving list where they could estimate but not exact), weight. Avfallweb and the CO_2 budget calculation are used for data analysis.

10. Arjeplog

Arjeplog is located in the countryside, which is the smallest municipality in the investigation, with only 2794 people living there. The waste in Arjeplog is handled by contractors, they cooperated with different contractors. When handling the waste, there is no separate facility for food waste, but 900–1000-ton residual waste generated per year, and everything mixed together in Arjeplog. Food and residual waste are collected in green bins, everything goes through the transhipment station and then 300 km to incineration. There is no container for bulk waste, people go to the recycling station by themselves. There are 2 vehicles for residual and food waste from households, both of them are diesel cars since no other fuels would work because of the distances. Every year, Arjeplog municipality collects bills/invoices from contractors containing the annual total collected weight. In the future, Arjeplog wants to get the environmental certification, so it has already started a biogas plant to replace cars. It also discusses a lot about route optimization and works internally.

11. Örebro

Örebro is an urban municipality, with 153,367 people living there. When collecting waste, food waste is collected in a brown bin, residual waste is collected in a green bin with many different bags for different packaging (orange for plastic, brown for paper packaging, gray for metal, blue for newspapers), and bulky waste is collected via recycling stations. Örebro municipality is responsible for handling waste but also uses contractors. Residual and food waste is shared, but sludge collection is done by the contractor. The municipality collects waste from one-family houses from around the city center, and contractors collect in the city center, mostly apartment buildings. They also have underground containers for apartment buildings, bins only at one-family houses which are both for food and residual waste, then everything goes through transshipment. The bulky waste is collected via containers and bins, the operators also pick up at apartment buildings. The majority goes from private households to recycling stations. There are 30 vehicles used for waste transports, all of them have two compartments and use biogas, only one truck with HVO, but that one is used for the electronics and hazardous waste.

Örebro collects data including fuel type, vehicle type, distance, and weight. Örebro only collects data as metrics for their own transport, and the number of emptied bins/km may help with route optimization in the future. They calculate twice a year, all data is in their system, but also from the contractor. There is no advanced tool to analyze data today, they have no route optimization system and always do it manually.

12. Härjedalen

Härjedalen is a small municipality, the waste is handled by contractors there, so far, they have not sorted out food waste from the residual waste. In 2020,3700 ton of residual waste was collected for incineration. About 3000 ton of bulky waste and 55-ton hazardous waste is collected by 2020. People will drive to recycling stations by themselves. Bins and containers (both above ground and underground) are used for food and residual waste. Everything goes via transshipment to incineration at Sundsvall, which is 230 km away. There are six vehicles used for waste transports, one side loaded vehicle, one for food, 3 back loaded and one crane truck. All of them reached environmental class 6 but all use diesels. Härjedalen collects data including fuel type, vehicle type, weight (only total yearly weight), and volume. Every year, Härjedalen receives Excel files via email from providers.

Avfallweb does not suit them because they collect data based on volume. They also do not calculate energy consumption, But the amount of waste and distances are collected to implement new measures. In the future, Härjedalen tries to use fossil-free fuels, now it has started to switch to biogas. A small truck on HVO will soon be replaced. Also, the part of the cargo park (excavators etc) is not available with gas nowadays, instead HVO is used there.

13. Umeå

Umeå collects food and residual waste in two separate flows, and many different contractors are responsible for waste handling, including sludge. Only bins and underground containers are used for residual waste, then goes directly to incineration. As for food waste, bins and underground containers go over transhipment and then to Skellefteå. The transhipment point is used by all the neighboring municipalities, the food waste is collected together and then goes to Skellefteå. Skellefteå drives residual waste to Umeå and then they use the same vehicle to transport the food waste from Umeå to Skellefteå. Most of the time (98%), people go to recycling stations to deal with bulky waste, there is a service for picking up, but it is seldom used because it is expensive. There are 9 vehicles used for waste transports, most are side loaders, and crane trucks are used for the underground containers. 30-50% of cars are HVO, the rest are using diesel. Umeå collects fuel type, distance, waste weight. Umeå receives weights from incineration and food transhipment monthly, as well as fuel consumption and distance driven from the contractor. The Avfallweb is used for data analysis. In order to optimize the route, the neighboring municipalities (Berg and Härjedalen) are added together, but it needs to cooperate with the contractors.

14. Karlskrona

There are 66,675 people living in Karlskrona. There is only food and residual waste collected in households, bulky waste is not collected. All of the waste is collected by Karlskrona municipality. Only bins used for residual and food waste, residual waste goes through the transhipment to incineration which is 60 km away (in Nybro), food waste goes over transhipment to incineration which is 220 km away in Lidköping. Bulky waste is only collected at recycling stations, containers are offered, the incineration is in Malmö. There are 6 vehicles used for transport and all of them are HVO. Karlskrona collects data including fuel consumption, distance, and waste weight (They weigh every truck before emptying and then get weight per district).

Since they want to be fossil free in 2030, CO2 emission is also measured. There is a route optimization program in Karlskrona, which is an ongoing process. So that they can find which part of the route is overlapped, then improve it.

15. Stockholm

Stockholm is the capital city of Sweden, which is also the largest urban city and owns the largest size of population. There are three different contractors handling the waste in Stockholm, including food and residual waste, garden waste, sludge, and latrine waste. Bins, underground containers, and suction systems are used for collecting residual and food waste without transhipment. When collecting at one-family houses, they use two compartment vehicles, otherwise, separate vehicles for the two different fractions. From one-family houses, most bulky waste is delivered to recycling stations by households, but people can also order a container. There are 100 vehicles used for food and residual waste. There are different types of vehicles, normal one fraction or two fractions with back loaders, container trucks, mobile vaccumers, bottom emptying container cars, cargo and crane cars, special vehicles (for garages and other tight spaces). There is no electric vehicle used, all of them are biogas or HVO.

There are different types of data collected in Stockholm, including fuel type, vehicle type, fuel consumption, distance, and weight (only for one-family houses, not for apartment buildings, weigh when a car is being emptied). All data is collected through Excel files via email from providers, except the weight, which is coming in continuously over their system.

Technology is the biggest challenge for the Stockholm municipality. The system they use needs registration entering into it, if the car breaks down, the system also cannot work. Another challenge is they need to decide which types of data they should collect in the future. Stockholm municipality wants to be fossil-free by 2030, so now they try to start using electric vehicles. There are also some ongoing projects which focus a lot on digitization, for example, customers receive push notices that waste will be collected tomorrow.

5 Analysis

Based on the interview with municipalities, the current waste management situation was illustrated in the last chapter, while this chapter gives an analysis of the current waste transport situation of Swedish municipalities, including the challenges they face and the requirements towards the standardized system. Then the model building process is introduced in detail, from deciding the input parameters to the calculation process. Finally, a finished model is described, and the operation is introduced, the purpose of each step is explained.

5.1 The summary of current situation

5.1.1 The challenges which municipalities face

Sustainability is becoming a common and popular target for many municipalities. However, after analyzing the interview findings, it is easy to find that there are several challenges which hinder the process. Five challenges are identified and explained in the following:

1. The waste transport routes go across several municipalities.

There are many municipalities mentioned that they face difficulty to analyze the environmental impact of waste transports because vehicles drive across the municipal border. Without a clear boundary between municipalities in transport routes, it is difficult to calculate the fuel consumption and air emission in each area. The data is obscure and unclear currently.

2. Information in transparent between different handlers

In many municipalities, there are more than one contractor hired to handle the household waste. The waste transport routes can be overlapped in some areas. After municipalities get data from contractors, it cannot be added directly, which hinders the deeper analysis.

3. Different handling ways in different municipalities

The waste processing varies a lot among different municipalities. In some municipalities, they do not even collect waste according to the detailed sorting system. The different handling ways in different municipalities make it hard to do the environmental impact analysis.

4. No advanced technologies used in vehicles which can help to store data.

There is a lot of data that should be collected by some advanced technologies. For example, the transport distance and fuel consumption should be collected in vehicles. However, most vehicles that municipalities use do not have those advanced technologies, which causes difficulties to collect data.

5. No standardized system for data collection and analysis

After analyzing the data types that municipalities collect, it can be easily found that they do not have a standardized system for data collection and analysis. Most of them collect different types of data, for example, some municipalities collect fuel consumption of waste transport, but others do not care about it. Without a standardized system for data collection and analysis means that they cannot do comparison towards environmental impact between different areas.

5.1.2 The requirements towards a standardized system in the future

From the interviews it can be emphasized that the municipalities have some requirements towards a standardized system in the future. Some of the municipalities calculate the energy consumption in different ways which gives different results. The municipalities want to calculate their energy consumption in the same way because this will be one of the foundations in order to be able to use a standardized system in the future.

The municipalities also use different units when calculating fuel and energy consumption. Using the same unit would make the results more comparable which will then also lay the foundations for a standardized system.

From the interviews it can also be extracted that the municipalities collect their data in different ways, also the frequency of the data collection varies. They want to have the same data collection system for the energy and fuel consumption of their waste transports so that the data can have high credibility but also be comparable.

5.2 Calculation model building

5.2.1 Input parameters

The first step when developing the calculation model is to identify input parameters that will influence the energy and fuel consumption for waste transports, which in fact is the first research question of this master thesis. The input parameters are categorized into three different categories. The first category is called *basic municipality information* which includes the name of the municipality and the number of residents and households which live in that particular municipality, see figure 5-1. These input parameters will make it possible for the municipality to see how much a person/household consume waste (kg)/year and also to see the energy and fuel consumption per person/households/year. The inspiration for the input parameters for this category is given as a result of the interviews and the data collection from the different municipalities.

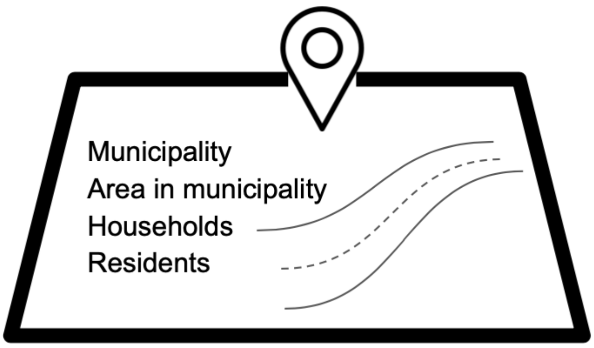

Figure 5-1 Basic municipality information

The second category is called *waste information* which includes the type of waste and the amount of the waste, see figure 5-2. The type of waste consists of food waste, residual waste, and bulky waste. These types of waste are considered because they are more common as a household waste. The amount of waste (kg) is a vital input parameter because it will influence the load factor which in fact will also have an impact on the energy and fuel consumption for the waste transports. The inspiration for using these input parameters for this category are given thanks to the report published by Avfall Sverige that summarizes their waste handling in Sweden (Avfall Sverige, 2020).

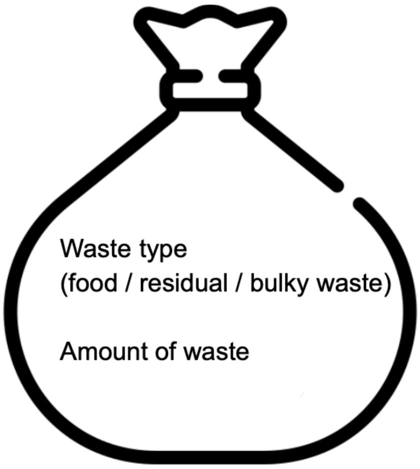

Figure 5-2 Waste information

The third category is called *vehicle information* which includes the type of vehicle, load capacity, transport distances (km), the type of energy that are used for the vehicle, the amount of energy and fuel consumption when driving with a full or/and empty vehicle and lastly the different Euro classes (1-7), see figure 5-3.

All of the selected input parameters in this category influence the energy and fuel consumption of waste transports except the Euro classes (1-7) which in fact influence the pollutant emissions, which should be considered because vehicles that uses the latest Euro classes are more likely to emit less pollutant emissions. The inspiration of these input parameters is thanks to vehicle data which are provided by Gothenburg city.

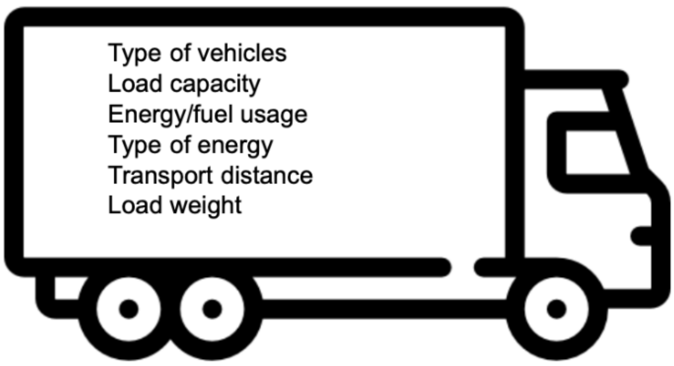

Figure 5-3 Vehicle information

It should also be noted that some of the selected input parameters are inspired from calculation models such as VECTO, COPERT and ETW, but especially NTM.

After analyzing all those input parameters, it can be easily found that not all of them should be input by users, there are some parameters that need to be set by model builders, or default values should be provided. In addition, these two parts of input parameters are not independent with each other. For example, the vehicle type and fuel type will influence the amount of energy consumption for empty or full driving, the frequency of waste transportation and transport distance are impacted by waste amount. So, it is necessary to set different default values for some parameters according to the requirements of users.

5.2.2 Formulas for energy and fuel consumption in waste transports

After deciding all the input parameters of the calculation model, the next step is to analyze the quantitative relationship between those factors and energy consumption in waste transports. In order to study the relationship, the general delivery process of waste transport needs to be analyzed firstly, see figure 5-4. Each vehicle departs from the recycling center to the first pick-up stop, which can be an apartment community or a one-family house, then stops in each pick-up point, finally it goes back to the recycling center with full loading, but in real situations, vehicles go back with almost full loading, since the volume of waste needs to be considered, here it is called max loading (<= full loading). Every vehicle repeats this trip cycle during the data collection period. Figure 5-4 describes the relationship between energy usage and distance, the energy usage increases as the loading weight grows, and the loading weight varies among different transport distances. In every transport trip, the energy usage is in the upward trend with the driving distance growing. Through multiplying the energy usage and distance, the total energy consumption in the data collection period (one year) can be obtained.

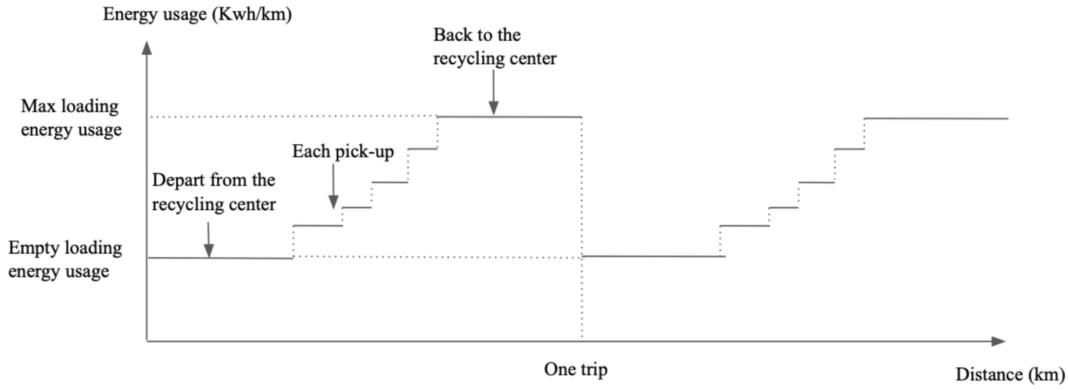

Figure 5-4 The waste transportation process

Since the waste transport trips are repeated, one trip can be a sample for quantitative analysis, see figure 5-5. The area of the shaded drawing is the total energy consumption of one trip. In order to calculate the area, it is needed to collect the distance between each pick-up point. However, it is impossible for municipalities to get such detailed data. In the thesis report, authors assume the pick-up process as a continuous process, which means the energy usage increases fluently, see figure 5-6.

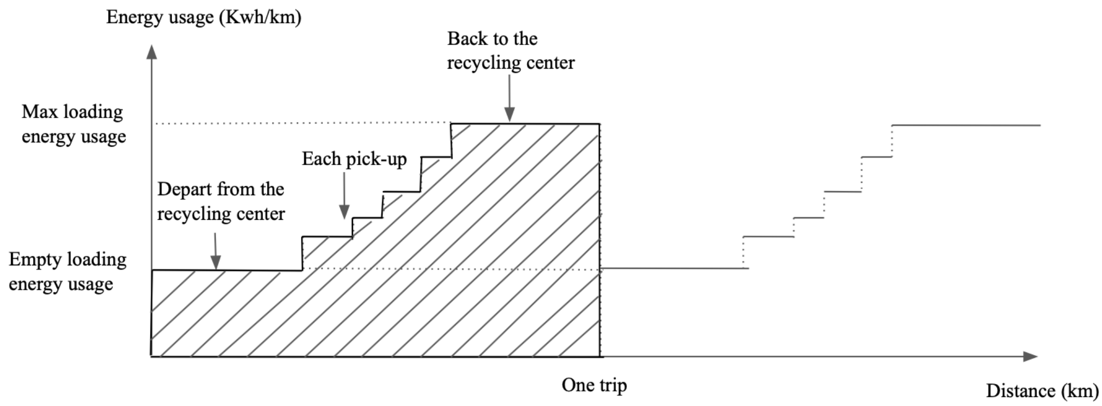

Figure 5-5 One round trip of waste transport

In figure 5-6, the initial pick-up point is connected with the last one by a straight line, which makes it easier to do the calculation. In figure 5-6, the drawing consisting of two rectangles and one trapezoid. The area calculation is shown below.

$$A = E_{empty} * D_1 + (E_{empty} + E_{max}) * D_2 / 2 + E_{max} * D_3$$

A: Total energy consumption of one trip (kWh)

E_{empty}: Empty loading energy usage (kWh/km)

E_{max}: Max loading energy usage (kWh/km)

D_1: Distance between the recycling center to the initial pick-up point (km)

D_2: Distance between the initial pick-up point and the last point (km)

D_3: Distance between the last point and recycling center (km)

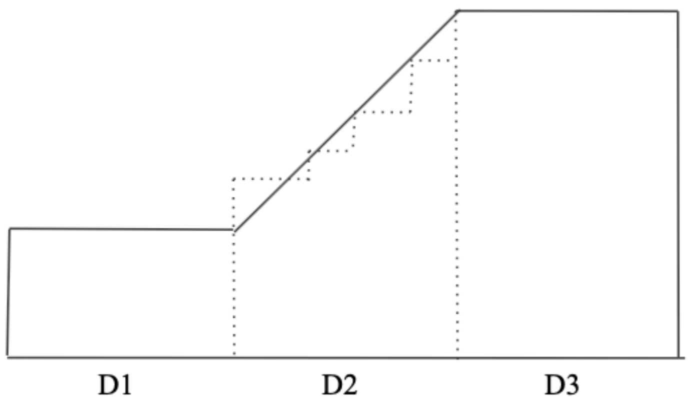

Figure 5-6 The assumption of one round trip of waste transport

It is impossible for municipalities to get detailed distance information during each waste transport trip, D_1, D_2 and D_3 vary among different trips and pick-up zones and cannot be determined. Since there is the same possibility between $D_1 > D_3$ and $D_1 < D_3$, authors assume $D_1 = D_3$, then the calculation can be derived into the formula below.

$$A = (E_{empty} + E_{max}) * D / 2$$

A: Total energy consumption of one trip (Kwh)

E_{empty}: Empty loading energy usage (Kwh/km)

E_{max}: Max loading energy usage (Kwh/km)

D: Transport distance per trip (km)

In the developed model, there are two different calculation ways provided. The first one using default data, which is provided for some municipalities which lack detailed vehicle driving data. More specifically, some municipalities never collect the driving distance of each waste transport trip as well as the max loading weight. Then they do not need to fulfill the load weight information but choose to use the default data of the model which is already provided.

In order to set the default data for the model, more assumptions need to be done. The max loading weight can directly determine the energy consumption, but not all of the municipalities collect it for every vehicle. In general, every vehicle goes back with full loading, so authors assume the max loading weight as the full loading weight, then the max loading energy usage is equal to the full loading energy usage. In addition, the transport distance can be added together and only the total transport distance is required. The calculation formula in the model is shown below. In other words, the default number of loading capacity utilisation is 50%.

$$A_{yearly} = (E_{empty} + E_{full}) * D_{yearly} / 2$$

A_{yearly}: Total energy consumption per year (kWh)

E_{empty}: Empty loading energy usage (kWh/km)

E_{full}: Full loading energy usage (kWh/km)

D_{yearly}: Total transport distance per year (km)

If users want to get more accurate results, the driving distance of each waste transport trip as well as the max loading weight should be collected. In some municipalities, like Kalskrona and Umeå, every truck is weighted before emptying, which is equal to the max loading. Through those max loading data, an average loading weight of each vehicle can be obtained. In the advanced model, the loading capacity utilisation can be calculated based on the average loading weight.

$$LCU = W_{average} / LC$$

LCU: Load capacity utilisation (%)

$W_{average:}$: Average load weight (kg)

LC: Load capacity (kg)

$$E_{max} = E_{empty} + (E_{full} - E_{empty}) * LCU$$

E_{empty}: Empty loading energy usage (kWh/km)

E_{full}: Full loading energy usage (kWh/km)

E_{max}: Max loading energy usage (kWh/km)

LCU: Load capacity utilisation (%)

5.2.3 Calculation Model for Energy and Fuel Consumption of Waste transports

The next step after identifying input parameters and designing the calculation method of each input parameters based on quantitative relationships makes it possible to develop the calculation model for energy and fuel consumption of waste transports in Sweden. The figure 5-7 visualizes the design of the model and the different input parameters.

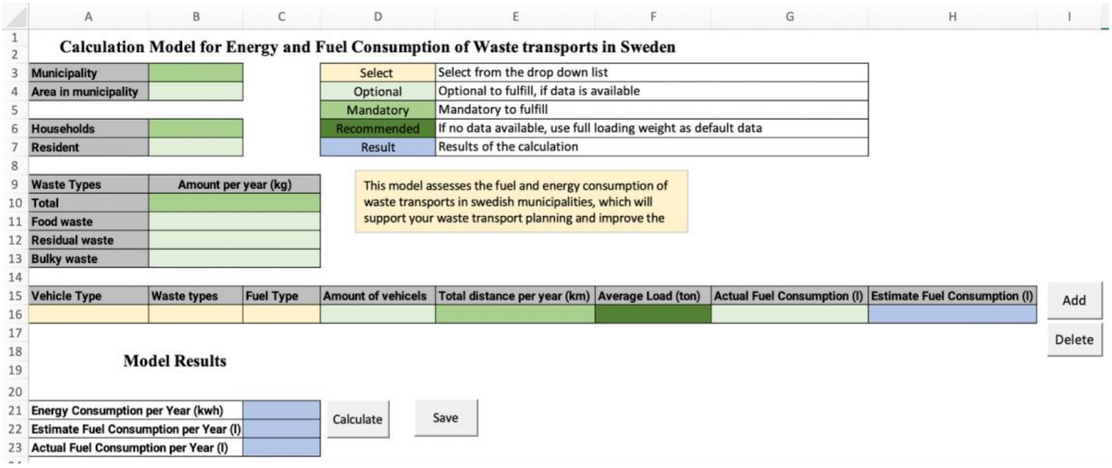

Figure 5-7 Visualization of the energy and fuel consumption calculation model

There are four input parts for users to get the calculation results, the first part of the model is to type in the name of the municipality, which is used for data collection and further comparison among different municipalities.

The second step is to type in the number of households that live in that specific municipality. This data is mandatory for users to fulfill since it is used for calculating the waste generation per household and the energy or fuel consumption per household.

The third step in the model is to type in the waste information (food waste, residual waste and bulky waste) that are collected in that municipality. The users should type in the amount of waste (kg) manually. If there is less waste generated per household, then less energy or fuel will be used for waste transport. The data is useful for municipalities to set targets for waste management.

The fourth step is to select one or several types of vehicles that are used in that municipality and the fuel types that are used for the vehicles. Then the usage of the vehicle, total transport distance (km) and average load weight (kg) of the vehicle should be typed in manually. However, the average load weight per vehicle is not mandatory, since not all municipalities collect this data. If the cell of average load weight is empty, the model will use the default data, which equals to full loading weight. The calculation result of each vehicle type is shown in the estimated fuel consumption. However, if there are some municipalities which already collected the fuel consumption of some vehicles, then the user can directly type into the actual fuel consumption.

The final step is to press the calculation button in the model that will calculate the energy consumption per year, estimated fuel consumption per year and actual fuel consumption per year.

The calculation uses the data in the vehicle information sheet, which is also provided in the excel document with the model. The vehicle information spreadsheet that consists of vehicle information of the different vehicles that includes pictures of the vehicle, their energy and fuel consumption, their weight, etc.

The model is not only for calculation, but also provides an option where the user can save the results of the calculation model in a separate excel sheet as shown in the figure 5-8 below. This option will allow the municipality to compare their sustainability situation with other municipalities.

	A	B	C	D	E
1	Manicipality	Area in municipality	Waste (kg per household)	Energy consumption per year per household (kwh)	Fuel consumption per year per household (l)
2					
3					
4					
5					

Figure 5-8 The data collection sheet in the model

6 Discussion

During the workshop with Gothenburg Stad and Chalmers Industriteknik, the model was tested by using the data of Gothenburg waste transports. After the workshop, the strengths and weaknesses of the model were highlighted. In addition, the practicality of the model was discussed, which gave inspiration for further study.

6.1 Strengths

Some strengths existing in the model can provide the municipalities with important functions. One of the first strengths of the model is that it is user-friendly since it is easy to operate the model and navigate through it. This was one of the prerequisites of the model that it should be easy to operate it. The model also has instructions that guide the operators through the model.

Since the model is developed through excel, it is easily accessible. In comparison to other calculation tools or models that cost to operate and also have a lower availability, an excel tool is operable for nearly all municipalities.

Another strength of the model is that it can continuously be improved by adding new functions. The use of excel makes it possible to add or remove functions immediately.

The model will allow the municipalities to compare fuel consumption among different transport vehicles, which allows them to analyze the waste transport vehicles' fuel and energy consumption, so that the municipalities can operate waste transport vehicles that are more energy and fuel-efficient. This information can also be used when the municipality decides to purchase new vehicles that are more energy and fuel-efficient.

The model does also provide vehicle information of the different vehicles, which makes it possible for the municipalities to perform their calculations if they do not have their own data available. The model also provides default settings if the municipality in cases where the municipalities do not have more exact data. An example of this is that the load cargo capacity is set at 50 %, but if the municipality has the data, then the results will be even more accurate. In section 5.2.2 of this thesis, it is explained why 50% were chosen as a default setting.

Lastly, this model gives inspiration for further studies which analyze the energy and fuel consumption in waste transportation, since there are not many models that consider waste transports. The majority of fuel and energy consumption models consider personal vehicles and trucks instead of waste transport vehicles.

6.2 Weaknesses

There are some weaknesses existing in the model which can provide an inspiration for further improvement. Firstly, this model is only used for energy and fuel consumption calculation which means there is no GHG emissions calculation function included. However, the environmental impact system of waste transport used in the City of Gothenburg provides CO_2 emissions data for users, since the GHG emissions are also an aspect of environmental impact. It is also possible to develop the model to include this aspect as well, which will be achieved in the further study.

The second weakness of the model is that it is missing some input parameters. There are at least two parameters that should be added into the model, one is the traffic characteristics, another one is the Euro classes. The geographic characteristics mainly refers to the type of the road, such as rural, urban and motorway, which is in the is a suggestion for further work to improve the accuracy of the model.

The geographic factors largely influence the driving characteristics, like driving speed, brake operations, acceleration, or deceleration. All of those operations influence the energy and fuel consumption during transportation.

As for the Euro class, which is used for calculating the harmful air emissions, which is not included in the model, but could be collected for further development.

Although the total amount of waste is used for analyzing the waste generation in the model, the amount of each waste type is not used in the model. Hence, the third weakness is that there is no link between the energy and fuel consumption and amount of each waste type. Users cannot get the data about the energy and fuel consumption per ton of waste.

6.3 Practicality

The practicality of the model varies in different municipalities. In big municipalities, like Gothenburg, they already have a relatively complete system to assess the environmental impact of waste transportation, but the existing model does not make it possible to compare the situation in different municipalities. In order to apply the model in those municipalities, the data compatibility is important, which means the old models should be easily integrated into the new one. However, this model has not been designed to be compatible with different current systems in this master thesis.

As for some municipalities, which do not have mature systems currently, this model can be applied easily and help them to collect and calculate energy and fuel consumption data of waste transportation. The main obstacle is that if they do not have enough data to be typed into the model, this might influence the accuracy of the result.

In summary, the model can be applied in different municipalities, even if they have different situations. Since this thesis is embedded in a project, the model will be improved until the end of the project and then be put into use.

7 Conclusion and future recommendations

In this chapter, the challenges that municipalities face and requirements towards a standardized system are listed in a table. Then the three research questions are answered, followed with recommendations for the future relevant research.

7.1 Conclusion

This thesis research has established a calculation model for energy and fuel use of waste transports in Swedish municipalities. The model is embedded in a user-friendly tool and achieved through Excel VBA. Through workshops and interviews with municipalities, the current waste transport situation of municipalities in Sweden, including the challenges they face and the requirements towards the standardized system were listed in table 7-1.

Table 7-1 Current waste management situation in Swedish municipality

Challenges that municipalities face	• The waste transport routes go across several municipalities. • Information is not transparent between different handlers. • The waste collection process varies from municipalities to municipalities. • Currently no advanced system is used in vehicles that could store valuable data. • There is no standardized system for data collection and analysis
Requirements towards a standardized system for energy and fuel consumption of waste transports	• Energy and fuel consumption should be calculated in the same way for all of the municipalities. • Same units should be chosen when calculating the data through the model. • The municipalities should choose the same data collection process

Based on the summary of the current waste management situation, as well as the analysis during the research, the three research questions were answered.

RQ1 What input parameters impact the energy and fuel usage in waste transportation?

The input parameters of the model are categorized into three different categories. First one is basic municipality information, which was given as a result of the interviews and the data collection from the different municipalities. The second category is called waste information, which was inspired from the report published by Avfall Sverige that summarizes their waste handling in Sweden. The last category is vehicle information, which was inspired from the vehicle data provided by Gothenburg city. All of those input parameters were also inspired from calculation models, mainly NTM, but also VECTO, COPERT and ETW.

RQ2 How does each factor in the model quantitatively impact the energy and fuel consumption?

In order to integrate all of the input parameters into the model, the quantitative relationships between some parameters and final energy and fuel consumption have been analyzed. In order to convert the relationship into formulas, the waste transport driving processes have been visualized in figures. Considering the data shortage of municipalities, the default data is provided for users, which helps to make the model working smoothly.

RQ3 How can municipalities improve the sustainability in waste transports through the model?

The use of the model will allow the municipalities to compare their results with previous years and also let them compare with other municipalities. The reason for this is that the model is a standard where the different municipalities will use the same model, and this will lead to more comparable results. When different municipalities use the same model, it will also allow them to have meetings/discussion on how to be more sustainable, because for instance if one of the municipalities improve their results then other municipalities can get the same data/information on how to improve their results or some input that can be beneficial.

In addition, the fuel consumption of each vehicle type is calculated in the model, which gives a guidance to municipalities when they purchase waste transport vehicles and compare the fuel consumption among vehicles.

7.2 Future recommendations

This thesis provided a general model which was used for environmental assessment of waste transport in Sweden. However, this model development is still in the initial stage of the project, which means there are some improvements that should be done in further studies. Here are some recommendations provided by authors based on the calculation model.

1. Road types should be added in the model as an input parameter.

The traffic conditions on different roads vary a lot, for example, motorways are built for long-distance and fast-speed travelling, so there are less traffic lights in motorways than urban ways. The frequent acceleration or brake operation leads to more energy or fuel consumption. In the NTM model, the information of fuel consumption in motorways, rural ways and urban ways is provided, and users can select the road type to calculate the environmental impact of their transport. However, the fuel consumption information of waste transport vehicles collected by municipalities is not comprehensive, which leads to this input parameter missing in the model.

2. Euro class could be added in the model to calculate the harmful air pollution.

Since this thesis focuses on the energy and fuel consumption, air emissions are not included in the calculation. In order to achieve higher Euro class standards, cleaner energy is needed to reduce the harmful air pollution, which is also the environmental target of waste transport in Sweden. In further studies, municipalities could add the Euro class into the model to calculate the harmful air pollution and establish a more comprehensive transport assessment model.

3. Detailed vehicle information should be collected.

The energy and fuel consumption of different waste transport vehicles are collected by municipalities, but there is no detailed energy and fuel consumption information of empty loading or full loading, which limits further studies.

4. Transport routine or transport time should be considered.

In order to get more accurate results, the transport routine or transport time should be considered. The driving condition during transports can be determined through the transport routine or transport time since it influences the energy and fuel consumption. However, it is too complex to analyze, which needs long-term research.

5. More advanced technologies should be installed in vehicles.

As it is mentioned in the challenges that municipalities face, there is a lot of data which could have been collected by some advanced technologies in vehicles. For example, the transport distance and fuel consumption should be collected in vehicles. However, most vehicles that municipalities use do not have those advanced technologies, which cost time and resources to collect data manually.

6. More advanced IT system between contractors and municipalities, make the information more transparent.

Both municipalities and contractors should use a more advanced IT system between them so that every kind of information is stored and well documented. This will allow them to find data/information easier and will also result that the input data in the model are more accurate which will make the results more accurate.

7. More environmentally friendly vehicles are needed.

The municipalities should, if possible, use vehicles that have a lower fuel and energy consumption in order for them to improve their sustainability. This is a recommendation that the municipalities should consider because it will have a positive impact and result in a lower energy and fuel consumption if the municipalities for instance use an electric vehicle instead of vehicles that are driven by an internal combustion engine.

8. Build a web application instead of the Excel model.

The model is currently on Excel, but in the future, it could be more beneficial for the municipalities to transfer the model to a web application where it can be more flexible and more accessible for the municipalities. The use of web applications will also allow for more functions for the model to be developed further, because the use of Excel is limited.

9. More cooperation with some traffic assessment institutions, like NTM

It is recommended that the municipalities collaborate with traffic assessment institutions in order to get more inspiration on how the model can be improved or also to get some help if there are some problems with the model.

10. More cooperation among different municipalities in order to make the waste management more sustainable.

Lastly it is recommended that the different municipalities collaborate together in order to have a more sustainable waste management. This could be through meetings where some of the representatives from the different municipalities go through problems/obstacles that they face or some solutions that they use in order to prevent problems from occurring. This kind of information sharing will be beneficial and will lay the foundations to work proactively and continuously improve the waste management, so it becomes more sustainable.

11. CO_2 emissions should be considered as an input parameter.

The use of CO_2 emissions as an input parameter will allow the municipalities to compare their CO_2 emissions with other municipalities together with their fuel and energy consumption. The model will become more comprehensive since the CO_2 emission is also an important aspect of the environmental impact.

12. The amount of waste types should be linked to the energy and fuel consumption.

The amount of different waste types is collected in the model, but it has not been linked to the final calculation results, which means that the users do not have the data about how much energy and fuel are used in the different waste types. It would be beneficial to add a function which calculates the total energy and fuel usage per ton of different vehicles. This function can also help to complete the vehicle information, since there is only energy and fuel consumption per km now.

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Appendix A: VBA Code

```
Function FuelToInt(str As String) As Integer
  Dim FuelTypes() As String
  ReDim FuelTypes(0 To 4)
  FuelTypes(0) = "Diesel"
  FuelTypes(1) = "HVO"
  FuelTypes(2) = "Biogas"
  FuelTypes(3) = "Battery"
  FuelTypes(4) = "Fuelcell/Hydrogen"

  Dim i As Integer
  For i = LBound(FuelTypes) To UBound(FuelTypes)
      If FuelTypes(i) = str Then
         FuelToInt = i
         Exit For
      End If
  Next i
End Function
```

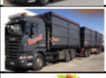
```
Sub onAddVechicleClick()
   Dim lastRow As Long
   lastRow = Range("H:A").Find(What:="Model Results", LookIn:=xlValues).row - 2
   With Worksheets("Model")
      .Rows(lastRow).Copy
      .Range("A" & CStr(lastRow + 1)).Insert Shift:=xlDown
   End With
   Range("A" & CStr(lastRow + 1) & ":" & "H" & CStr(lastRow + 1)).ClearContents
   ActiveSheet.Range("A" & CStr(lastRow + 1)).Select
End Sub
```

```
Sub onDeleteClick()
   Dim firstRow As Long
   Dim lastRow As Long
   firstRow = Range("H:A").Find(What:="Vehicle Type", LookIn:=xlValues).row + 1
   lastRow = Range("H:A").Find(What:="Model Results", LookIn:=xlValues).row - 2
   If lastRow = firstRow Then
      MsgBox "The last row cannot be deleted"
   Else
      Rows(lastRow).EntireRow.Delete
   End If
End Sub
```

```
Sub onCalculateClick()
   Dim firstRow As Long
   Dim lastRow As Long
   firstRow = Range("H:A").Find(What:="Vehicle Type", LookIn:=xlValues).row + 1
   lastRow = Range("H:A").Find(What:="Model Results", LookIn:=xlValues).row - 2

   Dim TotalEnergyConsumption As Long
   Dim TotalFuelConsumption As Long
   Dim ActualFuelConsumption As Long
   TotalEnergyConsumption = 0
   TotalFuelConsumption = 0
   ActualFuelConsumption = 0

   Dim VehicleType As String
   Dim FuelType As String
   Dim Distance As Long
   Dim AvgLoadWeight As Long
   Dim Fuelconsumption As Long

   Dim RowIndexVehicleInfoSheet As Long
   Dim FullLoadVehicleInfoSheet As Long
   Dim EmptyLoadVehicleInfoSheet As Long
   Dim LoadCapacityVehicleInfoSheet As Long
   Dim Vehicleamount As Long

    Dim RowIndex As Integer
    For RowIndex = firstRow To lastRow
       VehicleType = Range("A" & CStr(RowIndex))
       FuelType = Range("C" & CStr(RowIndex))
       Distance = Range("E" & CStr(RowIndex))
       AvgLoadWeight = Range("F" & CStr(RowIndex))
       Fuelconsumption = Range("G" & CStr(RowIndex))
       Vehicleamount = Range("D" & CStr(RowIndex))

       RowIndexVehicleInfoSheet = ThisWorkbook.Sheets("Vehicle Information").Range("G:C").Find(What:=VehicleType, LookIn:=xlValues).row
       FullLoadEnergyVehicleInfoSheet = ThisWorkbook.Sheets("Vehicle Information").Range("J" & CStr(RowIndexVehicleInfoSheet + FuelToInt(FuelType)))
       EmptyLoadEnergyVehicleInfoSheet = ThisWorkbook.Sheets("Vehicle Information").Range("K" & CStr(RowIndexVehicleInfoSheet + FuelToInt(FuelType)))
       FullLoadFuelVehicleInfoSheet = ThisWorkbook.Sheets("Vehicle Information").Range("L" & CStr(RowIndexVehicleInfoSheet + FuelToInt(FuelType)))
       EmptyLoadFuelVehicleInfoSheet = ThisWorkbook.Sheets("Vehicle Information").Range("M" & CStr(RowIndexVehicleInfoSheet + FuelToInt(FuelType)))
       LoadCapacityVehicleInfoSheet = ThisWorkbook.Sheets("Vehicle Information").Range("F" & CStr(RowIndexVehicleInfoSheet))

    If AvgLoadWeight = 0 Then
       Range("H" & CStr(RowIndex)) = (FullLoadFuelVehicleInfoSheet + EmptyLoadFuelVehicleInfoSheet) * Distance / 2
       TotalEnergyConsumption = TotalEnergyConsumption + (FullLoadEnergyVehicleInfoSheet + EmptyLoadEnergyVehicleInfoSheet) * Distance / 2
       TotalFuelConsumption = TotalFuelConsumption + (FullLoadFuelVehicleInfoSheet + EmptyLoadFuelVehicleInfoSheet) * Distance / 2
       If Fuelconsumption <> 0 Then
          ActualFuelConsumption = ActualFuelConsumption + Fuelconsumption
       Else
          ActualFuelConsumption = ActualFuelConsumption + (FullLoadFuelVehicleInfoSheet + EmptyLoadFuelVehicleInfoSheet) * Distance / 2
       End If
    Else
       Range("H" & CStr(RowIndex)) = (EmptyLoadFuelVehicleInfoSheet + (FullLoadFuelVehicleInfoSheet - EmptyLoadFuelVehicleInfoSheet) * AvgLoadWeight / LoadCapacityVehicleInfoSheet) * Distance
       TotalEnergyConsumption = TotalEnergyConsumption + (EmptyLoadEnergyVehicleInfoSheet + (FullLoadEnergyVehicleInfoSheet - EmptyLoadEnergyVehicleInfoSheet) * AvgLoadWeight / LoadCapacityVehicleInfoSheet) * Distance
       TotalFuelConsumption = TotalFuelConsumption + (EmptyLoadFuelVehicleInfoSheet + (FullLoadFuelVehicleInfoSheet - EmptyLoadFuelVehicleInfoSheet) * AvgLoadWeight / LoadCapacityVehicleInfoSheet) * Distance
       If Fuelconsumption <> 0 Then
          ActualFuelConsumption = ActualFuelConsumption + Fuelconsumption
       Else
          ActualFuelConsumption = ActualFuelConsumption + (EmptyLoadFuelVehicleInfoSheet + (FullLoadFuelVehicleInfoSheet - EmptyLoadFuelVehicleInfoSheet) * AvgLoadWeight / LoadCapacityVehicleInfoSheet) * Distance
       End If
    End If

       Next RowIndex

    Dim resultRow As Long
    resultRow = Range("G:A").Find(What:="Energy Consumption per Year (kwh)", LookIn:=xlValues).row
    Range("C" & CStr(resultRow)) = TotalEnergyConsumption
    Range("C" & CStr(resultRow + 1)) = TotalFuelConsumption
    Range("C" & CStr(resultRow + 2)) = ActualFuelConsumption
End Sub
```

```
Sub onSaveClick()
    newRow = Sheets("Data Collection").Cells(Rows.Count, 1).End(xlUp).row + 1
    Sheets("Data Collection").Range("A" & CStr(newRow)) = Range("B3")
    Sheets("Data Collection").Range("B" & CStr(newRow)) = Range("B4")
    Sheets("Data Collection").Range("C" & CStr(newRow)) = Range("B10") / Range("B6")
    Dim resultRow As Long
    resultRow = Range("G:A").Find(What:="Energy Consumption per Year (kwh)", LookIn:=xlValues).row
    Sheets("Data Collection").Range("D" & CStr(newRow)) = Range("C" & CStr(resultRow)) / Range("B6")
    Sheets("Data Collection").Range("E" & CStr(newRow)) = Range("C" & CStr(resultRow + 1)) / Range("B6")
'    Sheets("Data Collection").Range("F" & CStr(newRow)) = Range("C" & CStr(resultRow + 2)) / Range("B6")
    MsgBox "Results have been saved to 'Data Collection' sheet"
End Sub
```

Appendix B: Energy and fuel usage of waste transport vehicle

#ID	Picture (example)	Type	Useage	Curb weight ton	load capacity (weight) ton	Max gross weight ton	length m	Fuel type	Energy usage: Full loading kWh/km	Energy usage: Empty loading kWh/km	Fuel consumption: Full loading l/km	Fuel consumption: Empty loading l/km
1		Two axle rear loader	al- and foodwaste (plastic, paper, cardboard, corrug	12.5	7	19.5	8 - 8,5	Diesel	3,300	2.850	0,338	0,292
								HVO	4,400	3,800	0,469	0,405
								Biogas				
								Battery				
								Fuelcell/Hydrogen				
2		Three axle rear loader	al- and foodwaste (plastic, paper, cardboard, corrug	14.55	11	26.5	9,5	Diesel	4,400	3,800	0,450	0,389
								HVO	4,400	3,800	0,469	0,405
								Biogas				
								Battery				
								Fuelcell/Hydrogen				
3		Rear-loading two-compartment car	aste at the same time. Division into compartments	15.505	11	18	9,5	Diesel	4,400	3,800	0,450	0,389
								HVO	4,400	3,800	0,469	0,405
								Biogas				
								Battery				
								Fuelcell/Hydrogen				
4		Cable car	Can empty both bins and containers	14.55	10	26.5	9,5	Diesel	4,400	3,800	0,450	0,389
								HVO	4,400	3,800	0,469	0,405
								Biogas				
								Battery				
								Fuelcell/Hydrogen				
5		Side loader	al- and foodwaste (plastic, paper, cardboard, corrug	13.95	7	29	9	Diesel	4,400	3,800	0,450	0,389
								HVO	4,400	3,800	0,469	0,405
								Biogas				
								Electricity				
								Fuelcell/Hydrogen				
6		Four-compartment car	Four waste compartments	17.57	7	26.5	8,7	Diesel	4,400	3,800	0,450	0,389
								HVO	4,400	3,800	0,469	0,405
								Biogas				
								Electricity				
								Fuelcell/Hydrogen				
7		Crane truck	For underground containers	18.38	9	27	8 - 8,5	Diesel	4,400	3,800	0,450	0,389
								HVO	4,400	3,800	0,469	0,405
								Biogas				
								Battery				
								Fuelcell/Hydrogen				
8		Demountable	th operational waste. In terms of household waste,	12.805		29		Diesel	4,400	3,800	0,450	0,389
								HVO	4,400	3,800	0,469	0,405
								Biogas				
								Electricity				
								Fuelcell/Hydrogen				
9		Lift dumper	For bulky waste collection	11.42	7	19.5	8 - 8,5	Diesel	3,300	2,850	0,338	0.292
								HVO	3,300	2,850	0,351	0,303
								Biogas				
								Battery				
								Fuelcell/Hydrogen				
10		Mobile vaccum	ected in underground tanks and then sucked up wi	20.145		29.5		Diesel				
								HVO				
								Biogas				
								Battery				
								Fuelcell/Hydrogen				
11		Demountable with trailer	t stations for incineration or in some cases from rec	12.655 + trailer 5.92	50	29+trailer 38	22	Diesel	5,500	4,750	0,562	0,485
								HVO	5,500	4,750	0,585	0,505
								Biogas				
								Battery				
								Fuelcell/Hydrogen				
12		Tractor with trailer	d primarily to transport slag from incineration to la	10.47 + trailer 11.33	45	27+trailer 48	20	Diesel	5,500	4,750	0,562	0,484
								HVO	5,500	4,750	0,585	0,505
								Biogas				
								Battery				
								Fuelcell/Hydrogen				
13		Frontloader	Mostly used for industry waste	20.26	11	35	10	Diesel	5,500	4,750	0,562	0,485
								HVO	5,500	4,750	0,585	0,505
								Biogas				
								Battery				
								Fuelcell/Hydrogen				

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