Sustainable Reverse Logistics for Household Plastic Waste

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“Real knowledge is to know the extent of one’s ignorance.”

Confucious

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Contents

Chapter 1

Introduction

1.1 Introduction to the research project

In January 2010, I worked as an intern at a logistics company in Germany. The department I worked in was involved in waste recycling business, which gave me the opportunity to visit a number of German sorting and re-processing plants. There, I saw many piles of plastic waste baled and placed in open yards with tags marking their origins. People working in these plants told me where the baled plastics came from, how the quality differed, how they dealt with it, and some of the problems they saw. I started to picture the story behind this plastic waste, what it had been through, and how it had ended up in the bale in front of me. I became interested in this topic and, serendipitously, five months later I started this PhD project, which gave me the luxury of four years to look into the subject of plastic waste recycling in the Netherlands.

The European Union has about 502 million inhabitants who generate an average of 520 kg of municipal solid waste per year each, which equates to 260.5 million tons in total (EEA, 2012). Handling such a large amount of municipal solid waste (MSW) can be quite challenging. Despite a great deal of legislation and public attention, 40 percent of the waste in Europe was still landfilled as of 2009 (EUROSTAT, 2011). Recycling is one of the waste treatment options that has the greatest potential for further improvement.

Regarding plastic waste recycling, four percent of oil consumption in Europe is used for the manufacture of plastic products (PracticalAction, 2010). Recycled plastic can be used in the manufacturing of plastic products to reduce the use of virgin plastics material. The cost of recycled plastics is usually lower than that of virgin plastics. Therefore, it is environmentally and economically beneficial to improve the plastic recycling system to ensure more plastic waste from households are properly collected and processed for recycling.

To do so, there is a need to build a more suitable, efficient and sustainable recycling system from collection to the final processor. The current system is rather complex, as plastic waste recycling in the Netherlands is characterized by various collection, separation and treatment systems. for example, the first step of the processing system, separating plastics from other waste, can occur at households or in separation centers, which makes a difference in terms of infrastructure, collection frequency of vehicles, vehicle types, etc. The collection method determines whether the quality and quantity of the plastics material to be recycled is high enough to be economically efficient and environmentally effective.

Motivated by the need to gain greater insights into the plastic waste recycling system, the Post-consumer Packaging Recycling project of Top Institute Food & Nutrition (TIFN) was founded, in cooperation with Kenniscentrum Nascheiding (KCN), an expertise center located in Wageningen, the Netherlands. KCN investigates the technological and economic feasibility, as well as the environmental impact, of new technologies for the treatment of plastics (packaging waste) found in household waste. The project is built on economic, technological, environmental, and logistics research. This thesis aims to analyse the collection, separation and treatments systems of plastic waste and proposes redesigns for the recycling system using quantitative decision support models.

1.2 Research problem description

The complexity of plastic waste recycling decisions are determined by external factors and characteristics of plastic waste recycling. In this section, we describe the problem by firstly introducing the related external factors and specific characteristics of plastic waste recycling. Then, we describe the desired outcome of the decision making process, i.e. eco-efficiency, and present issues related to various decision levels in the context of plastic recycling.

External factors:
During recent years, post-consumer waste recycling has been stimulated by regulation. EU regulations provide an enormous incentive for national governments to improve their recycling systems (EU, 2008). Response rates in these directives are set for each type of recyclable waste, including glass, paper, plastic, wood, and metals. EU Directive 2004/12/CE requires a response rate of 22.5 percent of plastic packaging, while for other packaging materials, the response rate is set at around 50-60 percent. The aim to improve plastic packaging recycling is high. EU Directive 2008/98/EC specifies that, by 2020, the preparation for reuse and recycling of plastic materials from households must be increased to a minimum of 50 percent by weight. In the Netherlands, the targets were set at a response rate of 43 percent in 2013, increasing gradually up to 52 percent of post-consumer plastic packaging waste by 2022 (Cramer, 2007).

Besides regulations, rising oil prices, combined with the cost reductions from using recycled plastics instead of virgin polymer-based plastics also made plastic recycling environmentally and economically favorable. For instance, according to Arena et al. (2003) producing 1kg of flakes out of recycled PET instead of virgin PET saves roughly 30MJ of energy. Thus, the demand for recycled plastics as production input is mostly from manufacturing industries.

Furthermore, plastic waste recycling involves a number of stakeholders, including householders, collection companies, and municipalities, whose interests must be considered and balanced. Municipalities are among the most important stakeholders, and each one has different characteristics such as population density. They can opt for different taxation schemes for household waste management, varying from a fixed (or differentiated) fee to volume/collection frequency, called DIFTAR (means "pay as you throw" in English). DIFTAR is usually applied because it is seen to contribute to waste reduction and a fair cost sharing (AgentschapNL, 2011). To sum up, regulations, market, stakeholders and taxes are important external factors that have an impact on the logistics design of plastic waste recycling.

Plastic waste characteristics:
The special characteristics of plastic packaging make the recycling of plastic waste different from other recyclable materials. Household plastic waste recycling is a complex system that involves a combination of different collection alternatives for municipal waste management. Two recycling schemes exist in the Netherlands. Plastic packaging is either separated from other household waste at the household level via source-separation, or separated from the household residual waste in a waste treatment center (post-separation). In combination with the two separation methods, two collection options are possible: curb-side and drop-off collection. Waste is placed at the curb-side in front of houses in the former and at central points in large containers in the latter. These systems occur simultaneously in the Netherlands, even in the same municipality. All these combinations make it complicated to grasp the collection of plastic waste into a waste collection cost model, let alone the different sizes and types of bins and trucks used in practice and the relatively large number of municipalities (418) in the Netherlands.

Plastic is also a light and voluminous material. This feature gives plastic material an advantage in being used for packaging purposes but makes it difficult to achieve efficiency in the transportation of the recycling procedure. In comparison with other recyclable waste, plastic containers and collection vehicles are quicker to be fully filled while weighing much less. Besides, many types and compositions of plastic materials are widely used in various applications in people's daily life. The most common examples of the plastic types that can be found in household plastic waste are PET (Polyethylene Terephthalate), PP (Polypropylene), and PE (Polyethylene). To achieve a mono-material flow of secondary raw material for plastic waste recycling, each of these fractions need to be sorted out of the household waste. A mix of different plastic types or contaminated plastics can not be used in re-processing for making recycled plastic sheets or granules to be used in manufacturing.

The characteristics of plastic waste recycling, as described above, can be summarized as (1) post-separation and source-separation, (2) drop-off and curb-side collection, (3) light material (low in density), and (4) complex composition (consist of various types of plastics).

Eco-efficient performance:
The purpose of investigating the recycling system of plastic is to make it more sustainable. This research views plastic recycling as an application of reverse logistics. It combines the concept of reverse logistics with that of sustainable logistics. Reverse logistics is the process of planning, implementation, and controlling the efficient, effective inbound flow and storage of secondary goods and related information, as opposed to the traditional supply chain directions, with the aim of recovering value and proper disposal (Fleischmann et al., 1997). The rapid evolution of sustainable development has changed the goals of almost every supply chain, including reverse logistics for waste management. Sustainable development involves achieving a balance between ecological, economic, and social impacts at the level of society in the long term (Aiking and Boer, 2004, Seuring and Muller, 2008). The requirement of sustainable logistics is to conduct the activities in a sustainable manner; that is, to pay attention to environmental impacts and social well-being in addition to cost minimization. This thesis focuses on eco-efficiency in supply chain within the scope of sustainable supply chain. The concept of *eco-efficiency* is based on the concept of creating more goods and services while using fewer resources and creating less waste and pollution (WBCSD, 2000). From a modelling point of view Quariguasi-Frota-Neto et al. (2009) defined a set of solutions to be eco-efficient when it is not possible to decrease environmental damage, or increase total environmental quality of each environmental category, unless increasing costs.

Decision levels:
In order to improve the eco-efficiency in the complex recycling system of plastic packaging waste, insights into the system are required. Decisions in MSW management can typically be classified into three levels: strategic, tactical and operational. Operational level decisions are issues related to the day-to-day schedule of operations such as delivery of goods to customers. Typical tactical decision are related to capacity and locations of production and positioning inventory. Strategic decisions deal with issues with a relatively long planning horizon (e.g. a few years) and investment decisions (Schmidt and Wilhelm, 2010). The combined decisions at these inter-related levels, or even on one level specifically, are often too complex to be solved at once. The complexity of such large-scale problems exceeds the capabilities and insights of even the most knowledgeable and experienced decision makers (Goetechalcks and Fleischmann, 2008). A common approach is to decompose the total decision-making problem into several sub-problems on each level.

Decision support systems are developed based on optimization techniques to explore the power of mathematical modelling for assisting decision-making process. By modeling the sustainable reverse logistics of plastic waste recycling, this study provides decision support at the three decision levels. Ghiani et al. (2014) stated that, a waste management system can be decomposed into two major sub-systems: a regional waste management system, and a municipal collection system. The regional waste management system deals foremost with the network design at strategic level, and allocation of waste flows and recycling channels at the tactical level. Transport routes and internal logistics-related issues are part of the operational level. In sum, in the context of plastic waste recycling, decisions in strategic, tactical and operational levels can be characterized as network design, flow allocation, and collection planning, respectively. A conceptual model has been developed accordingly for this research, comprising external factors and complexity of the problem based on plastic waste characteristics. The aim is to provide decision support from the three decision levels for the redesign of the plastic waste reverse supply chain resulting in an improved sustainable performance (see Figure 1.1).

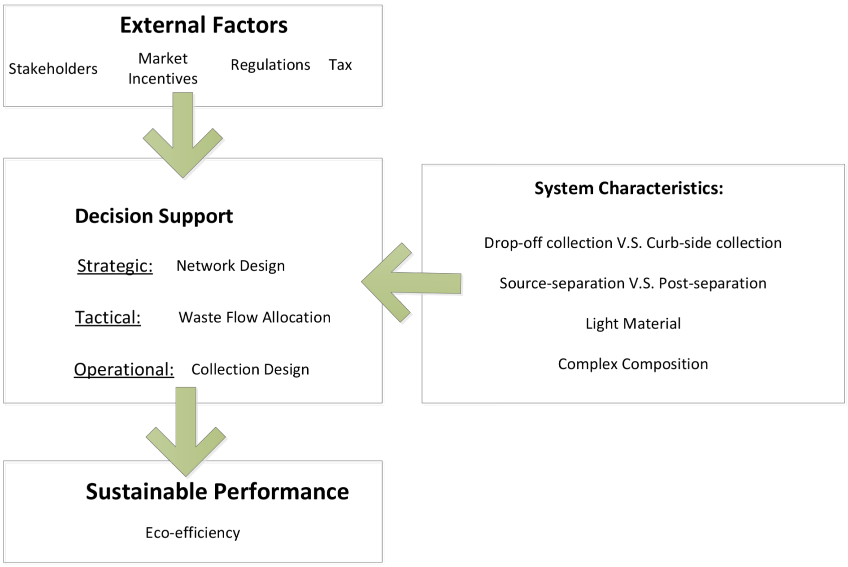


Figure 1.1: Conceptual research model

1.3 Research Questions

1.3.1 Research opportunities

As described above, waste recycling in the Netherlands is a complex system that involves various collection and separation options. On the European scale, there are also large differences between countries in terms of their practice and performance in household waste recycling. To understand the system in more depth, these differences must be investigated in practice. Through a comparison of practices of various countries, essential characteristics of recycling systems can be identified and taken into account in the modeling and analysis of such systems. Issues and problems must also be identified in order to provide direction for future research.

> **Research Question 1:** What are the research *opportunities* in reverse logistics for municipal solid waste recycling?

We answer **Research Question 1** in **Chapter 2**. Based on the methodology described in the previous section, we present a review of current recycling practice of various countermines and then link that with the literature to identify research opportunities. These results will provide directions for the research presented in the following chapters.

1.3.2 Sustainable municipal collection redesign

Collection starts at the municipalities. When considering building up a recycling system, an initial dilemma is whether or not to collect plastics separately at households. This makes a difference in logistics in terms of transportation frequency, collection vehicle type and infrastructure installation, etc. This has to do with further separation techniques, treatment input requirements and, more importantly, the trade-off between the cost for collection infrastructure and processing. Due to a higher volume-to-weight ratio compared to other recyclables, plastics have a larger number of kilometers traveled per tonne, which equates to more emissions and less efficiency per kg of plastic waste transported (Craighill and Powell, 1996). In practice, however, the collection route for source-separated plastic waste is often the same as for other recyclables such as paper and glass. To improve the sustainable performance of plastic waste collection, decision support is needed for collection planning at the municipal level.

Municipalities must make comparisons between the collection options for plastic waste in order to make decisions about which collection method to invest in. The collection cost of the various options is the most primary measurement to support this decision-making process. Increasing environmental concerns mean that the environmental and social performance of the collection options is another important measurement that should be taken into account together with costs. Plastic waste collection should be eco-efficient. Eco-efficiency concerns the trade-off between environmental impacts and costs. The eco-efficient performance of the collection options must be tested, together with the potential to further reduce environmental impact. The continuous improvement in waste recycling in terms of householder's behavior and technology input requires a design of collection that can cope with future changes. Therefore, the capability of these collection options to meet future demand should also be investigated. Accordingly, the second research question is formulated, which focuses on the tactical and strategic level on a municipal scale.

> **Research Question 2:** What are the key issues in the redesign of the municipal collection system for household plastic waste in order to improve sustainable performance?
>
> **2a** What opportunities can be found from the comparison of the collection alternatives to improve the sustainable performance of the collection system?
>
> **2b** What are the impacts of various collection and taxation alternatives on the performance of the collection system?

We answer **Research Question 2a** in **Chapter 3** and **Research Question 2b** in **Chapter 3 and 4**. The scale of the problems investigated in the two chapters are different. Chapter 3 presents a case study on one representative municipality to demonstrate how collection routes can be redesigned to improve sustainability performance and the impact of collection alternatives on the performance. In Chapter 4, we developed a generic cost model for estimation of collection cost and environmental impact that are applied to all municipalities in the Netherlands in order to show the impact of collection alternatives, as well as taxation differences on the sustainable performance of collection.

1.3.3 Sustainable regional network redesign

At the scale of the whole nation, including facilities in the neighbouring countries, the first decision alternative is between source separation and post-separation. This choice decides which separation technology to use and what kind of facilities are needed for processing, as well as the location of the facilities. In order to improve sustainable performance, it is important to choose the correct location for facilities like cross-docking stations and processing units. Currently, both systems exist in the Netherlands. However, since source separation is dominating as suggested by legislation, there are more facilities for source separation than for post-separation. This means that if some municipalities are shifting from source separation to post-separation, the capacity and location of the current facilities must be re-planned in order to adapt to the change. Other possible future changes are derived from the considerations of various stakeholders when choosing a separation method; for instance, the preferences of householders in different types of municipalities.

Environmental parameters should be taken into consideration when planning the location and capacity of the facilities. The purpose is not just to choose an efficient way to deal with plastic, but also a sustainable one. Furthermore, the capacity for separation and processing of plastic waste is limited in Netherlands, while in Germany, there are many processing companies. The extent to which those facilities should be used in the chain in order to balance between efficiency and sustainability needs to be decided. Other issues, such as the density of plastic waste and tax charge variety in municipalities that can result in diversity in response rate, should also be considered at this level. The third research question, which focuses on tactical/strategic level on a regional scale, is as follows.

> **Research Question 3:** What are the key issues in the redesign of the regional network for household plastic waste to improve sustainable performance?
>
> **3a** What are the key issues that determine the sustainable performance of the regional network?
>
> **3b** What strategy can be used to redesign a regional supply chain to improve sustainable performance?

We answer **Research Question 3a** in **Chapter 5** and **Research Question 3b** in **Chapter 6**. Chapter 5 presents the network model built for the regional network design. Scenarios are defined to explore the impacts of making various strategic changes. Chapter 6 further investigates the improvement of sustainability of the network by integrating a multi-model strategy into the network design. As road transport is mostly used in transporting plastic waste, we propose exploring the possibilities of using other transport mode such as train and barge as alternatives to road transport. The network model is then extended with inputs for such multi-modality options.

1.3.4 Sustainable global network redesign

Apart from regional demand (within Europe) for recycled plastic material, overseas demand is also quite significant. With the increasing scarcity of global resources and the concern for sustainability, waste should be recycled and re-used on a global scale. Recycling of household plastics has less environmental impact than the use of crude oil to produce virgin plastics. However, with globalization, production is geographically detached from consumption, which means that recycling is no longer just a regional problem. It needs to be managed by an integrated approach on a global scale to link the consumption phase with the manufacturing phase in a reverse supply chain. Consequently, there is a need to design an eco-efficient reverse supply chain from a global perspective.

A reverse network for waste recycling should process all waste eco-efficiently, as processing of waste is one of the major sources of pollution in the recycling process. Emission trading schemes (ETS) can function as mechanisms to control the emission impact in the process as a key to the sustainable performance of the network. ETS function under the "cap and trade" principle, whereby a cap is set on the total amount of greenhouse gases that can be emitted by all re-processors involved. Allowances for emissions are then allocated and can subsequently be traded between participating re-processors. More insights are needed to explore the feasibility of building a global reverse supply chain for household plastic waste recycling and to demonstrate the impact of ETS on the network design towards an improved sustainable performance on a global level. Accordingly, the research question that focuses on the strategic level on a global scale is as follows:

> **Research Question 4:** What strategy can be used to redesign a global supply chain to improve sustainable performance?

We answer **Research Question 4** in **Chapter 7** by conducting a case study on plastic waste collected in the Netherlands with an end market for the recycled plastics in China. We present a global network design that takes emission trading schemes into account. The results offer insights into the feasibility of building a global reverse supply chain for household plastic waste and increase the synergy between waste trading policy and the market demand of recycled material.

1.4 Methodological design

The first research question is initially addressed by a literature review of the different waste recycling systems between countries. Household waste recycling systems are compared between various European countries (Netherlands, UK, Spain, etc.), with the aim of illustrating the characteristics of these systems. Data collection is conducted with the help of KCN (Kenniscentrum Nascheiding) and other project partners in various European countries, in addition to secondary data source such as industry reports and publications of related organizations. The issues that emerged from a review of recycling practice of various countries are summarized, followed by a literature review on the reverse logistics of waste recycling. By comparing the issues addressed in literature and those derived from practice, we analyze the research gaps and subsequently propose research opportunities.

For the second research question, on the municipal level, several interviews are conducted with processing companies like SITA and some logistics companies that takes charge of collection within the municipality, in order to gather information on collection vehicle types, frequency, and various costs. The collection problem is modeled as a vehicle routing problem. Collection alternatives are compared using a scenario study approach. The scenario study is conducted based on real case data of a representative Dutch municipality. Scenarios are designed according to the collection alternatives with different assumptions regarding the collection method, vehicle type, collection frequency, and collection points, etc. Furthermore, a comprehensive cost model is developed in order to compare the costs of the municipal collection schemes of plastic waste collection. The municipal waste collection cost model is based on such variables as fixed and variable costs per vehicle, personnel costs, container or bag costs, as well as emission costs (using imaginary carbon taxes). The model aims to provide decision support when strategic changes to the collection scheme of municipalities are considered, as applied to the Dutch case. The model considers the characteristics of municipalities, including the degree of urbanization and taxation schemes for household waste management.

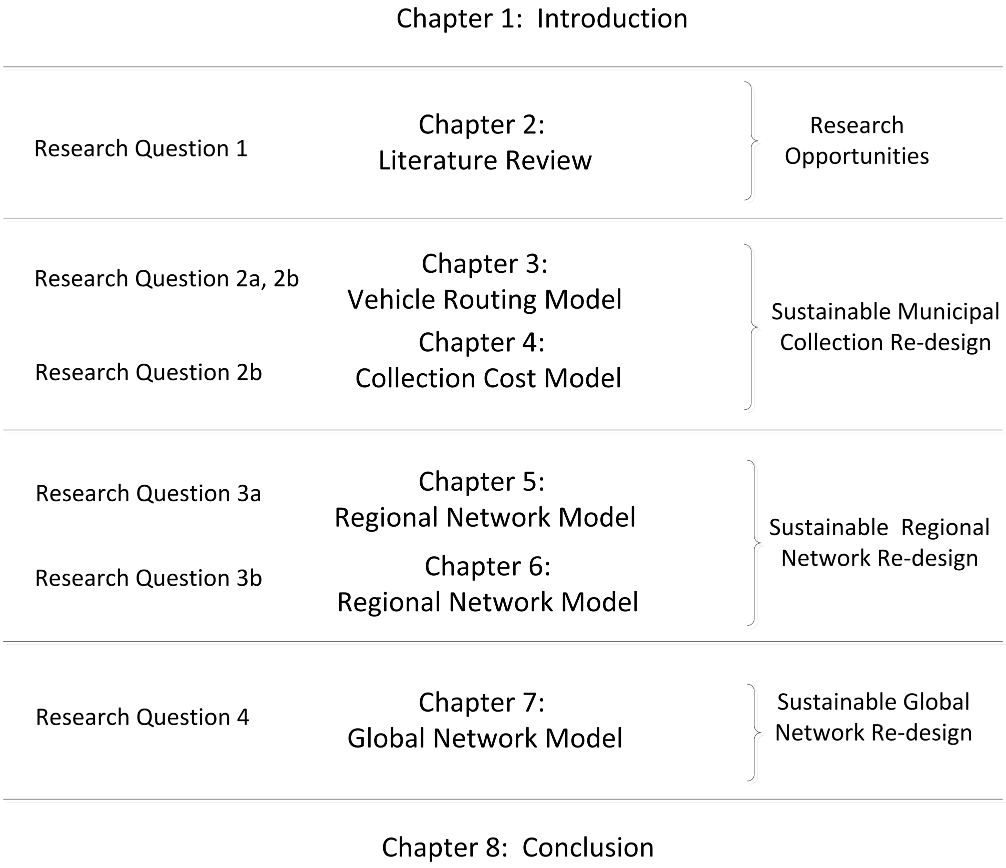
For the third research question, on the regional level, data is mainly acquired from Nedvang and the partners of Aachen University, who have expertise in the technological aspects regarding sorting system. Statistics about the municipalities come mainly from the CBS (Central Bureau of Statistics in Netherlands). Besides, the TIFN post-consumer packaging recovery project group shares the same input data for all the modeling work. The research for the regional level follows the method of forming a list of scenarios first and then various scenarios are simulated separately in the model. In this model, environmental impact is evaluated together with the transportation cost. In each scenario, different network layout, assumptions on the choice of collection channels and the characteristics of municipalities define the quantity of the products, their flow and the availability of facilities in the network, which are constraints for the model. We start this scenarios study with the current situation based on source separation with separate PET bottle collection. We then investigate the impacts of various strategic changes. Modeling results are compared and discussed in order to answer the research question. For each scenario, we suggest improvements in the network by repositioning the locations for sorting, separation, and reprocessing sites. Based on this work, to further explore the possibility of improving the eco-efficient performance of the regional network, the model is then extended by integrating multi-modality options on the links while taking into account all the costs of various stages in the network. In this way, impact of the strategy of multi-modality on the sustainable network design is investigated.

For the fourth research question, we have redesigned an eco-efficient reverse supply chain from a global angle. Data obtained for the previous network and collection design studies, along with some of the results, are used as modeling input in this study, based on a case of household plastic waste that is collected in the Netherlands and has a market in China. Emission trading schemes (emission cap and emission trading credits) are applied, both in Europe and China, on the re-processing plants as the mechanism for emission control on the re-processing plants. A network optimization model is developed to decide the location re-allocation of intermediate processing plants under such restrictions. The objective is to maximize the total profit under ETS. The results offer insights into the feasibility of building a global reverse supply chain for household plastic waste recycling and demonstrate the impact of ETS on the network design. The results also provide decision support for increasing the synergy between the policy of global shipping of waste material and the demand for recycled material.

In sum, each part of this research conducts data collection with research partners and industry partners. Secondary data sources such as industrial reports, scientific articles, national statistical databases are also used. With the support of these data, scenarios are designed to match the current situation and a few possible changes to the current situation. Decision support models are used to analyze the most influential factors developed models on municipal collection, regional network design, and global network design.

1.5 Thesis outline

The outline of the thesis is summarized as:


Chapter 1: Introduction
Research Question 1
Chapter 2: Literature Review
Research Opportunities
Research Question 2a, 2b
Chapter 3: Vehicle Routing Model
Research Question 2b
Chapter 4: Collection Cost Model
Sustainable Municipal Collection Re-design
Research Question 3a
Chapter 5: Regional Network Model
Research Question 3b
Chapter 6: Regional Network Model
Sustainable Regional Network Re-design
Research Question 4
Chapter 7: Global Network Model
Sustainable Global Network Re-design
Chapter 8: Conclusion

Chapter 2

Research Opportunities in Modelling Household Waste Logistics

This Chapter is based on the article submitted to an international journal:

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"Research Opportunities in Modelling Household Waste Logistics"

In this chapter we answer research question 1:
What are the research opportunities in reverse logistics for municipal solid waste recycling?

Abstract:
EU legislation over the last two decades has placed increasing pressure on member countries to achieve specified waste recycling targets. This paper aims to provide guidelines for moving waste recycling towards a more efficient and sustainable direction. It does this by comparing municipal solid waste (MSW) management practices in various EU countries in order to identify the characteristics and key issues from waste management and reverse logistics perspectives. The issues addressed by modeling methods used in the literature are compared with the identified issues in practice that have resulted in research gaps and research opportunities. We conclude that waste recycling is a multi-disciplinary problem and that research opportunities can be identified by considering different decision levels simultaneously. It is necessary to take an holistic view and to consider characteristics of different waste types when analyzing a reverse supply chain for MSW recycling.

Key Words:
Household waste recycling, reverse logistics, sustainability, review, operations research

2.1 Introduction

During the last 100 years, global fossil fuel consumption has increased 12-fold and extraction of material resources has increased 34-fold (Potočnik, 2012). A resource-efficient Europe in the future must pay more attention to municipal solid waste (MSW) recycling. There are approximately 502 million people living in the European Union, each of whom generates an average of 520 kg of municipal solid waste per year, or 260.5 million tons in total (EEA, 2012). Handling such a large amount of MSW is a challenging task. Despite a great deal of legislation and public attention, 40 percent of the waste in Europe was still landfilled as of 2009 (EUROSTAT, 2011). Recycling is one of the common waste treatment options that has the most potential for further improvement in Europe. Increased recycling reduces environmental impact, consumption of energy sources, and economic costs (Eriksson et al., 2005).

Countries vary greatly in terms of their practice and performance in MSW recycling. Statistics from EUROSTAT (2011) show that Germany, Sweden, and Belgium have the highest rates of recycling, while collection and recycling are still in their infancy in the new EU Member States, with landfill rates ranging from 62 percent in Slovenia to 100 percent in Bulgaria. On average, more than 30 percent of the EU's waste goes into landfill, which indicates a need to improve the recycling of MSW (EUROSTAT, 2011).

Householders, municipalities, logistics, and recycling service providers are stakeholders in the decision making process, and all have interests that must be balanced. MSW recycling includes decisions such as logistics network design and collection design. Dealing with each of these aspects involves solving several combinatorial optimization problems, which can be assisted by operations research techniques (Ghiani et al., 2014). Decision support systems have been developed and published in the literature, based on optimization techniques to exploit the power of mathematical modeling to assist in the decision-making process. However, it is unclear whether the available models can cope with the key issues in practice. Therefore, the objective of this paper is to identify research opportunities for modeling MSW recycling with a focus on operations research models.

2.2 Research Design

2.2.1 Research Methodology

This research was conducting using a three-step approach. In the first step, we used the literature to identify a general research framework that comprised all of the relevant factors to analyze municipal waste recycling. The second step was to analyze and identify issues in real-life waste recycling that need to be addressed because they have a major impact on the performance of the recycling system or show differences in the practices of various countries. These findings have been brought together in the research framework. The third step, using the framework, was to survey the operations research literature to analyze and evaluate the issues that have been addressed, as well as the modeling methods used to address them. More importantly, we also identify the issues not yet addressed and the methods that can be used to address them. The research framework is used again to categorize the literature review findings and identify major research opportunities for modeling MSW recycling.

In the second step of identifying the main issues that need to be addressed in municipal solid waste recycling, we have conducted a comparison of current recycling practices in European countries. This comparison required countries that have recycling as their major waste handling strategy and vary in the recycling performance; hence, the countries chosen were the Netherlands, Germany, Sweden, the United Kingdom, Spain, and Portugal. These countries were selected because they are reported by Eurostat (the statistics database of the European Commission) as countries that treat a higher percentage of their waste by recycling than by composting and landfill. These countries also differ in their recycling practices and all have relatively high-ranking waste recycling performance

(Eurostat, 2009). The main sources of data and recycling system descriptions are as follows:

- Scientific and industrial publications related to waste collection in the countries of interest.(Bing et al., 2012; Wong, 2010; Ramos and Oliveira, 2011; Ramos et al., 2014a; Ramos et al., 2014b; EIMPack, 2011)
- Industrial reports (INE, 2012; SPV, 2011; REA, 2011; APA, 2012; DEFRA, 2012; Nedvang, 2012)
- Publications of EU and national organizations. (EU, 2012; WRAP, 2012)
- Interviews with industry partners and field visits to the waste collection and processing facilities.

Scientific journal papers are the major source in the third step of the literature review. Key words are selected based on the results of the first step, as explained in section 2.4.

2.2.2 Research Framework

Decisions in MSW management can typically be classified into three levels: strategic, tactical, and operational. The combined decisions on these inter-related levels, or even at one level specifically, are often too complex to be solved at once. A common approach is to separate the total decision making problem into several sub-problems at each level; this process is called decomposition. Ghiani et al. (2014) stated that, for planning purposes, a waste management system can be decomposed into two major sub-systems: a regional waste management system and a collection system. A commonly cited literature review on the characteristics of research in reverse logistics (Rubio et al., 2008) suggested examining the design of the reverse logistics network, the analysis of transport routes, and internal logistics. Reverse logistics network design belongs to the regional management system, which is on the strategic level. Collection planning, transport routes, and internal logistics-related issues are part of the tactical and operational levels. Accordingly, we have partitioned the decision making into two levels, as presented in Figure 2.1.

Externally, certain drivers and incentives can influence decision making on the reverse logistics network and processes. Dekker et al. (2004) identified three main drivers that influence reverse logistics: economics, legislation, and extended responsibility (public, social, and economic). From a macro-environmental angle, the well-known PESTEL

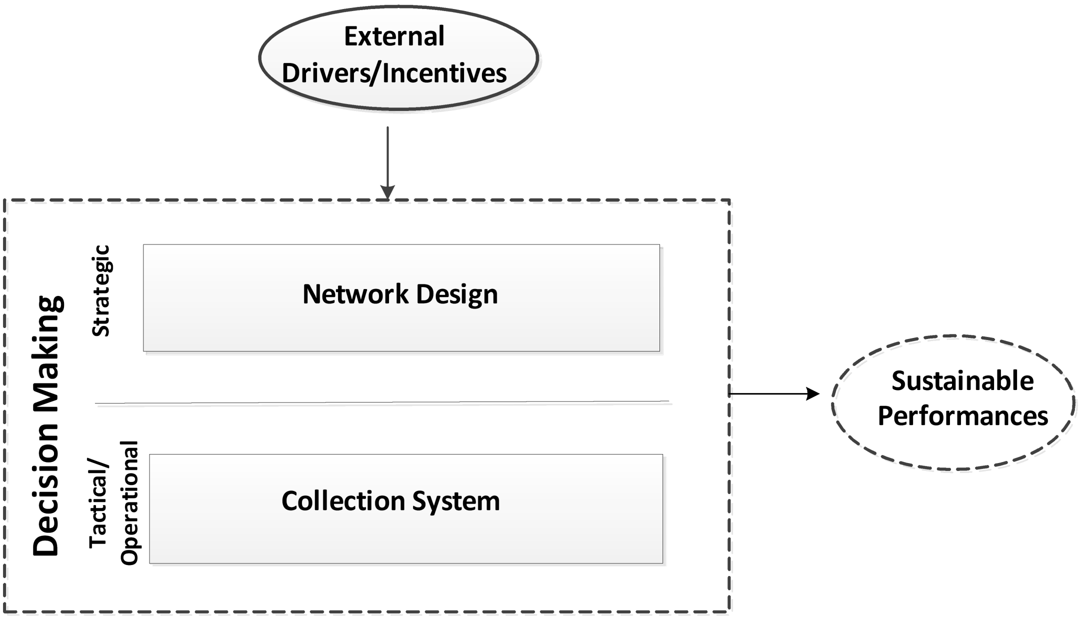

FIGURE 2.1: Framework of reverse logistics for household waste recycling

analysis has also identified political, economic, social, technological, ecological, and legal factors as being key to guiding strategic decision-making (Law, 2009). Specific key external factors for municipal waste recycling are identified in section 2.3.

Despite the obvious environmental gains from waste recycling, there is an environmental cost associated with the collection and transportation of recovered products, and minimizing this cost is important in order to increase the total environmental gain from recovery (Tsoulfas and Pappis, 2006). The rapid evolution of sustainable development changes the goals in almost every supply chain, including reverse logistics for waste management. Sustainable development involves balancing the ecological, economic, and social impacts at the level of society in the long term (Aiking and Boer, 2004; Seuring and Muller, 2008). This involves stressing the importance of key issues closely related to human welfare and the natural environment. To meet the future demands of sustainable development, sustainable performance is the output of the decision-making on municipal solid waste management (see Figure 2.1).

In sum, we have categorized decision making into two levels: strategic and tactical/operational. External factors have an impact on decision-making processes and the output of the decision-making is sustainable performance. These aspects form the basic framework for reviewing practices in which issues related to each of the aspects will be identified. The following sections expand the structure by adding the identified issues derived from the review of recycling practices in various countries. These sections summarize the explicit external factors, the issues to be addressed in the decision process at different levels, and the key sustainable performance indicators in in the municipal solid waste recycling context. By comparing the issues addressed in literature and those derived from practice, we analyze the research gap and then propose research opportunities.

2.3 Review of waste recycling practices in different countries

Following the framework described above, we compare the practices in various countries in three parts: the external factors, strategic, and tactical/operational decision levels. Each part includes a discussion on what sustainable performance is all about. For the external factors, we present an overview of EU regulations, followed by a discussion of incentives as external drivers and actors' strategies regarding environmental impact control. At the strategic decision level, the recycling procedures of various waste types and the recycling network characteristics are reviewed. At the tactical/operational level, emphasis is given to collection planning. This section ends with a summary of identified issues from practice.

2.3.1 External Factors

EU regulations on waste treatment are the main source of the increasing pressure on member countries to transfer landfilling into recycling and re-use. The European Union Landfill Directive of 1999 was introduced to encourage the diversion of waste treatment away from landfill. Each Member State is now required to build its own disposal capacities by establishing a system of national treatment facilities. The European Commission has also defined several specific "waste streams" for priority attention (packaging waste, end-of-life vehicles, batteries, electrical and electronic waste, etc.). EU Directive 2008/98/EC specified that, by 2020, the preparation for reuse and recycling of municipal solid waste shall be increased to a minimum of 50 percent by weight (EU, 2012). The directive not only sets the target for waste recycling, but also specifies the requirements for recycling network design. EU Directive 2008/98/EC states that the recycling network shall be designed in such a way that the Member States become self-sufficient in terms of waste disposal and recovery, while taking into account geographical circumstances or the need for specialized installations for certain types of waste. The Directive specifies the capacity of the recycling network together with the geographical location of facilities. It also implies that waste should be treated differently by taking the specialized installation requirements into account.

In order to meet the targets set by the regulations, taxation is commonly used as an incentive in many countries to promote waste recycling and cover the cost of waste collection and treatment. The Netherlands attains a higher recycling rate by using a so-called DIFTAR system (pay as you throw) to distinguish the separated and non-separated waste by the tax that householders should pay. Several Swedish municipalities have also introduced a waste management fee based on weight, which means that the households pay per kilogram of waste collected, on top of the basic fee. Germany and Norway have similar special taxes based on the weight/volume of waste. In the UK, households commonly pay a council tax to the local authority that is used to cover various services, including schools, police, street lights, and waste/recycling collection (Abbott et al., 2011). There is no specific tax for waste (Kipperberg, 2007).

In addition to incentives to push recyclable waste into the recycling channel, there is also a demand driver in the market for recycled material. The price paid for the recycled materials is important for the competitiveness of recycling initiatives. Prices are currently volatile and measures are needed to enhance the price stability and profitability of recycled materials. An argument about whether waste should be allowed to be exported from Europe to be recycled partly in the Far East has attracted considerable public attention in recent years. From an ethical point of view, the social conditions in the Far East are not comparable to European standards, which means that European waste is treated by companies that hardly comply with European social standards and working security (Pro-Europe, 2009). On the other hand, the imbalance of trade between Far East countries like China and the European Union means that most container ships heading from Europe to China are empty and they produce CO_2 emissions regardless of whether or not they carry cargo. These empty containers can be used to ship waste. Furthermore, it has been argued that waste recycling should be operated in a free market and systems should be free to choose whichever end market best suits their needs in terms of price and quality depending on material demand (Pro-Europe, 2009).

The above-mentioned incentives and drivers create pressure on the reverse logistics network and processes towards the direction of delivering an efficient and sustainable performance. The government of the UK, for example, like those of many other countries, is adopting a green economy (DEFRA, 2012) in which value and growth are maximized across the whole economy while managing the sustainability of natural assets (WRAP, 2012).

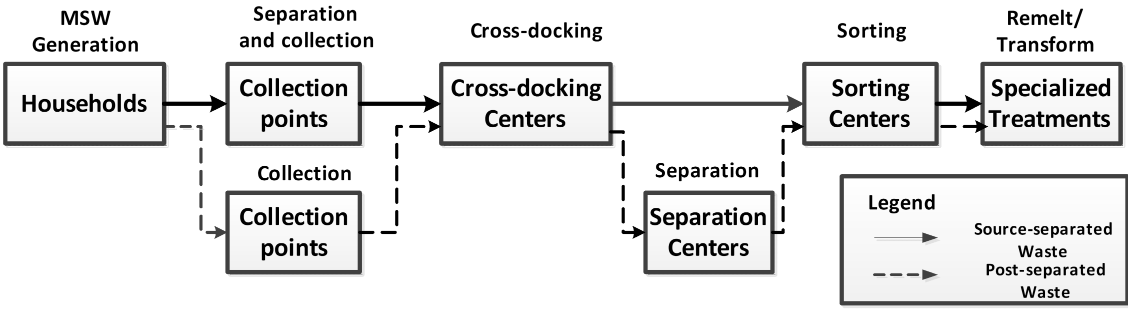

Figure 2.2: The recycling network flow of municipal solid waste

2.3.2 Network Design

At the strategic level, decisions are made on the network design of a recycling network that includes the process of collection, separation, sorting, and re-processing[1]. In some cases, the separation of recyclable waste (paper, metal, plastic, etc.) from other waste is done at the collection point, while in other cases the waste is collected and sent to a separation center for this procedure. After separation, the waste is normally sent to a sorting center, where the further sorting of the material by color and/or composition is conducted. Trans-shipment and baling of waste takes place at cross-docking centers. The sorted waste is then transferred to specialized treatment facilities to be re-melted or transformed for recycling (See Figure 2.2).

In practice, separation and sorting processes might take place in different stages for different recyclables. Table 2.1 summarizes the recycling practices of some waste types in various countries. In the Netherlands, glass is sorted by color and put in separate containers (often underground containers) at the collection point. In several countries, including Sweden, Germany, and Belgium, paper is separated at the collection point, while aluminum is normally separated in separation centers in countries like Sweden, the UK, and the Netherlands. Different waste types go through different treatment processes in the network due to technological variations in the recycling procedure. The network structure to be designed must account for these specificities. The capacity and location of facilities also varies. Countries such as Germany, the UK, and Portugal have domestic material recovery facilities (sorting and other treatments), while for small countries like the Netherlands, most of the sorting process done in the facilities of neighboring countries. Reprocessing, which is specialized treatment for each material, is normally done in facilities all over Europe. For example, plastic is sorted into different types and grades in the Netherlands and then sent, by each type, to specified facilities located in various

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[1] We are only taking recycling procedures into account here. The processes are restricted to those for waste treatment, which means that no remanufacturing procedures for chemical or electronic products (e.g., batteries, household appliances) are taken into account.

	Processes	
	Separation	**Sorting**
Collection Point	Paper (SE, GE, BE) Glass (NL) Plastic (UK, NL)	glass (NL)
Separation Center	Aluminium (SE, UK, NL) Plastic (UK, NL, PT)	

* Examples of countries are given

Table 2.1: Treatment processes of various waste types

European countries for further treatment. Some of these materials are exported overseas. Therefore, in general terms, the recycling network of MSW is geographically dispersed from local to global.

The capacity of the processing facilities (separating, sorting, etc.) also varies from one country to another. Some facilities in countries with relatively more developed waste recycling systems and advanced technology have a problem of over-capacity. For example, the UK is at risk of heavily over-investing in residual waste treatment infrastructure. If all of the facilities that have received planning consent are actually built, the UK will have 5 million tonnes more capacity than it requires (Waste Management World, 2012). Countries like Germany and Sweden have already a problem with over-capacity, mostly in the sorting plants. In order to make use of the existing capacity and improve the overall recycling rate to meet the EU recycling target, countries are also cooperating in waste recycling. An incineration plant in Rotterdam, the Netherlands, is planning to process the waste it ships from Naples, Italy. The waste would have been sent to landfill in Italy, but is now going to be converted to energy, saving approximately 160 kg CO_2 emission per tonne of waste (Van Gansewinkel Groep, 2012).

To improve the sustainable performance of the recycling network, some countries with good railway and waterway infrastructures have initiated the practice of multi-modal transportation between facilities, both domestically and between countries in Europe. In 2004, for example, 172,500 tons of waste was transported by inland waterway in Liege, Belgium, of which 133,000 tons was shipped by lorry and 39,500 tons by barge (MONAMI, 2005).

2.3.3 Collection planning

The main issues at the collection planning level are the types of waste to be collected, the organization of collection, and the vehicles used. There are generally two types of collection locations for municipal solid waste: either curbside (curbside collection) or at central collection points to which householders must to bring their waste (drop-off collection). In Spain, mixed waste is usually collected in curbside bins, while paper/cardboard, glass and lightweight packaging are deposited at drop-off points (Gallardo et al., 2010).

Regarding the collection method, UK municipalities have adopted three common schemes. The first is curbside-sort, in which recyclables are separated at curbside into different compartments of a specialist collection vehicle. The second method is single stream co-mingled, which involves collecting materials in a single-compartment vehicle and sorting them at a materials recovery facility (MRF). The third method is two-stream co-mingled. In this scheme, householders are provided with two recycling containers and are asked to place different materials in each container; typically paper/card (fiber) in one and plastics, glass, and cans (containers) in the other. These materials are kept separate, but collected by a single vehicle that has two chambers.

The organization of waste collection is often done by municipalities. In the Netherlands, each municipality is responsible for organizing its own waste collection. Some neighboring municipalities may share the services of the same collection company. In Portugal, the selective collection and sorting of packaging waste are performed by the municipal waste collection companies, so-called SMAUTs. There are two types of SMAUTs: (1) municipal and inter-municipal and (2) multi-municipal. SMAUTs usually have more than one depot and the municipalities boundaries are respected when defining depot's service areas and the collection routes.

The vehicles used for collection also vary. Trucks with a pressing function are commonly used in countries like the Netherlands, the UK, Germany, and Portugal. In Portugal, they are used to collect paper/cardboard or plastics/metal. The pressing function increases the vehicle's capacity by approximately 150-200 percent. In the curbside system, a rear-loaded truck is used while the drop-off containers are mainly collected by a top-loaded truck that has a single compartment and no pressing function. However, there are some SMAUTs that have multiple compartment trucks, in which paper/cardboard and plastic/metals are collected together. In Sweden, some collection vehicles are equipped with vacuum pipes to avoid heavy lifting (Afvall Sverige, 2010). The same type of vehicles can be used in different collection methods for different waste types. In the Netherlands, for example, curbside collection of plastics is conducted by the same truck that collects other waste types. This means that when the truck is used for collecting light-weighted waste types, it is used less efficiently. In Portugal, the vehicles used for the curbside collection of paper/cardboard and plastic/metal are the same as those used for the non-differentiated waste.

In the near future, countries will continue to aim to improve the efficiency of waste recycling. Some efforts can be made on the collection phase in order to improve the collection efficiency. For example, Portugal aims to increase its curbside collection in urban areas since the amount collected and the quality (low percentage of contaminants) are higher in such a system than in the drop-off system. Moreover, possible synergies and economies of scale are still to be explored further. The Netherlands will combine the separately collected PET bottles (through a deposit refund system) with the normal plastic waste in order to improve collection efficiency and reduce costs. For the same purpose, efforts are being made to optimize routes and decrease the collection frequency in order to collect containers with a high landfill rate. In Portugal, the number of SMAUTs tends to decrease so that collection can be further aggregated.

Additionally, in order to collect waste in a more sustainable manner, collection companies are searching for solutions of alternative vehicles. Hybrid trucks are starting to be applied in waste collection. In 2008, the first hybrid waste collection truck was launched in Gothenburg, Sweden. The advantage of such trucks is in curbside collection, where idling and loading and compacting the waste takes most of the operating time of collection trucks (Helming, 2009).

2.3.4 Summary of identified issues

To summarize, EU member countries that are externally driven by regulations are making their municipal solid waste recycling more efficient and sustainable. Waste recycling is being promoted in various countries by using taxation as an important incentive. However, the reference indicator to which tax is charged varies by country. EU regulations also indicate treatment of different waste types according to the facilities and technology they require. Consider market demand, price measurements and valorization of recycled waste requires more attention. Therefore, we can summarize the external issues derived from the review as: (1) differentiated taxation, (2) differentiated recycling targets, (3) increased recycling targets, and (4) lack of valorization of recycled waste.

At the strategic decision level, the major differences in the recycling networks are related to the locations at which the various materials are separated and sorted. The locations of intermediate facilities (separation, sorting) vary among the European countries, as does the quantity and capacities of these facilities. Municipal solid waste is a mixture of materials with diverse characteristics and the recycling network for each material is different, in terms of structure and functionality in various stages. Therefore, it is a multi-commodity problem and the associated network design should be able to fit the specific requirements of each material and handle the different materials together. The locations and capacities of processing plants in different countries also vary greatly. In terms of strategy for improving sustainable performance, the multi-modality transport started to be used in practice for the transportation for waste. Therefore, we can summarize the issues from the strategic level derived from the review as: (1) facilitate multi-commodity (handle different composition of waste differently and simultaneously), (2) variability in network configuration, (3) facility capacity plan (capacity design and over-capacity problem), (4) facility location choice, and (5) sustainable recycling network (for example, facilitating multi-modality).

In terms of collection practices, the major differences relate to the organizing unit of the collection, the allocation of waste types to curbside or drop-off collection points, and the type of trucks used. The organizing unit of collection can affect the routing design as well as the collection schedule. Among the important factors that decide which truck types are to be used for collection are the separation method and the allocation of waste collection locations (which waste types to be put where for collection). Collection trucks with multiple or single compartments can make a difference in the routing and scheduling of waste collection. The issues from the operational/tactical level derived from the review can be summarized as: (1) collection method, (2) collection coordination, (3) collection scheduling, (4) capacity planning (vehicle and bin), (5) vehicle routing, and (6) attention for sustainable collection.

Essentially, MSW recycling outputs are the recycled materials, together with the emissions of all the processes and transportation and the total cost involved. Thus, the aim of decision-making is to deliver a sustainable performance measured by (1) cost, (2) environmental impact, and (3) societal impact. The above issues derived from the comparison of recycling practices in various countries are identified according to the research framework. We conducted a literature review to identify which issues are addressed by the modeling methods and how.

2.4 Literature Review

The literature search process in this section was carried out with the scientific-technical bibliographic databases Web of Science and Science Direct. We conducted the search by combining the key words of waste recycling (municipal solid waste, recycling, municipal solid waste) with those of each of the identified issues (such as multi-commodity network, sustainable collection, vehicle routing). Because our focus is on modeling approaches used to address these issues, and because most of the issues identified are related to supply chain optimization from different decision levels, the scope of the literature search was set to the modeling methods used in operations research and supply chain management literature, as applied to waste management. The most relevant scientific papers between 1990 and 2014 are selected and reviewed in this section.

2.4.1 Network design

The characteristics of a reverse logistics network for waste recycling determine its network configuration. The existing methods in network modeling have addressed some of the key issues in network design, such as the network structure and channel choices, location allocation, capacity design of processing facilities, network with multi-commodity, as well as sustainable network design.

Regarding the network structure, most reverse logistics networks have a convergent network structure rather than a divergent structure (Fleischmann et al., 1997). Fleischmann et al. (2001) developed a generic MILP network model for product recovery network design, which they illustrated with an example on paper recycling. McLeod and Cherrett (2011) identified the channel structure as the difference between reverse logistics of waste and other return goods Intermediate points often exist in the reverse supply chain for the consolidation of waste, which could be at regional distribution centers, transfer stations, or other locations, before transportation to the final disposal site. Bing et al. (2012) further identified the availability of intermediate processing plants as the key factor that determines the performances of various channels for collecting the same type of waste, based on a case study on plastic waste recycling.

Several studies in reverse logistics network design have provided decision support for processing capacity design and location allocation problems. Such models have also considered the convergent structure from many sources to a few demand locations. Many studies have been conducted regarding product recall or end-of-use returns. Krikke et al. (1999) described a case study dealing with a reverse logistics network for the returns, processing, and recovery of discarded copiers. They presented a mixed integer linear programing model to determine the locations and capacities of the recovery facilities as well as the transportation links connecting various locations. In recycling logistics models, Barros et al. (1998) modeled the network constructions and waste recycling in the Netherlands. The model determined the optimal number, capacities, and locations of the depots and cleaning facilities. Louwers et al. (1999) designed a recycling network for carpet waste and proposed a location-allocation model for the collection, pre-processing, and re-distribution of carpet waste. Huang et al. (2002) introduced an interval fuzzy capacity expansion integer programming model for the decision support of waste recycling facility capacity expansion. Gomes et al. (2011) modeled the WEEE (Waste Electrical and Electronic Equipment) Portuguese recovery network. A MILP model is proposed in which the best locations for collection and sorting centers are chosen simultaneously with network planning. The multiple recycling processes have been taken into account in these models and problems such as location allocation and capacity design have been studied in depth.

MSW consists of various waste types, which means that the network design is also a multi-commodity problem. Numerous studies have been conducted on multi-commodity networks since Geoffrion and Graves (1974), among others, introduced a multi-commodity logistics network model for optimizing product flows. The study f multi-commodity networks in a reverse supply chain setting is relatively new. Ko and Evans (2007) developed a multi-commodity network model that handles forward and reverse flows simultaneously, but not in the context of reverse supply chain for waste recycling. The specialty of the multi-commodity problem in waste recycling is the process of waste separation throughout the process steps in the chain. This waste separation is similar to a process of product disassembly. Disassembly is a systematic method of separating a product into its constituent parts, components, subassemblies or other groupings (Taleb and Gupta, 1997). Waste separation means that one "commodity" of mixed waste will be separated to several "commodities" after the process of separation or sorting. The fact that waste is a loose mix means that the separation of waste materials is more dynamic and stochastic than the disassembling process in which components of the objects are fixed (for example, old cars). The separation will have an impact on the particular distribution channel choice. The point at which separation occurs could have an impact on the overall performance of the network. Bing et al. (2012) studied such a multi-commodity network for the case of plastic recycling, in which the locations of separation points in the network is analyzed.

Regarding the key performances of a supply chain, a lot of recent research has been devoted to improving sustainability. Environmental issues have become an important parameter in logistics network design and the purpose of many of these studies has been to achieve a balance between profit and environmental impact. The new concept of green supply chain management, which combines the concepts of sustainability and logistics, leads to a shift from minimizing cost to a balance between cost and environmental impact (Srivastava, 2007). Quariguasi Frota Neto et al. (2008) used multi-objective programming (MOP) to apply this sustainability concept in the design of a sustainable logistics network. Chaabane et al. (2012) introduced a mixed-integer linear programming-based framework for sustainable supply chain design and demonstrated that efficient carbon management strategies can help to achieve sustainability objectives in a cost-effective manner. Cachon (2009) discussed how the objective of reducing carbon footprints affects supply chain operations and structures. We therefore see a trend of including sustainability-related parameters in the network modeling of reverse logistics.

In sum, the issues addressed in network modeling of waste recycling are: (1) curbside or drop-off collection, (2) network structure, (3) capacity design of facilities, (4) location of recovery facility and transportation links, (5) handling different types of waste composition, (6) multi-modality strategy, and (7) balancing emission and economic concerns.

2.4.2 Collection planning

When dealing with waste collection, different practices have led to different problems. Several approaches have been proposed in the literature, where diverse variations of the so-called routing problems have been analyzed. In particular, existing approaches have explored important aspects such as: type of collection, number of waste streams collected, collection frequencies, and dynamic characteristics of the problems. These aspects are briefly analyzed below in connection with real waste collection systems.

MSW collection location typically originates from two different routing modeling approaches: an arc-routing or a node-routing approach. With regard to curbside collection, the problem is frequently modeled as an arc-routing problem, in which all arcs in a graph must be visited in order to allow waste collection in every street of a city. Mora et al. (2013) formulated a waste collection vehicle routing problem as a capacitated arc routing problem (CARP) and proposed a heuristic procedure to solve it. This was applied to the solid waste management in the city of Reggio Emilia (Italy). A waste collection problem was also modeled as an arc-routing problem in the work of Amponsah and Salhi (2004), which considered characteristics of developing countries. Bautista et al. (2008) also proposed a model for the mixed CARP with turn constraints, where the collection routes consider ”forbidden turns” due to street junctions and traffic signals (Spain). On the other hand, at the drop-off collection, the vehicle must visit all the central spots, which means that the problem is modeled as a node-routing problem with demand occurs at the nodes. Examples of real-life waste collection problems modeled as a node-routing approach can be found in Baptista et al. (2002), where the collection of recycling paper containers in Almada municipality of Portugal was solved by a heuristic procedure. Nuortio et al. (2006) developed a guided variable neighborhood thresholding metaheuristic to solve the mixed waste collection of 3386 bins in Eastern Finland, while Karadimas et al.

(2007) used an ant colony algorithm to design optimal routes for the MSW collection in the Athens municipality of Greece.

An important point to consider for waste collection systems is the number of waste streams that are collected in the same route. To deal with this, the problem can be modeled either as the classic capacitated vehicle routing problem (CVRP), where each stream is collected in separated routes (separate collection), or as the multi-compartment vehicle routing problem (MCVRP), where two or more streams are collected simultaneously without commingling them (co-collection). While the CVRP is a widely studied problem and has had several models proposed in the literature (see Golden, Raghavan et al. (2008) or Laporte (2009) for recent surveys), the MCVRP has received limited attention. Muyldermans and Pang (2010) have proposed a local search procedure for the MCVRP and have investigated the benefits of co-collection over separate collection based on literature instances. They concluded that the improvement over separate collection increases due to different factors. They also noted that imbalances in commodities demand a reduction in the benefits from co-collection. This brings extra challenges in terms of how the vehicle capacity should be partitioned by the compartments and when each site should be visited, since waste streams have different containers' fulfilling rates.

Another feature of MSW collection is the variation in collection frequencies from site to site. For instance, some sites in a network may be visited every day while others in the same network may be visited two or three times a week. This problem is modeled as a periodic vehicle routing problem (PVRP) since decisions relate to the day when each site will be collected, along with the routing visit sequence. Tung and Pinnoi (2000), Angelelli and Speranza (2002), and Teixeira et al. (2004) are examples of studies in which PVRP heuristic algorithms were developed and applied to real waste collection systems.

Most of those studies have focused on static routes, with only a tackling dynamic routing and scheduling aspects, which are present in real-time operations. According to Johansson (2006), dynamic routing and scheduling can yield lower operating costs and shorter collection and hauling distances. Faccio et al. (2011) and Anghinolfi et al. (2013) also approached dynamic optimization in waste collection problems; the former updates input data concerning waste generated through sensors, and the latter does so through a GIS-based waste-generation simulation model. However, there is much to do on these aspects and the academic community should explore such aspects in order to match the developed solution methodologies to actual waste collection problems.

Some other waste routing variants have been studied in the literature. Benjamin and Beasley (2010) explored a waste collection problem with multiple disposal facilities and a single depot that acts only as a vehicle station. Ramos and Oliveira (2011) studied a recyclable packaging waste collection network with multiple depots, where service areas are defined by depot along with the collection routes. Bektas and Laporte (2011) proposed the pollution-routing problem (PRP), which accounts not just for the travel distance, but also for the amount of greenhouse emissions, fuel, travel times, and their costs in the vehicle routing modeling. Groot et al. (2014) developed a comprehensive collection cost model that includes the emission costs for estimating the economic and environmental impact of municipal collection of plastic waste. Groot et al.'s study also analyzed the impact of differentiated waste taxation alternatives, using the proposed model. Ramos et al. (2014a) studied the planning of recyclable waste collection systems while accounting for economic and environmental concerns. Service areas and vehicle routes are defined for logistics networks with multiple depots where different products are collected. Ramos et al. (2014b) further combined a social objective with environmental and economic objective in modeling reverse logistics systems. A trend towards sustainability has also been observed in collection planning.

To summarize, the issues addressed in the network modeling literature of waste recycling are: (1) number of waste streams collected, (2) collection frequencies, (3) dynamic routing and scheduling, (4) multi-compartment vehicles, (5) vehicle capacity, (6) road conditions, (7) number of depots, (8) differentiated municipal waste tax, and (9) balance emission and economic and social concerns.

2.5 Research gap analysis

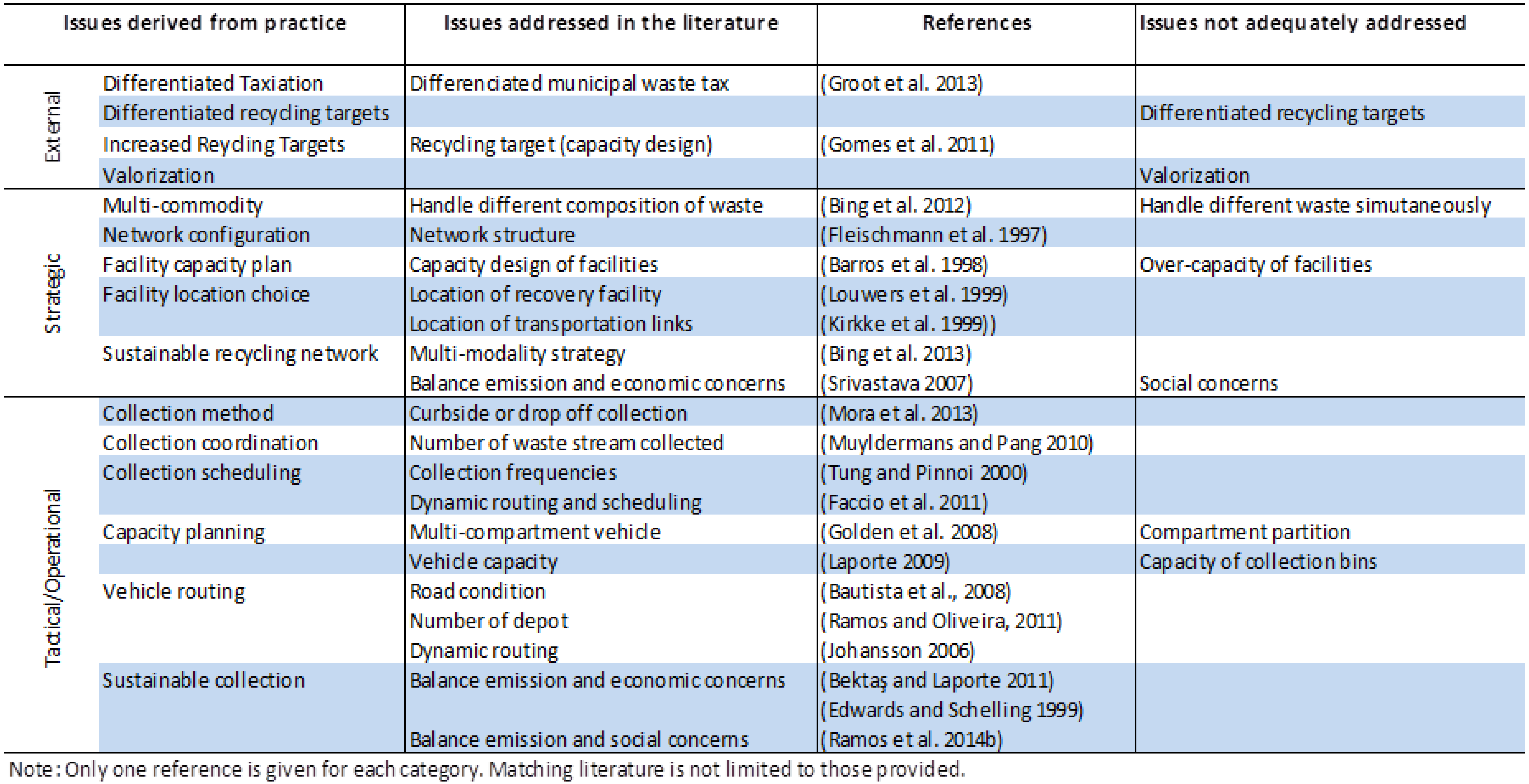
2.5.1 Research Gap

The issues derived from practices and the issues addressed in the literature are summarized in Table 2. We have also compared and identified those issues that are not adequately addressed by the current methods in the literature. Our first observation is that some issues appear in multiple decision levels. For example, capacity planning is an important issue both at the strategic level on facility and network capacity plans, and at a very detailed level on collection bin and collection vehicle capacity plans. Differentiating between waste types is a regulatory requirement, but also an issue in network design and collection design. Handling waste simultaneously is in line with the vehicle partition problem. There are also issues that can be inter-related with issues from other decision levels. For example, the location of transportation links and capacity of facilities on a strategic level can influence the operational level on the vehicle capacity planning and routing. Waste valorization and market demand can have a significant impact on network configuration and facility capacity design.

Most of the models addressed in the literature address efficiency issues. To further provide insights for policy makers and address issues like valorization while including end market demand, researchers and practitioners need to take a broader view of the network of waste recycling; they should consider the end market, rather than focusing only on the waste collection and treatment. This holistic view is also necessary for the planning of capacity on a larger scale across borders to solve the problem of over-capacity. In other words, a holistic view is needed to strengthen the applicability of modeling tools for tackling real-life waste recycling problems.

In addition to all the profound methods already used in addressing problems to increase efficiency, the most promising direction for further improvement is to specify and partition waste flows to be treated differently. Issues such as tailored network design, waste composition, and compartment partition should be addressed separately for each waste type, while still taking into account the co-relation in facility sharing with other waste types. This is in congruence with current regulation to treat different types of waste in a tailored way. Contemporary studies often treat municipal waste as a single unit, instead of investigating the distinguishing feature of each waste type; this means that the characteristics of different recyclables are worth further study.

Regarding sustainability issues, the current modeling methods have explored the balance between economic goals and emission control, whereas the societal objectives have only been started to be integrated in the quantitative models. There is a clear need to define concrete social objectives and impact measurements that can be used in modeling. Hutchins and Sutherland (2008) proposed that labor equity, healthcare, safety, and philanthropy can be the measurements of social sustainability for supply chain decision making as a starting point. This again calls for the integration of other research disciplines (especially related to social studies) with operations research modeling methods. In order to model the dynamic nature of supply chain operations and include all aspects of the relationships with its environment, it is necessary to have modeling techniques that are capable of including the multi-dimensional qualitative and strategic characteristics (Sarkis, 2002).



	Issues derived from practice	Issues addressed in the literature	References	Issues not adequately addressed
External	Differentiated Taxiation	Differenciated municipal waste tax	(Groot et al. 2013)	
	Differentiated recycling targets			Differentiated recycling targets
	Increased Reycling Targets	Recycling target (capacity design)	(Gomes et al. 2011)	
	Valorization			Valorization
Strategic	Multi-commodity	Handle different composition of waste	(Bing et al. 2012)	Handle different waste simutaneously
	Network configuration	Network structure	(Fleischmann et al. 1997)	
	Facility capacity plan	Capacity design of facilities	(Barros et al. 1998)	Over-capacity of facilities
	Facility location choice	Location of recovery facility	(Louwers et al. 1999)	
		Location of transportation links	(Kirkke et al. 1999))	
	Sustainable recycling network	Multi-modality strategy	(Bing et al. 2013)	
		Balance emission and economic concerns	(Srivastava 2007)	Social concerns
Tactical/Operational	Collection method	Curbside or drop off collection	(Mora et al. 2013)	
	Collection coordination	Number of waste stream collected	(Muyldermans and Pang 2010)	
	Collection scheduling	Collection frequencies	(Tung and Pinnoi 2000)	
		Dynamic routing and scheduling	(Faccio et al. 2011)	
	Capacity planning	Multi-compartment vehicle	(Golden et al. 2008)	Compartment partition
		Vehicle capacity	(Laporte 2009)	Capacity of collection bins
	Vehicle routing	Road condition	(Bautista et al., 2008)	
		Number of depot	(Ramos and Oliveira, 2011)	
		Dynamic routing	(Johansson 2006)	
	Sustainable collection	Balance emission and economic concerns	(Bektaş and Laporte 2011)	
			(Edwards and Schelling 1999)	
		Balance emission and social concerns	(Ramos et al. 2014b)	

Note: Only one reference is given for each category. Matching literature is not limited to those provided.

TABLE 2.2: Research gap analysis

2.5.2 Research Opportunities

Based on the discussion of the research gaps above, we propose research opportunities with the three key perspectives described below.

- Multiple dimensions

  MSW management cannot be viewed from a one-dimensional perspective, as many issues from different decision levels are inter-related. The combined decisions on these inter-related issues are often too complex to be solved at once. One possible approach is to decompose the total decision making problem into several subproblems, which then are solved on a step-by-step basis. However, multidimensional problems often introduce differentiated optimization objectives. Separating problems and pursuing the objectives on one decision level at a time will result in suboptimal solutions. Global optimal solutions can only be obtained using an integrated approach that simultaneously takes problems at different decision levels into account.

  A multiple dimensional perspective on MSW management indicates an integration of various disciplines in modeling MSW recycling. To improve sustainability performance, especially regarding addressing environmental and social concerns, it is essential to integrate operations research modeling methods with methods from other disciplines. For example, the life cycle assessment (LCA) methodology is among the most commonly used methods for assessing sustainable waste recycling systems. Edward and Schelling (1999) conducted an LCA on municipal waste with a special focus on transportation, including a sensitivity analysis on recycling plant capacity. Björklund and Finnveden (2007) focused their LCA study on the assessment of tax issues regarding national waste policy. These two examples, among others, suggest that operations research methods have the potential to be integrated with other methods at multiple decision levels. Azapagic and Clift (1999) were among the first researchers to propose combining LCA with multi-objective optimization.

  Other disciplines in technological studies also have the potential to be integrated with OR methods. For example, technology development can bring new parameters into the modeling process, such as new packaging design, RFID technology applied to the measurement of waste quantity, and re-processing technology for the application of recycled materials. Such integrated approaches have been used in other sustainability-related studies. For example, Vlyssides et al. (2004) have studied the environmental problem caused by olive oil production and used an integrated approach combining waste treatment technology, production processes, and the valorization of by-products. In waste management, technological development can have an impact on the estimation of waste quantity, recycling channel allocation, market demand for recycled material, and so on. Thus, by taking technological development into account, new opportunities can be found in modeling waste logistics.

- Holistic view

  The export of waste between continents has helped make waste recycling a global issue. To solve issues such as over-capacity and valorization, and to meet the high requirement of waste recycling rates and satisfy the increasing global demand of the recycled material, a new perspective in research and practice to look into waste recycling is needed. That is, waste recycling must be considered as a procedure of retrieving waste as a global resource that is substitutable for raw material on a regional and a global scope.

  A holistic view is necessary as a local "best" solution might not be optimal on a regional or global scale. For example, in order to measure the cost of waste recycling, it is necessary to take the entire reverse supply chain into account. In order to develop a sustainable supply chain, the complete supply chain must be taken into account. Just as economic globalization creates opportunities and poses challenges to supply chains, so does environmental globalization. Furthermore, the existing theories and models of global supply chain can be applied in a waste recycling context to address the problem on a global scale. From a modeling perspective, global supply chain constraints, such as tax and trade barriers, can be considered in the modeling of reverse logistics network of municipal solid waste. Uncertainties in the global market in terms of the demand of recycled material and currency exchange rates can also be integrated in the models.

- Tailored solution

  Externally, the regulation distinguishes recyclables by setting different recycle targets for each material. In practice, efforts have been made to treat different types of waste in a tailored manner. To meet future demands of further improving the efficiency and sustainability of municipal waste recycling, much more should be done to tailor the solution for each waste type.

  Understanding the characteristics of waste, such as the density (weight-to-volume ratio) difference, quantity difference, and treatment procedure differences, can help tailor the network design for each type of waste in order to further improve the recycling efficiency. As some waste shares the facilities at initial stages of the recycling chain, it is interesting to investigate the combined network for several types of waste. At the tactical and operational decision level, it is only after these different characteristics of each waste type have been investigated that we will be able to move on to fill such research gaps as the design of combined collection with suitable multi-compartments and channel choices or handling different waste differently and simultaneously.

2.6 Conclusion

In order to provide guidelines to future research to improve waste recycling in a more efficient and sustainable direction, this paper has reviewed the current practices and operations research modeling methods. This paper has taken a new angle, by looking at practice first in order to identify the issues that are important now and will be in the future.

Three perspectives of research opportunities have been identified in order to guide the research and practice towards future sustainable municipal solid waste recycling management. These are (a) include multiple dimensions, (b) take a holistic view, and (c) consider tailored solutions for different waste types. The integration of OR with other disciplines such as LCA in the research can help address issues in a more thorough manner. A holistic view should also be taken, especially once practice has already started to globalize waste flows. Research with a tailored design for different waste types has the potential to help further improve the efficiency and sustainable performance of waste recycling.

Chapter 3

Design of a Sustainable Collection System for Household Plastic Waste

This chapter is based on the published journal article:
X.Bing, M. de Keizer, J. M. Bloemhof-Ruwaard , J.G.A.J. van der Vorst (2014) “Vehicle routing for the eco-efficient collection of household plastic waste” Waste Management, online available, http://dx.doi.org/10.1016/j.wasman.2014.01.018

In this chapter we answer Research Question 2a and 2b:
2a What opportunities can be found from the comparison of the collection alternatives to improve the sustainable performance of the collection system?
2b What are the impacts of various collection and taxation alternatives on the performance of the collection system?

Abstract:
Plastic waste is a special category of municipal solid waste. Plastic waste collection is featured with various alternatives of collection methods (curbside/ drop-off) and separation methods (source-/post-separation). In the Netherlands, the collection routes of plastic waste are the same as those of other waste, although plastic is different than other waste in terms of volume to weight ratio. This paper aims for redesigning the collection routes and compares the collection options of plastic waste using eco-efficiency as performance indicator. Eco-efficiency concerns the trade-off between environmental impacts, social issues and costs. The collection problem is modeled as a vehicle routing problem. A tabu search heuristic is used to improve the routes. Collection alternatives are compared by a scenario study approach. Distances between locations are calculated with GIS-assistance. The scenario study is conducted based on real case data of the Dutch municipality Wageningen. Scenarios are designed according to the collection alternatives with different assumptions in collection method, vehicle type, collection frequency and collection points, etc. Results show that the current collection routes can be improved in terms of eco-efficiency performance by using our method. The source-separation drop-off collection scenario has the best performance for plastic collection assuming householders take the waste to the drop-off points in a sustainable manner. The model also shows to be an efficient decision support tool to investigate the impacts of future changes such as alternative vehicle type and different response rates.

Keywords:
vehicle routing problem, waste collection, sustainability, plastics, municipal solid waste, reverse logistics

3.1 Introduction

Plastic waste is a special category of municipal solid waste. Plastics have substantial benefits in terms of their low weight, durability and lower cost relative to many other material types (Andrady and Neal, 2009). This feature makes plastic material favorable for all kinds of packaging use, however makes it difficult for recycling. Separation and sorting of plastic is more complicated than for other waste types due to a large variety in composition. Two alternatives for the collection of waste are possible, either at a central collection point in the neighborhood (drop-off collection) or at the curbside on the street outside the house (curbside collection). There are also two methods for the separation of waste: source-separation and post-separation. Source-separated plastics is separated from other waste at households. Post-separated plastics is mixed and collected together with other waste. Separation of plastics from other waste happens later in a separation center. Trade-offs between these collection options are in terms of costs, facility requirement and householder's involvement. Municipalities need a comparison between these collection options for plastic waste to make a decision on which collection method to invest in.

The collection cost of the various options is the most primary measurement to support this decision making process. Besides, due to the increasing environmental concerns, another important measurement that should be taken into account together with costs is the environmental and social performance of the collection options. Plastic waste collection should be eco-efficient. The concept of eco-efficiency is based on the concept of creating more goods and services while using fewer resources and creating less waste and pollution (WBCSD, 2000). Waste recycling is sustainable in itself as it avoids landfills (Carlson, 2001). Moreover, from a sustainable logistics perspective, there is also a requirement of conducting the activities in a sustainable manner, that is paying attention to environmental impacts and social well-being in addition to cost minimization (Quariguasi Frota Neto et al., 2009b). The eco-efficient performance of the collection options should be tested, together with the potentials to further reduce environmental impact. The continuous improvement in waste recycling in terms of householder's behaviour and the technology input requires a design of collection that can cope with future changes. Therefore the capability of these collection options to meet future demand should also be investigated.

This research starts from current practice and redesigns the collection of various options based on the case of the Netherlands. Each Dutch municipality (more than 400 in total) has to decide which collection method to adopt. Recently, source-separated plastic waste recycling is promoted with free waste bags distributed to households with a "Plastic Hero" icon printed on each bag. In the future, municipalities are facing the choice of investing in an alternative collection system. It is also difficult to predict how capable these alternatives are in dealing with future changes in plastic recycling. Therefore, the purpose of this research is to compare different options of collection alternatives with an improved eco-efficiency performance, and to explore the potentials for coping with future development. "Eco-efficiency" in waste collection means to deliver the collection service that satisfies the needs of householders while progressively reducing environmental impacts. Based on the current collection practice of a representative Dutch municipality, heuristics are used to improve the current collection routes. A scenario study approach is used in the analysis to compare different collection alternatives. Scenarios are designed with various collection methods in combination with the possible separation methods.

Results are compared to provide decision support for choosing suitable collection options for municipalities.

The collection of plastic waste is modeled as a vehicle routing problem (VRP). A tabu search algorithm is proposed to solve the model. The current collection routes are used as initial solution and the algorithm improves the routes with an objective of minimizing total cost. Emissions from driving and idling of vehicles are transferred to a cost factor that is added to the total cost. The costs considered in the model, therefore, consist of transportation cost, labour cost and emission cost. In order to model the problem in a realistic manner, distance matrices between locations are generated by a GIS tool Microsoft MapPoint (Microsoft, 2012). In this way, the distance input of the model can reflect the actual shortest driving distances between each pair of locations in the chosen geographic area.

The remainder of the paper is organized as follows. In Section 2, we present the scientific relevance of the research. In Section 3, we describe the problem and formulate the model. Section 4 presents the scenarios and present the data we use in the modelling Section 5 presents the algorithm we use to obtain the results as presented in Section 6. Section 7 presents the sensitivity analysis and discussion. Conclusions are stated in Section 8.

3.2 Scientific Relevance

The collection of municipal plastic waste is within the scope of reverse logistics (Fleischmann et al., 1997c). Redesign of the collection routes for municipal plastic waste is essentially a vehicle routing problem. The Vehicle Routing Problem (VRP) can be described as the problem of designing optimal delivery or collection routes from one or several depots to a number of geographically scattered demand points, subject to side constraints (Christofides, 1976). The VRP plays an important role in logistics with a large number of variants (Desrochers et al., 1990). A few VRP variants can be applied to waste collection problems. Waste collection can be divided into three categories: residential, commercial and skip waste collection (Benjamin, 2011). Residential waste is collected in front of the houses in small bins or garbage bags. The collection vehicles will collect all the waste along the streets which is often solved as an arc routing problem where demand is on arcs. Commercial collection (waste in restaurants, retail outlets and apartments in containers) and skip collection (waste in construction sites in big containers) problems are typically solved as node routing problems (demand on nodes) and the location of every customer is known. Waste collection involved in these strategies is point-to-point collection (Ramos et al., 2013). In practice, a combination of the two types of collection in the routing problem (demand on both arcs and nodes)also exists, which makes it a general routing problem (Beullens et al., 2004). For plastic waste collection, drop-off collection is a typical node-routing problem. In curbside collection, as in practice, householders aggregate their plastic bags with the close-by neighbours at curbside, collection points can be aggregated and also modeled as a node-routing problem.

Given the complexity of the problem, heuristics are usually used to efficiently solve VRP for waste collection problems. Karadimas et al. (2007) employed the ant colony algorithm for optimizing costs for different scenarios of urban solid waste management systems. A capacitated clustering-based algorithm is proposed by Kim et al. (2006a) to solve their waste collection vehicle routing problem with time windows considering the route compactness and workload balancing of a solution. Benjamin and Beasley (2010a) work on a waste collection vehicle routing model with time windows. They generate their initial solution with a method that fully utilizes a vehicle and improves the initial solution using an interchange procedure. Bautista et al. (2008a) described their urban waste collection problem as a capacitated arc routing problem. They applied a transformation procedure of the problem into a node routing one and solved it with ant colony heuristics. Scheuerer (2006) used a tabu search heuristics for the truck and trailer routing problem and concluded that the tabu search obtained better solutions in comparison with the other construction heuristics used. Ismail and Md Yunos (2010) designed a reactive tabu search to solve the solid waste collection scheduling problem with a dynamic tabu list. The previous research shows Tabu search is an appropriate method to solve a waste collection vehicle routing problem. Thus, in our research, we also designed a Tabu search algorithm to solve our vehicle routing problem. This algorithm is featured with a combination of three types of moves and a reactive frequency indicator to favor moves with a better performance progressively.

A number of studies have been conducted on comparing waste collection options. Gallardo et al. (2010) investigated the extent to which clean materials are recovered of four different selective collection scenarios in Spain. They concluded that the best values were obtained from the system with paper/cardboard, glass and lightweight packaging (e.g. plastic packaging) at drop-off points, organic waste and mixed waste in curb-side bins. Dahlén et al. (2007) performed a sampling and composition analysis of different collection methods for sorted household waste in Sweden and concluded that with curb-side collection more metal, plastic and paper packaging was separated and sent to recycling. These studies investigated the differences between various waste types in the comparison. The focuses are mainly on collection alternatives. Whereas, our study takes a closer look into plastic waste in specific and takes into account the combined effect of collection and separation methods. We examine the different combinations of these methods with a vehicle routing model. The key performance indicator is eco-efficiency measured by a combination of transportation, labour and emission costs.

With the increasing concern for sustainable logistics, minimizing emission and fuel use are also considered by both researchers and practitioners to be the objectives of VRP for waste collection, apart from objectives such as minimizing the traveling distance, transportation cost and the number of vehicles used. Tavares et al. (2009) use a GIS 3D route modeling software for waste collection and transportation to solve the routing problem in a case study. Driving routes are optimized for minimum fuel consumption. Results show a 8% cost saving compared to the approach of simply calculating shortest route. The Pollution-Routing Problem (PRP) as a variant of VRP is proposed by Bektas and Laporte (2011a). The objectives of PRP not only account for the travel distance but also for the greenhouse emissions, fuel, travel times and their costs. The PRP is significantly more difficult to solve to optimality but has the potential of yielding savings in total cost. There is a need to design a method that is easy to solve and still gives a good result for a sustainable re-design of waste collection routing problem, which is also more practical and starts from reality. In our research we aim to re-design the collection routes by taking into account emission cost in the total logistics cost to be optimized. The goal is to model the collection system in a realistic and comprehensive way so that such a method can be used to provide support to improve eco-efficiency performance and assist future decision making process. We use Microsoft MapPoint to obtain shortest driving distances between each pair of collection points in order to assist our modeling.

3.3 Vehicle Routing Problem with Eco-efficiency Objective

In curbside collection, waste is normally placed outside each house on the side of the streets. In practice, Dutch householders on the same street usually put their plastic waste bags together on the parking place nearby or at the road junctions. Collection vehicles do not have to make stops at each house to collect plastic waste bags, but only have to stop at the point where all the bags are put together. In this case, the curbside collection can be addressed as a node routing problem. We aggregate the nearby households which share a spot to put their plastic waste bags as a “section”. By making a stop in such a section, all the aggregated addresses can be served by the collection vehicle together. A single address that can not be aggregated will also make a section. In drop-off collection, the collection points are the central locations where households bring the waste to, which is in the neighborhood, although not as close-by as the curbside points. This is a typical node-routing problem.

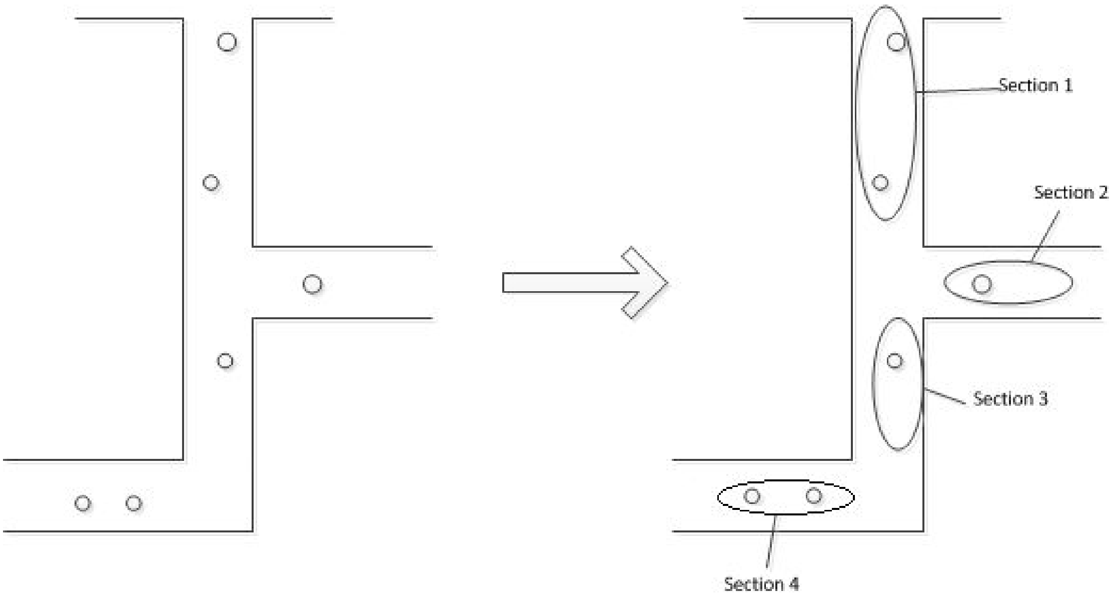


FIGURE 3.1: *Example of sections*

In this way, we describe both the curbside and drop-off collection problem as node routing problem defined in a connected graph. So let $G = (V, A)$ be a graph with V_0 as depot and two subsets of V, V_c and V_d. V_c denotes the points of curbside collection and V_d denotes the points of drop-off collection. Both V_c and V_d cover the service of the whole area. There is a set of parameters $\{q_i, t_i^s\}$ associated with each node in V, in which q_i denotes the expected amount of waste to be collected at node i, t_i^s denotes the idling time at node i. f^s denotes the fuel consumption per hour when the collection vehicle is idling at nodes. For both subsets V_c and V_d, a solution is a set of tours $R_1, ..., R_k$, where $R_k = (V_0, V_{r_1}, V_{r_2}, ..., V_0)$. Each vertex V_i belongs to exactly one tour. The objective is to minimize:

$$\sum_k \sum_{(i,j)\in R_k} (c^f + ec^e) f^d d_{ij} X_{ij} + c^l (t_i^s n + d_{ij} X_{ij}/v) + n t_i^s f^s (c^f + ec^e) \tag{3.1}$$

Subject to:

$$\sum_{k}\sum_{i\in V\backslash\{j\}} x_{ijk} = 1 \qquad \forall j \in V\backslash\{0\} \tag{3.2}$$

$$\sum_{k}\sum_{j\in V\backslash\{i\}} x_{ijk} = 1 \qquad \forall i \in V\backslash\{0\} \tag{3.3}$$

$$\sum_{i\in V\backslash\{j\}}\sum_{j\in V\backslash\{i\}} x_{ijk}(t_{ij} + f_i) \leq T_k \qquad \forall k \in K \tag{3.4}$$

$$u_i - u_j + Ux_{ijk} \leq U - d_j \qquad \forall i, j \in V\backslash\{0\}, i \neq j, \forall k \in K \tag{3.5}$$

$$q_i \leq u_i \leq U \qquad \forall i \in V\backslash\{0\} \tag{3.6}$$

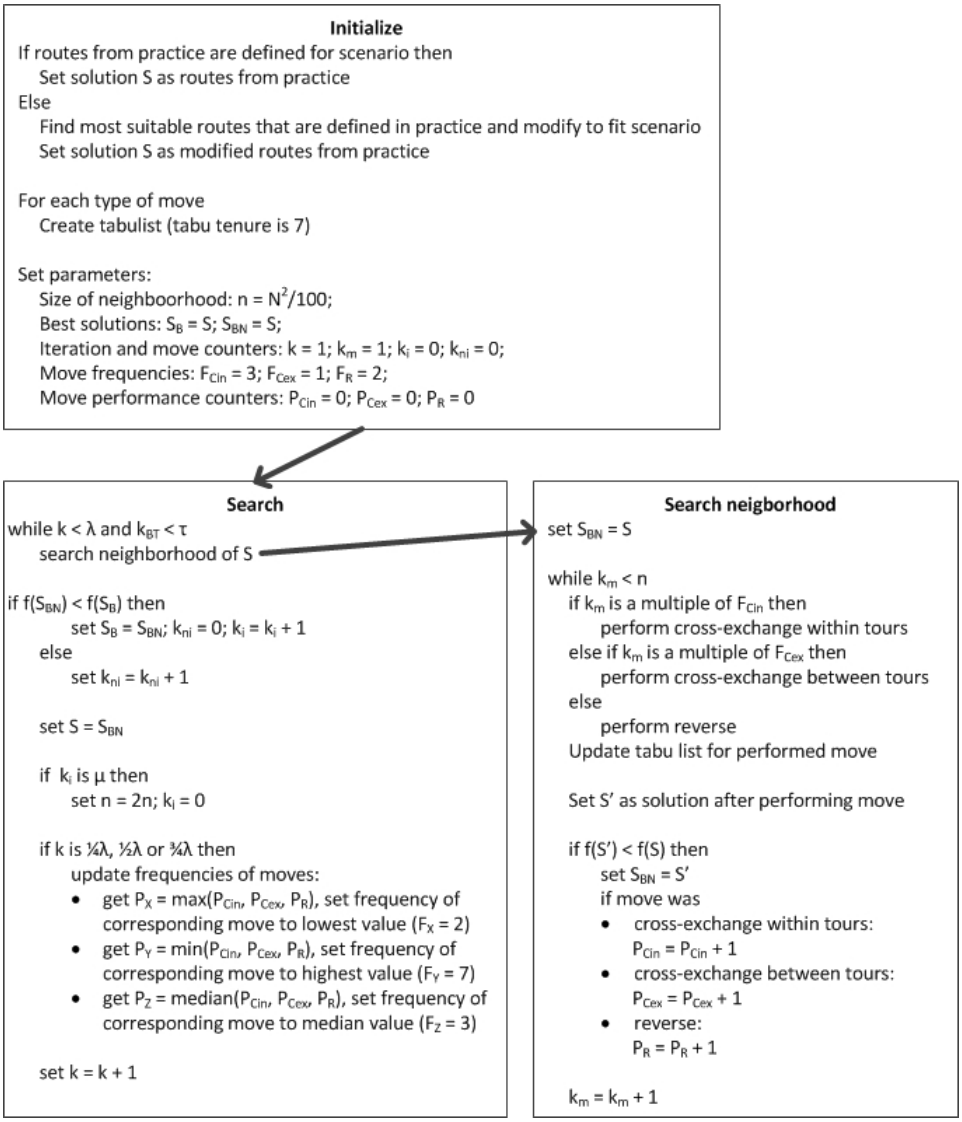
$$x_{ij} \in \mathbb{B}, u_i \in \mathbb{R}_+ \tag{3.7}$$

The objective (1) minimizes the total transportation cost which includes transport and emission cost when the vehicle is driving, emission cost while idling and labor cost. In this objective function, c^f is the fuel cost of the collection vehicle, v is the average speed and x_{ij} denotes whether arc i, j is traversed, which is binary. f^d is the fuel consumption per kilometer when the collection vehicle is driving between nodes. The emission cost when driving between nodes is calculated by carbon cost c^e and carbon conversion factor e (carbon equivalent emission per liter of fuel consumed by the collection vehicle). Labor cost is calculated by multiplying the labour cost per hour c^l with the total time of traveling and idling. The fuel cost while idling is calculated as $nt_i^s f^s c^f$. The emission cost while idling at nodes is $nt_i^s f^s ec^e$, which is the number of nodes × idling time in each node × fuel consumption when idling × carbon conversion factor × carbon cost.

Constraint(2) requires that every collection point has to be visited only once, and constraint (3) requires that the vehicle has to visit another collection point after visiting a collection point. Constraint (4) is the time constraint which limits the total time of a route (sum of all traverse time t_{ij} and service time f_i) within the maximum duration allowed for each route T_k. Constraints (5) and (6) are introduced to avoid forming a traveling loop which does not visit the original point and avoiding forming a traveling loop which needs a larger carrying capacity than the full container amount. Note that we denote $\{0\} \in V$ as the origin point that a vehicle has to go back to after finishing a traveling loop.

3.4 Tabu Search Algorithm

We solve our VRP with a tabu search algorithm. We initialize the algorithm with current routes from practice. Then we search neighborhoods using moves between and within tours. The details of the algorithm, including stopping criteria and how we intensify and diversify our neighborhood searches, are described next. An outline of the algorithm is given in Figure 3.2 (and a description of the used symbols is given in Table 3.1).



```
Initialize
If routes from practice are defined for scenario then
    Set solution S as routes from practice
Else
    Find most suitable routes that are defined in practice and modify to fit scenario
    Set solution S as modified routes from practice

For each type of move
    Create tabulist (tabu tenure is 7)

Set parameters:
    Size of neighboorhood: $n = N^2/100$;
    Best solutions: $S_B = S$; $S_{BN} = S$;
    Iteration and move counters: $k = 1$; $k_m = 1$; $k_i = 0$; $k_{ni} = 0$;
    Move frequencies: $F_{Cin} = 3$; $F_{Cex} = 1$; $F_R = 2$;
    Move performance counters: $P_{Cin} = 0$; $P_{Cex} = 0$; $P_R = 0$

Search
while $k < \lambda$ and $k_{BT} < \tau$
    search neighborhood of S

if $f(S_{BN}) < f(S_B)$ then
        set $S_B = S_{BN}$; $k_{ni} = 0$; $k_i = k_i + 1$
    else
        set $k_{ni} = k_{ni} + 1$

    set $S = S_{BN}$

    if $k_i$ is $\mu$ then
        set $n = 2n$; $k_i = 0$

    if k is ¼λ, ½λ or ¾λ then
        update frequencies of moves:
        •  get $P_X = \max(P_{Cin}, P_{Cex}, P_R)$, set frequency of
           corresponding move to lowest value ($F_X = 2$)
        •  get $P_Y = \min(P_{Cin}, P_{Cex}, P_R)$, set frequency of
           corresponding move to highest value ($F_Y = 7$)
        •  get $P_Z = \mathrm{median}(P_{Cin}, P_{Cex}, P_R)$, set frequency of
           corresponding move to median value ($F_Z = 3$)

    set $k = k + 1$

Search neigborhood
set $S_{BN} = S$

while $k_m < n$
    if $k_m$ is a multiple of $F_{Cin}$ then
        perform cross-exchange within tours
    else if $k_m$ is a multiple of $F_{Cex}$ then
        perform cross-exchange between tours
    else
        perform reverse
    Update tabu list for performed move

    Set S' as solution after performing move

    if $f(S') < f(S)$ then
        set $S_{BN} = S'$
        if move was
        •  cross-exchange within tours:
           $P_{Cin} = P_{Cin} + 1$
        •  cross-exchange between tours:
           $P_{Cex} = P_{Cex} + 1$
        •  reverse:
           $P_R = P_R + 1$

    $k_m = k_m + 1$
```

FIGURE 3.2: *Outline of Tabu Search Algorithm*

Initialize

In the scenarios we designed, there are two types of routes for waste collection in the municipality: one is for curb-side, one is for drop-off. Our purpose is to help improve the efficiency and sustainability of current practice to fit for the plastic waste in specific.

Symbol	Description
N	Total number of sections
n	Number of neighbors to consider in each neighborhood
S	Solution
$f(S)$	Total cost of solution S
S_B	Best found solution
S_{BN}	Best found solution in neighborhood
k	Iteration counter
k_m	Move counter
k_i	Number of improving iterations
k_{ni}	Number of non-improving iterations since best solution found
F_{Cin}	Frequency of performing cross-exchange moves within tours
F_{Cex}	Frequency of performing cross-exchange moves between tours
F_R	Frequency of performing reverse moves
P_{Cin}	Number of improving cross-exchange moves within tours
P_{Cex}	Number of improving cross-exchange moves between tours
P_R	Number of improving reverse moves
λ	Maximum number of iterations allowed
τ	Maximum number of consecutive non-improving iterations allowed
μ	Maximum number of improving iterations

TABLE 3.1: Symbols used in outline of Tabu Search Algorithm

The current routes are to some extent optimized as they are designed by the experienced drivers. Therefore we try to make use of these routes and use them as an initial solution. If the scenario is not exactly the same as current practice (in terms of truck type and collection method, etc.), we generate an initial solution by the following method:

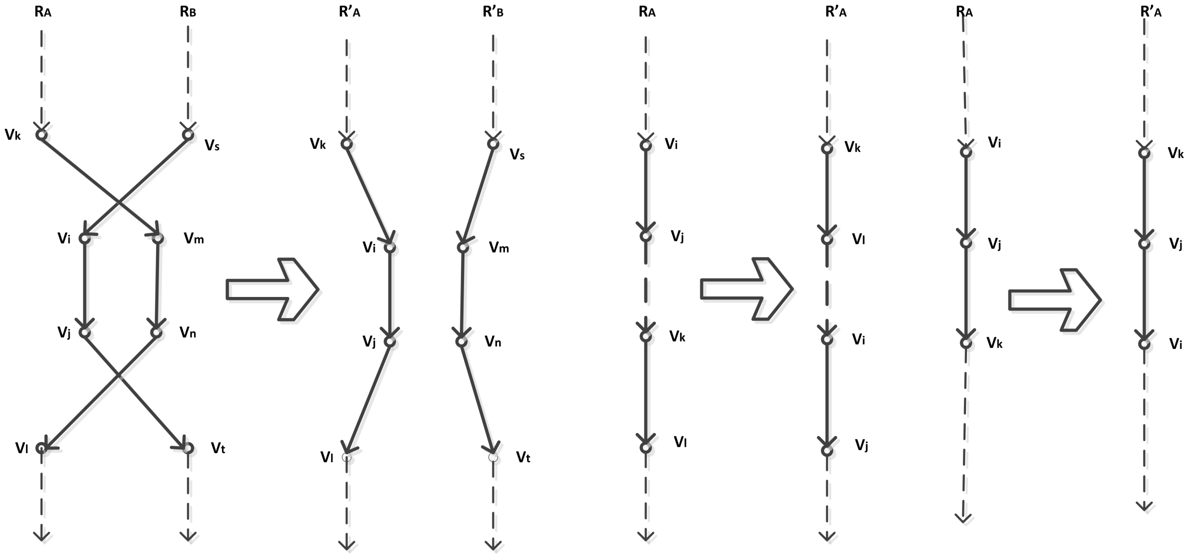
Number each collection point (vertex) following the sequence of collection in practice (the sequence by which each cluster is visited in the drop-off collection routing). Then we start from depot V_0 and connect V_1 from and back to the depot to form a current tour $\{V_0, V_1, V_0\}$. Check if the capacity limit of a vehicle or the maximum time allowed in one tour is met at vertex V_1 and whether adding another vertex adjacent to this vertex V_2 will violate the capacity limit. If so, we complete the tour and start from depot again to generate a new tour, otherwise, we add V_2 to the current tour. The current tour is then updated to $\{V_0, V_1, V_2, V_0\}$. Repeat the procedure until all vertices are in the tours.

Neighborhood Search

"Cross-exchange" and "Reverse" are used in the neighborhood search. Cross-exchange is conducted by exchanging sections and happens on the same route as well as between routes. Reverse changes the direction in which a section is traversed. Detailed description of the moves are described in the following (see also Figure 3.3).

- Cross-exchange between tours

  Step 1:



Cross-exchange between tours

Cross-exchange within a tour

Reverse

FIGURE 3.3: *Examples of moves used in the neighborhood search*

- Start with a solution S, and randomly select a vertex V_i.
- Determine tour R_A that V_i is currently in.
- Check whether there are other vertices that belong to the same section as V_i. If there are, find the complete section in which V_i is located and set section $A = \{V_k, V_l, ..., V_i, V_j\}$. Else, set section $A = \{V_i\}$
- Let $Q(A)$ be the total quantity of waste collected in the vertices of section A.
- Let $Q(R_A)$ be the total quantity of waste collected in tour R_A.

Step 2:

- Randomly select another vertex V_j in $S \setminus R_A$.
- Determine tour R_B that V_j is currently in.
- Check whether there are other vertices that belong to the same section as V_j. If there are, find the complete section in which V_j is located and set section $B = \{V_m, V_n, ..., V_j, V_s\}$. Else, set section $B = \{V_t\}$
- Let $Q(B)$ be the total quantity of waste collected in the vertices of section B.
- Let $Q(R_B)$ be the total quantity of waste collected in tour R_B.

Step 3:

- Let C be the capacity of the collection vehicle.
- Let $\triangle T(A \leftarrow B)$ be the time difference when replacing section A with Section B in tour R_A, and $\triangle T(B \leftarrow A)$ be the time difference when replacing section

B with Section A in tour R_B, which includes the difference in idling time and driving time.

- Let $T(R_A)$ and $T(R_B)$ be the total time of traversing tour R_A and R_B.
- Let T_{max} be the time limit of one tour.
- If
  $Q(R_A) - Q(A) + Q(B) \leq C$ and $Q(R_B) - Q(B) + Q(A) \leq C$
  and
  $T(R_A) + \triangle T(A \leftarrow B) \leq T_{max}$ and $T(R_B) + \triangle T(B \leftarrow A) \leq T_{max}$
  and
  exchanging sections A and B, {A, B}, is not tabu,
  continue.
  Else, go to Step 2.

Step 4:

- Put {A,B} in tabu, meaning that section A can not be exchanged with section B for a number of moves.
- Let R'_A be tour R_A after replacing section A with section B, and let R'_B be tour R_B after replacing section B with section A.
- Check whether the total cost of the tours after exchanging sections A and B, $f(R'_A) + f(R'_B)$, is smaller than that before exchanging, $f(R_A) + f(R_B)$. If so, perform the cross-exchange and update the best solution found in the current neighborhood. Else, go to Step 1.

- Cross-exchange within tours
  The general procedure is similar to the cross exchange between tours. The difference is that in this move, sections A and B are in the same tour. So in Step 2, section B should be found in the same tour as section A.

- Reverse
  - Randomly select a vertex V_i which is in a section A with more than one vertex. Set section A = $\{V_k, V_l, ..., V_i, V_j\}$.
  - Check whether section A is not tabu, whether the distance of the tour reduces and whether there is no violation of the time constraint for the tour when section A is traversed in reverse order $\{V_j, V_i, ..., V_l, V_k\}$. If so, perform reverse of section A and put section A in tabu, meaning that section A can not be reversed for a number of moves. Else, repeat from the beginning.

Stopping criteria

We set the stopping criteria as (1) the number of iterations meets the largest iteration number allowed, λ, (2) no further improvement can be found for τ iterations after the best current solution.

Diversification and intensification

Our diversification strategy is, firstly, to induce a higher frequency for performing cross-exchange moves between tours. Secondly, we gradually increase the number of neighbors that we consider in each neighborhood to allow for more search space (we do not search the whole neighborhood to speed up calculations). Our intensification is, firstly, to restart the search from the best found solution after every μ iterations. Additionally, we use a long-term memory of performance indicators to find out which move more frequently gives a better solution. We favor moves with better performance by performing it more frequently after a given number of iterations.

3.5 Scenario Study

3.5.1 Collection Alternatives

We conduct this study on a representative Dutch city with a combination of housing types (apartment buildings and houses). Collection is modeled on a weekly basis. The research method used in this paper is a VRP based scenario study. The scenarios used are presented in Figure 3.4.

	Source-Separation	Post-Separation
Drop-off Collection	Scenario 1	Scenario 3
Curbside Collection	Scenario 2	Scenario 4

FIGURE 3.4: *Scenarios used in the scenario study*

Scenarios are designed according to the existing collection options in the Netherlands. In practice, each municipality has one of the four collection options. In the Netherlands, there are about 90% source-separation municipalities, among which about 30% are using drop-off collection (Bing et al., 2014). As a sensitivity test, we apply, in the later phase of the study, a higher plastic waste input quantity and hybrid truck to investigate the potential improvement we can achieve in sustainability performance of waste collection. The scenario which fits the current practice of the chosen study area is the benchmarking scenario. By applying our heuristics method in improving the collection in this scenario, the result can show the potential in improving the eco-efficiency of the current practice. Applying other scenarios to the study area can show the difference between scenarios, thus to provide decision support for municipalities in making choices for future investments.

3.5.2 Data

Data collection for building up the model took place in cooperation with municipalities and research partners through interviews, industrial reports and literature. Collection company and municipalities are interviewed to get the data for collection details. Data sources and a summary of the data used in the model are presented below. Some detailed figures of curbside and drop-off collections for both source-separation and post-separation are presented in Table 3.2.

Municipality The Netherlands is a country with a high population density. We choose the municipality of Wageningen as the study area. It is a representative municipality with a combination of housing types. There are areas with tall apartment buildings and also areas with many houses in a low density. On average, it is a city with a relatively high population density. There are 37000 inhabitants in 20417 households. It is a municipality which has a drop-off source-separation collection of plastic waste, so Scenario 1 is the current situation in practice for this municipality.

Input parameters	Curbside	Drop-off	Unit
The average speed in collection round	50	50	km/hr
Fuel price / litre	1.4	1.4	Euro/l
The average time per stop	0,01	0,03	hr
Fuel consumption for vehicle per km while driving	0.33	0,4	l/km
Fuel consumption for vehicle per h while idling	3	3	l/h
The labour cost per year	30000	30000	Euro
The regular working hours of driver and loader per year	1650	1650	hr
The number of driver per vehicle	1	1	–
The number of loader per vehicle	1	0	–
The number of collection points	221	15	–

Table 3.2: Input data for the waste collection vehicle routing problem (Groot et al., 2013)

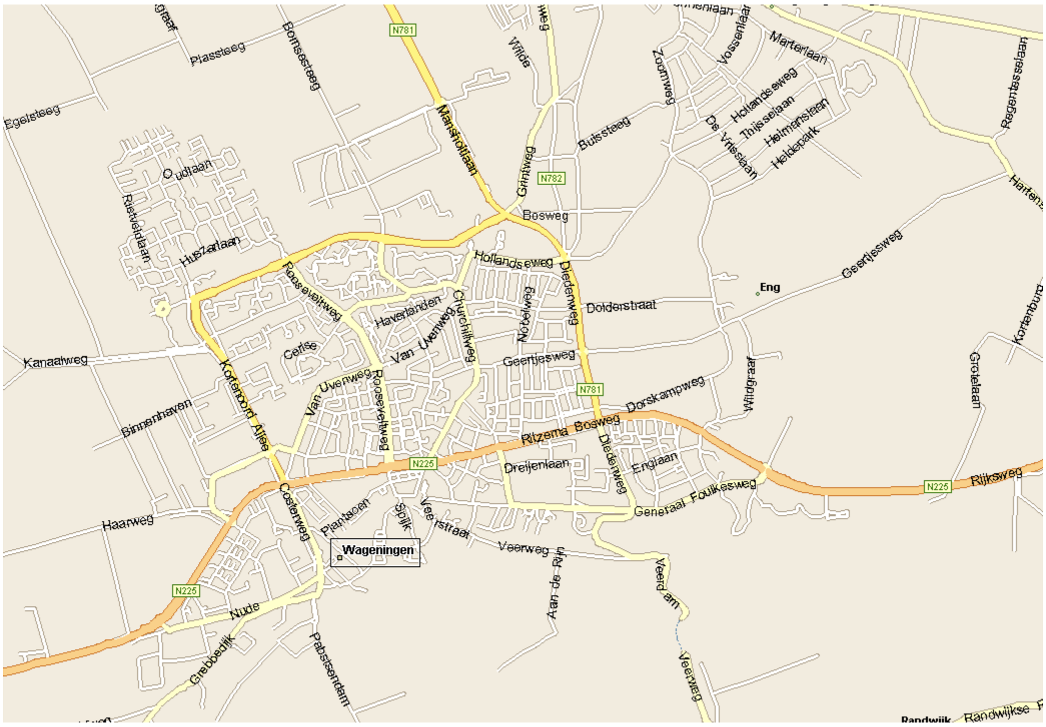


FIGURE 3.5: *map of the study area Wageningen, NL*

Quantity From both local municipalities and the Central Bureau of Statistics, we obtain the quantity of plastic waste collected by households in Wageningen area, that is on average 3563 kg/week.

Collection locations and collection rounds Data on the current practice of the collection rounds are collected through interviews with local authorities and collection companies. The locations of the bins are given by the collection company. There are 15 locations for drop-off collection points. The drivers work for 4 hours per collection round. For curbside collection, the collection company is investigating the feasibility to launch a project on promoting a device which can be attached to trees and street lamp poles, on which the plastic waste bags can be put to prevent bags to be blow away by wind on curbside. By using this device, the plastic bags of the nearby householders will be aggregated for curbside collection. As there is no curb-side collection in practice for plastic waste in this city yet, to generate the collection routes for the curbside scenarios, we follow the general principle of curbside garbage bin collection for other types of waste in generating the initial collection rounds. We select the aggregated curbside collection points near road junctions and parking lots. The density of the locations are according to the population density of the streets. We aggregate the nodes to sections according to the principle described previously. After aggregation, curbside collection has 221 collection points and the total number of drop off locations is 15.

Truck types and fuel use The trucks used in drop-off collection and curb-side collection are different. In drop-off collection, a truck has to be equipped with a lifting function to pick up the large containers. Both trucks used in the two collection methods have a pressing function. In source-separation, the maximum truck load is 3600 kg and in post-separation, it is 7200 kg. The difference is due to the different density of waste being collected. Plastic has a much lower density even after pressing, in comparison with other waste.

Fuel consumption, labour cost, idling time Fuel consumption during driving and idling are different in our model. Idling time is dependent on the waste volume of the collection point and the type of the collection point. Labour cost is referred as the average wage of truck drivers. For drop-off collection, one person is needed per truck for driving and operation. In curbside collection, two persons are needed, one driver and one loader.

Fuel conversion factor, emission cost For the cost of transportation emission, we refer to the price of EU carbon allowances 2008, that is 20 Euro per ton of CO_2-eq. The emission per unit of fuel consumption is presented as the GHG factor, which is 3.8 kg CO_2-eq per liter of diesel (Defra, 2012).

3.6 Results

For the municipality we chose in the scenario study, the first scenario (source-separation, drop-off collection for plastic waste) is the same as the current practice. We use this scenario for bench-marking. We obtained the current collection route from the local waste collection company and improved the route with the algorithm we designed. As this is a case with small instance, we also solved the problem with a Mixed Integer Linear Programming formulation by using the column generation method. With the exponential subtour elimination constraints, this linear program for our VRP is too large to consider all the variables explicitly. Since only a subset of variables need to be considered in theory when solving the problem, column generation generates only the variables which have the potential to improve the objective function (Chabrier, 2006). By using this method, we solved the MILP with ILOG CPlex solver and obtained the optimal solution of the VRP for Scenario 1. The comparison of results are presented in Table 3.3.

	solution		
	Initial(reality)	Heuristics	Optimal
Total Distance (km)	40.19	36.88	35.89
Total Time (h)	1.67	1.61	1.59
Total Cost (euro)	**51.68**	**48.78**	**47.91**
emission cost (euro)	1.42	1.32	1.29
other cost (euro)	50.26	47.46	46.62
Reduction in total cost	0	6%	7%

TABLE 3.3: Comparison of results for Scenario 1

The results indicate that improvements can be made to the current practice of collecting plastic waste towards an improved eco-efficiency performance. The optimal solution obtained from solving the MILP model shows an overall improvement of 7%. With the Tabu search heuristics, we obtain on average a solution which gives 6% improvement. The Java Program is run on a 64-bit, 2 GB RAM computer and the average time it takes to run the program is about 6 seconds with a maximum iteration number set to be 500. This result shows that the Tabu search heuristic we designed for the problem is efficient and gives a result with a relatively good quality.

3.6.1 Results of all scenarios

We apply the method also on other scenarios and obtained the results as shown in Table 3.4. Different inputs of collection frequency and total quantity of waste to be collected are used in each scenario. In general, as in post separation plastics are separated in separation centers, the machinery separation is more efficient than source-separation by householders, more plastics are collected in post-separation system for recycling than in source-separation system. Figures used as input for the model refer to data obtained from field study and results of technical experiments from this research project (Thoden van Velzen et al., 2013). We applied the same heuristics to the four scenarios and run the program for each scenario with a maximum number of iterations set to be 500. The results of total collection costs, time and distance presented in Table 3.4 are the average values.

The results show that to collect each kilogram of plastic waste, the cost of using post-separation and using source-separation does not differ much. However, since there is a

	Scenarios			
	S1	S2	S3	S4
System	Source-Separation		Post-Separation	
	Drop-off	Curbside	Drop-off	Curbside
Input				
Total quantity of waste collected (kg)	3563	3563	54077	54077
% of plastic waste	100%	100%	5,30%	5,30%
Quantity of plastic waste collected(kg)	3563	3563	8598	8598
Result per collection round				
Total costs (Euro)	48.78	217.51	177,35	492,10
Fuel cost (Euro)	24.31	59.05	96.91	132.65
Labour cost (Euro)	23.15	155,25	75,18	352,25
Emission cost (Euro)	1.32	3.21	5.26	7.2
Standard deviation of total cost	0.42	1.00	1.79	1.05
Total time(hr)	1.61	5.39	5.22	12,23
Total distance(km)	36.88	96.33	157.53	215.04
Result per kg of plastic				
Total costs (Euro/kg/week)	0.014	0.061	0.021	0.057

TABLE 3.4: *Comparison of results for all scenarios*

mechanical separation process needed for post separation to get the plastic out of the mixed waste, this cost should be added. For every kilogram of waste, the processing cost is 0.35 euro (Bing et al., 2013). Considering this cost, source-separation in general is cheaper than post-separation. Besides, as recyclable plastic waste is not mixed with other waste in the process, a resulting lower contamination rate adds to the advantage of source-separation.

For the collection of plastic waste in our studied area, the current practice of drop-off collection has the lowest unit cost in our model output. To collect the same amount of plastic waste with source-separation, the total driving distance and time is about two times less than the curbside collection. It is worth to notice that this difference is partly due to the different scopes in calculating total costs for the two collection options. In drop-off collection, the transportation from households to the drop-off points are not counted whereas in curbside collection, a door to door collection is counted in the calculation. Take source-separation as example, this factor implies that drop-off collection is cheaper than curbside collection only when the total cost (emission cost included) of all householders transporting their plastic waste to the drop-off collection points counts for less than 0.047 euro per kilogram. This cost can be neglected if bikes are used in transporting waste bags to the drop-off locations or if driving trips to shopping/to school/to work are combined with dropping waste. In other words, the performance depends a lot on the behaviour of householders and the locations of the containers. If householders transport their waste

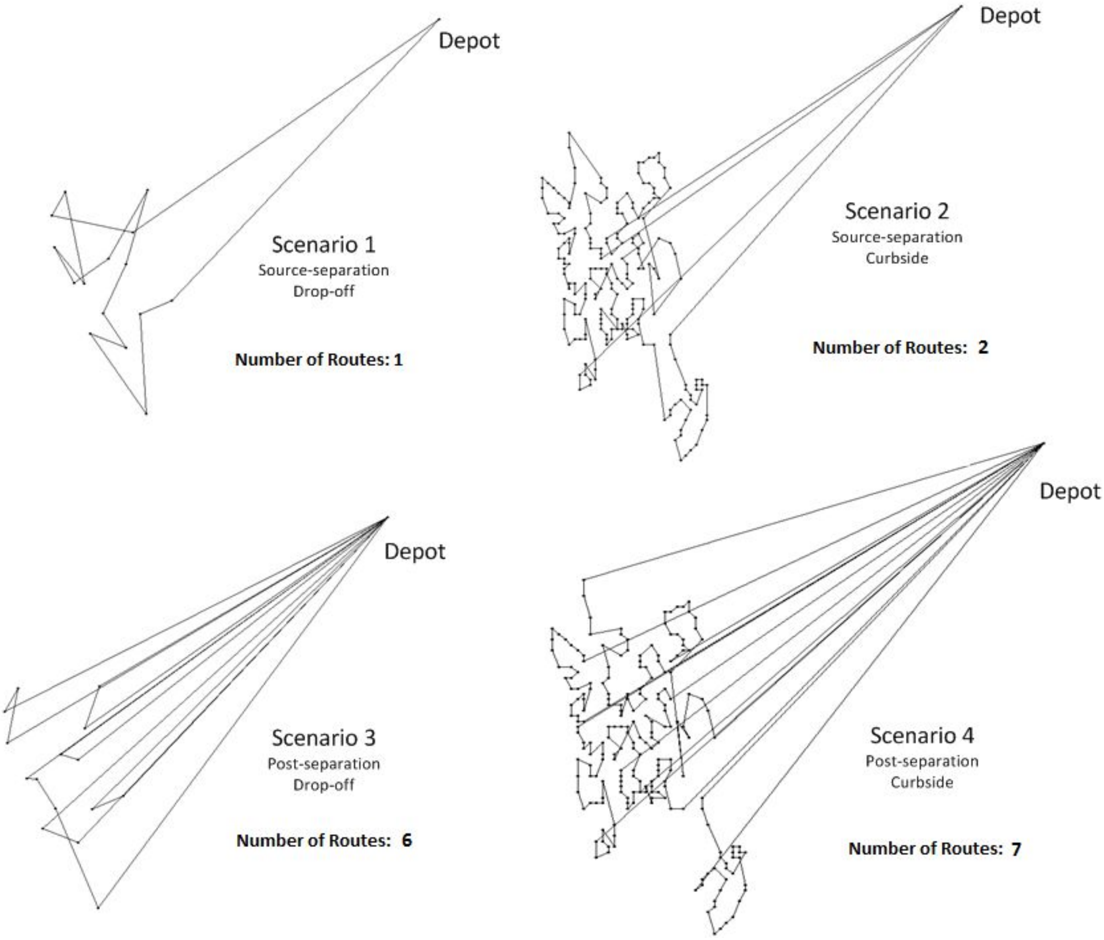


FIGURE 3.6: *Visualization of solutions for all scenarios*

in a sustainable way, costs can be neglected. Otherwise, this result gives a reference to decide how far way on average should the drop-off location be chosen from the households it serves.

The visualization of Java program output is presented in Figure 3.6. Note that in the figure, nodes are connected with straight lines. The length of the lines do not reflect the actual driving distance between nodes as we use the GIS tool to generate the actual driving distances as model input.

To further validate the model, we conducted a few tests with the model. We used the node aggregation method in the heuristics, that is nodes are aggregated in sections. In order to show the effect of the node aggregation on the quality of results, we tested the model without nodes aggregated to sections on Scenario 4. Results shows that with the same numbers of iterations, without sections, the total cost is about 17 percent more. It shows the advantage of using the node aggregation method. With the same iteration number, a better result is given when the nodes are aggregated in sections. The average run time for the test without sections is on average also longer than the one with sections. This shows the method we propose is efficient in solving a vehicle routing problem with the specific settings of our scenarios. With this model, we also conducted a few sensitivity analyses on input parameters to explore the potentials of these scenarios in further improving the performances. The test results and discussions are presented in the following section.

3.7 Sensitivity Analysis

Among the assumptions we made in the scenario study, a few of them play an important role in determining the eco-efficiency performance of the collection system. In this section, sensitivity analysis is also conducted on assumptions of truck type and the response rate of the plastic waste. The impacts of these parameters are analyzed accordingly.

- Hybrid trucks

The collection truck for collecting plastic waste is the same as the truck for collecting other types of waste. Due to the fact that plastic is a light material, the collection of plastics can be less efficient and generates more emission than collecting other waste. One way to reduce emissions is to use alternative vehicles which give a lower emission, such as hybrid trucks. With the trend that hybrid vehicles are becoming more and more popular in urban transportation for the purpose of reducing emissions, hybrid trucks start to be applied in waste collection. In 2008, the first hybrid waste collection truck is launched in Gothenburg, Sweden. The pioneer launch of the hybrid truck shows the advantage of such trucks in curbside collection, especially when the collection truck is idling, loading and compacting the waste for most of its operating time and often moves only short distances (Helming, 2012). Although such truck is not used in Netherlands for waste collection yet, it is interesting to see how much cost reduction can such technology bring in drop-off and curbside collection. We tested in the model with a hybrid collection truck. The hybrid truck has the same capacity but consumes 20% less fuel and with lower carbon conversion factor, that is 0.2kg CO_2-eq per km (DEFRA, 2012). The impacts of using hybrid trucks on the emission costs are presented in Table 3.5.

The results show that emission cost takes up to about 1.5 percent of total cost in curbside collection scenarios, whereas in drop-off scenarios, the percentage is around 3%. By using hybrid trucks, the emission cost is significantly reduced by 95.8% for all scenarios. The results indicates that significant improvement in sustainable performance of waste collection can be achieved by using hybrid trucks. Although, the investment cost for such truck can be 30 to 60 percent higher than conventional truck types (Mims, 2009).

	Scenarios			
	S1	S2	S3	S4
Normal truck				
emission cost(euro/collection round)	1.32	3.21	5.26	7.2
total cost	48.78	217.51	177.35	492.10
percentage of emission cost in total cost	2.7%	1.5%	3.0%	1.5%
Hybrid truck				
emission cost(euro/collection round)	0.06	0.13	0.22	0.30
total cost	42.65	202.63	152.93	458.67
percentage of emission cost in total cost	0.1%	0.1%	0.1%	0.1%
Impact				
reduction of emission cost	95.8%	95.8%	95.8%	95.8%
reduction of total cost	12.6%	6.8%	13.8%	6,8%

TABLE 3.5: *Sensitivity analysis on truck types for one collection round*

- Household response rates

Another important parameter which affects the plastic waste collection is the response rate of source-separation. This factor is related to the behavior of householders in separating the plastic waste from other waste at home. Although, in post-separation, machinery separating process can get more plastic out of the residue waste, the contamination level of post-separated plastic is much higher than source-separated plastic. A high contamination level will lead to more emission in further processing steps and will limit the application of recycled plastic material. Due to this trade-off, in source-separation municipalities, householders are encouraged to improve their behavior in separating waste. An improved separation behavior will result in an increased response rate of plastic waste in source-separation scenarios. As with mechanical separation, much more plastic can be separated from other waste. While, in source separation case, plastic waste separated depends on householders' behavior (8598 kg in compared with 3563 kg as in our model input), it indicates a large space for improving the source-separation efficiency. The average plastic packaging consumed by households is a few times more than the waste separated in source-separation, indicating there is still a large space to increase the response rate of source-separation (Thoden van Velzen et al., 2013). We tested in our model the effect of 50% increased response rate on the unit cost of collecting plastic waste in the two source-separation scenarios (scenarios 1 and 2). Due to the increase in collection quantity, the time used at each stop is assumed to be increased by 50% accordingly. Results are presented in Table 3.6.

Even with a 50% increase of response rate, 50% more plastic waste to be collected and longer idling time at each collection point, the collection cost per kg of plastic waste

	Scenarios			
	1	2	1*	2*
System	Source-Separation		Post-Separation	
	Drop-off	Curbside	Drop-off	Curbside
Input				
Collection frequency(No. of rounds/week)	1	1	1	1
Quantity of plastic waste collected(kg/week)	3563	3563	5345	8017
Increase of response rate	0	0	50%	50%
Result per collection round				
Total costs (euro)	48.78	217.51	86.04	355.20
Total time(hr)	1.61	5.39	2.95	9.28
Total distance(km)	36.88	96.33	60.66	117.58
Result per kg of plastic waste collected				
unit cost	0.014	0.061	0.016	0.066
Increase of unit cost	0	0	17.6%	8.9%

Note: 1* and 2* are scenarios with increased response rate

Table 3.6: *Sensitivity analysis on higher source-separation response rate*

has not increased. Almost the same unit cost can be achieved in drop-off collection. A smaller cost increase in curbside collection indicates that higher response rate can also make curbside collection more favorable to collection companies. It can potentially bring more convenience to householders, especially in urban areas, as taking plastic waste to the drop-off spot can be less needed. Such improvements in behaviour might be achieved through providing an easier access to information for householders, such as painting a clearer instruction on waste bags, designing an application (for tablets and phones) for providing collection information and local collection schedule, etc.

- Emission cost

Carbon price in the European Carbon Market is volatile. We use 20 euro per ton as input in the model. According to the statistics reported by World Bank, the carbon price in recent years has been fluctuating. The price peaked in 2008 at around 30 to 40 euro per ton and has been declining in recent years (Kossoy and Guigon, 2012). In August 2013, the price is around 4 euro per ton (EEX, 2013). Therefore, we also tested the impact of carbon price on the percentage of emission cost in total cost. Results show that emission cost changes has almost the same impact on drop-off collection scenarios 1 and 3. The same results hold for curb-side collection scenarios. When the carbon price was at its peak, the emission cost can takes almost 6 percent of the total cost. While in 2013, when the price drops, the emission cost counts for less than one percent for all scenarios. This sensitivity analysis test shows that the results are insensitive to the carbon price change. Although the change in cost is not significant, the actual emission quantity reduced by the re-design using our proposed method can still make a difference in the sustainable performance of plastic waster collection. With a high frequency of waste collection in residence area of city, a re-design which makes the collection more eco-efficient can not only reduce the emission quantity, but also other associated impacts(e.g. noise pollution, exposure of harmful odor). These impacts are difficult to quantify but still very important, especially for householders.

3.8 Conclusions

This paper investigates the various strategic collection alternatives for a sustainable waste collection re-design problem, by a scenario study approach based on vehicle routing model. The re-design performance indicator is eco-efficiency. The municipal plastic waste collection is modeled as a vehicle routing problem. The approach we designed serves as an efficient tool to provide decision support for real-life waste collection design, in which both separation and collection alternatives are considered. The scenario study is conducted based on the case of a Dutch municipality Wageningen. Scenarios are designed according to the collection alternatives with different assumptions in collection method, vehicle type, collection frequency and collection points, etc. The potentials of the collection alternatives in meeting future demand is also investigated. In our proposed solution approach, the heuristics aims to fit the application for real cases and to speed up solving the problem for easier application purpose. The mathematical interpretation of collection problem is also adjusted according to the real case. In the our scenario study, both curbside and drop-off collection scenarios are modeled as a node-routing problem. A node aggregation method is used for the curbside collection scenarios in order to model the collection as in practice, reduce problem size and speed up the calculation. A tabu search algorithm is designed to solve such a node-routing problem. Distances between locations are calculated with GIS-assistance, which are used as input of the model.

Results show that the current collection routes can be improved in terms of eco-efficiency performance by seven percent using the proposed heuristics method. The eco-efficiency is measured by a cost which combines the transportation cost, labour cost and the emission cost. The results also show the method we proposed is an efficient tool in analyzing differences between scenarios, and thus can serve as a decision support tool for a wider application. With the current input parameters, source-separation and drop-off collection of plastic waste can have the best performance in terms of eco-efficiency, provided that householders transport the waste from their homes to the nearby drop-off points in a sustainable manner. Furthermore, the results of applying our method in analyzing sustainable collection alternatives indicate that hybrid collection vehicles can bring more significant improvement in sustainability performance. A higher response rate of source-separated plastic waste will make curb-side collection more favorable. Thus the improved behaviour of householders can potentially bring more convenience to themselves. These results show that the method we developed can provide decision support for municipalities in choosing a collection method that is sustainable and efficient.

For further research, it is interesting to apply the same method on different municipalities and investigate which characteristics of municipalities has the most significant impact on the costs of all scenarios. It is also worth to extend the model in further investigating the efficiency issue in collecting plastic waste as a light material. Scenarios such as co-mingled collection of plastic waste with other types of waste (e.g. glass and plastic) in combination of curb-side and drop-off collection methods can be investigated. It is also interesting to combine other cost calculation with our model to provide a thorough cost analysis with emission considerations on a municipal level. To extend the scope, costs of further processes in the chain can be added for a more comprehensive analysis and comparison.

Chapter 4

A comprehensive waste collection cost model applied to household plastic waste

This chapter is based on the published journal article
J. Groot, X. Bing, H. Bos-Brouwers, J.M. Bloemhof-Ruwaard (2014) “A comprehensive waste collection cost model applied to post-consumer plastic packaging waste” Resources, Conservation and Recycling, Vol 85, pp. 79-87

In this chapter we answer Research Question 2b:
What are the impacts of various collection and taxation alternatives on the performance of the collection system?

Abstract:
Post-consumer plastic packaging waste (PPW) can be collected for recycling via source separation or post-separation. In source separation, households separate plastics from other waste before collection, whereas in post-separation waste is separated at a treatment center after collection. There are also two collection schemes, either curb side or via drop-off locations. These different schemes have impact on total costs of collection at the municipal level. It can also influence the facility choices and network design. Therefore, a method which can compare costs of various collection schemes is needed.

A comprehensive cost model was developed to compare costs of municipal collection schemes of PPW. The 'municipal waste collection cost model' is based on variables including fixed and variable costs per vehicle, personnel cost, container or bag costs as well as on emission costs (using imaginary carbon taxes). The model can be used for decision support when strategic changes to the collection scheme of municipalities are considered. The model takes into account the characteristics of municipalities, including urbanization degree and taxation schemes for household waste management.

The model was applied to the Dutch case of post-consumer plastic packaging waste. Results showed that that in general post-separation collection has the lowest costs and curb side collection in urban municipalities without residual waste collection taxing schemes the highest. These results were supported by the conducted sensitivity analysis, which showed that higher source separation responses are negatively related to curb side collection costs. Greenhouse gas emission costs are a significant part of the total costs when collecting post-consumer plastic packaging waste due to the low density to weight ratio of the materials collect. These costs can amount to 15% of the total collection costs.

Keywords: municipal waste collection; CO_2-eq cost; post-consumer packaging waste; plastic recycling; cost model

4.1 Introduction

Post-consumer waste recycling has been stimulated by regulation during the last decades. As the first recycling target rates, prescribed in EU Directive 94/62/CE, were successfully met, the bar was raised in the recent EU Directive 2008/98/EC on Packaging and Packaging Waste (PPW). This provided a strong incentive for national governments to improve their recycling systems for various waste materials (EU, 2012). Response rates in the Directives concerned are set for each material type of recyclable waste, including glass, paper, plastics, wood and metals. EU Directive 2004/12/CE requires a response rate of 22.5% of plastic packaging, while for other packaging materials, the response rate is set to be around 50 − 60%. However, the ambition for improving plastic packaging waste recycling is high. EU Directive 2008/98/EC specifies the preparation for reuse and recycling of plastic materials from households to be increased to a minimum of 50% by weight by 2020. Additionally, apart from EU regulations, some Member States also have their additional standards or regulations specifying target response rates. In the Netherlands, the target was set at a response rate of 43% in 2013, slowly increasing up to 52% of post-consumer plastic packaging waste by 2022 (VNG, 2012).

The aim of plastic packaging waste recycling is to make plastic packaging a recognizable high-quality secondary raw material (PlasticEurope, 2012). However, the special characteristics of post-consumer plastic packaging waste (PPW) make the recycling of plastic packaging different from other recyclable materials. There exist many types and compositions of plastics which are widely used in various applications. The most common examples of the plastic types that can be found in post-consumer PPW are listed below (Bing et al., 2012a).

- PET (Polyethylene Terephthalate): e.g. water bottles and soda bottles;
- PP (Polypropylene): e.g. microwaveable meal trays, ice-cream trays, detergent bottles;
- PE (Polyethylene): e.g. milk bottles, most shampoo bottles;
- Film: e.g. carrier bags, packaging foils;
- Mix of hard plastic: e.g. PVC (polyvinyl chloride), PS (polystyrene), non-bottle PET and falsely sorted PE, PP and PET.

To achieve a mono material flow of secondary raw material from post-consumer PPW , these fractions need to be sorted out of the household waste. Post-consumer PPW is also a light and voluminous material. These features provide an advantage in the use for packaging purposes, but makes it difficult to achieve efficiency in transport. Associated with this lower transport efficiency are higher cost and a larger amount of emissions generated during transportation per kilogram post-consumer PPW in the recycling process.

Post-consumer PPW collection is a complex system which involves multiple stakeholders, a combination of different collection alternatives, and various taxation schemes for municipal waste management. Our research draws upon the Netherlands as example case study. There are two major recycling schemes in the Netherlands; source separation and post-separation. PPW is separated from other household waste (residual waste) at the household level via source-separation, or is separated from the municipal residual waste in a waste treatment centre (post-separation). For source separation two different collection schemes are possible; curb side and drop-off collection. PPW is either placed at the curb side (curb side collection)or is dropped off at central points in big containers (drop-off collection). In the Netherlands, these systems occur in parallel, even in the same municipality. The variety of possible combinations make the PPW collection complex to model. Adding to the complexity are amongst others the different sizes and types of bins and trucks used and the fact that the responsibility of organising the waste collection is legally attributed to the municipal level. The number of municipality in the Netherlands is 418 (include year here)Furthermore, municipalities also can opt for different taxation schemes for household waste management, varying between a fixed fee or differentiated to volume/collection frequency, called DIFTAR ("pay as you throw" in English). The purpose of applying DIFTAR is usually referred to as contributing to waste reduction and a fair cost sharing (AgentschapNL, 2011). Also, there are frequent debates in the public domain which collection scheme for PPW is the most effective and efficient. To date, this discussion has not been settled definitively.

To improve the efficiency in the collection of plastic packaging waste, as such a complex system, an insight into the system is needed. Stakeholders involved need to compare all relevant costs of the different options in collection as well as the costs of greenhouse gas emissions, that might not be part of financial costs yet.

There already is an extensive body of literature on waste recycling and collection costs using various calculation methods. For example, Bel and Fageda (2010) analysed the factors that determine solid waste service costs by taking into account factors such as the frequency of waste collection, seasonal variation in the generation of solid waste, and the mean wages per employee at the provincial level. Rogge and De Jaeger (2013) advocated a non-parametric data envelopment analysis model for evaluating the cost efficiency of municipalities in the collection and processing of municipal solid waste. Beigl and Salhofer (2004) calculated costs of the transports for the regional waste management company (collection and other transports), individual transports of residents by car, the use of collection containers and waste treatment processes. They assume a linear relation between quantities of waste and the corresponding costs for collection. Larsen et al. (2010) included the costs for collection equipment, actual collection costs and treatment costs in their cost calculation for recycling glass and paper based on the case of Denmark. They also assume the costs for each tonne of waste, within each material fraction to be linear. Bohm et al. (2010) estimated cost functions for both municipal solid waste collection and disposal services by using a quadratic term with a non-linear relationship between quantity and both marginal and average costs of waste collection and disposal. Cruz et al. (2012) add extra cost on top of the operational cost of collection and sorting. Depreciation of assets and return on capital cost are added in order to compare the system with all benefits including subsidies, savings and financial support for local authorities.

Some studies also investigate impacts of issues such as tax, collection method and regional difference on waste recycling. Sahlin et al. (2007) conducted a case study in Sweden and investigated the effect of a tax on waste-to-energy incineration (which led to higher incineration gate fees) on the waste flow. The results indicated that the incineration gate fees as taxation instrument will have the largest effect on the biological treatment of kitchen and garden waste. There are also researches that compare waste collection methods. Beigl and Salhofer (2004) conducted a scenario study which compares the curbside collection with the drop-off collection of different waste types and concluded the difference in cost between the two methods is not significant in general. Curbside collection is ecologically better for waste paper or at least not worse for plastic packaging and metal packaging. The curbside collection of metal packaging leads to fundamentally higher costs. Larsen et al. (2010) had a similar conclusion that cost differences between the curbside collections, bring scheme with drop-off containers and recycling centres are relatively small. Furthermore, the regional difference of response rates has been studied. Hage and Soderholm (2008) investigated the main determinants of collection rates of household plastic packaging waste in Swedish municipalities by means of a regression analysis based on cross-sectional data for 252 Swedish municipalities and concluded that local policies, geographic variables, socio-economic factors and environmental preferences all help to explain municipal collection cost.

Apart from a selection of the variables mentioned above, we take into account carbon emissions from fuel consumption in waste collection schemes. In literature, the environmental issues of recycling processes have been addressed mostly by means of a life cycle assessment (LCA). Beigl and Salhofer (2004) analyzed the ecological impacts of collection methods using LCA and concluded that ecological benefits of curbside collection relative to collection in the bring system is higher for each impact category (such as global warming, waste, scarce resources). The benefits are due to lower fuel consumption for collective transports (curbside) versus individual transports. Larsen et al. (2010) conducted their research by using the EASEWASTE model which is a tool developed for life cycle assessment of waste management systems. Their results showed that enhanced material recycling is environmentally beneficial even when incineration with high-efficient energy recovery is optional. This result enhances our efforts of describing, modelling and comparing the Dutch plastic packaging waste collection schemes for recycling, as plastic is a light but hard-to-recycle material with a high-efficient energy recovery rate.

Our calculation method focuses, specifically, on the collection phase of plastics recycling, keeping separation and reprocessing out of scope. The costs we take into account includes vehicle cost, labour cost, facility costs as well as emission cost, which are not linear in the quantity of waste input. The parameters taken into account in the calculation are extensive, such as types of municipalities, tax charges and energy consumption differences. The tax we look into is the tax charged to Dutch citizens, which will affect the response rate and the householders behaviour in recycling. A distinguishing feature of this tax is that it differs a lot in the way it is charged and calculated among municipalities all around the country. Therefore our emphasis is on the difference between these variants of tax charges. In our research, we investigate the joint effects of different collection methods with other issues such as tax and municipal types. The hypothesis is that different collection methods function differently in municipalities with different characteristics (e.g. population density, tax).

This research aims at developing a cost calculation tool for the collection of post-consumer packaging waste. It takes into account the regional differences in collection rate in our input database and extends the investigation to other differences in collection cost and sustainable performance between regions by applying our proposed calculation method on the 418 municipalities of the Netherlands. Environmental issues (especially greenhouse gas emissions) are taken into account by converting carbon emissions during the collection process into cost by a carbon cost. This cost model can be used to calculate a cost on a municipality level with all the complexity as described above, therefore, it is a tool which can be easily used in a wide range.

The remainder of the paper is structured as follows. In Section 2, we describe the context of the Netherlands as case study and explain the data used, followed by the model formulation. In Section 3, we present results of applying the model to calculate collection costs for post-consumer plastic packaging waste for all Dutch municipalities. In Section 4.4, sensitivity analysis is performed with discussions of findings. The paper ends with conclusions stated in Section 4.5.

4.2 Material and Method

In this section we first discuss the data available, and then the suggested cost model to calculate PPW collection costs.

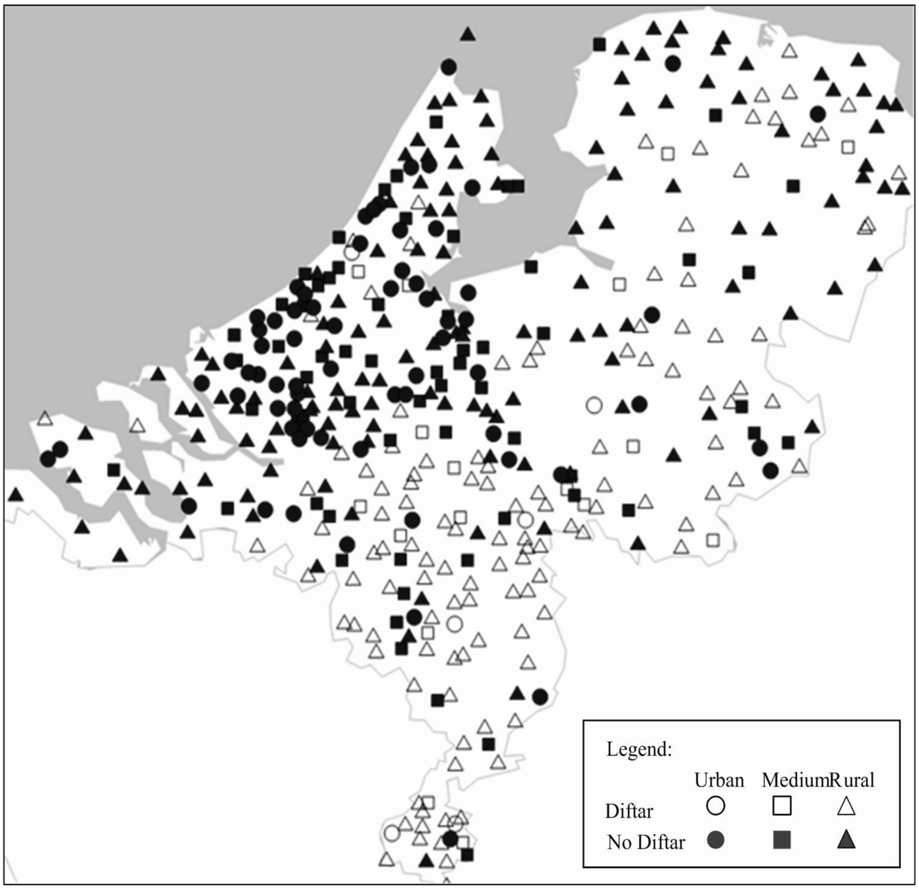


FIGURE 4.1: Geographical locations of all municipality types

4.2.1 Data available

In this research the cost breakdown is made for all 418 municipalities in the Netherlands (Figure 4.1) for the year 2011. Data from municipalities (number of inhabitants and number of households are extracted from Statistics Netherlands (CBS)). Plastic separated per municipality is calculated with this information combined with the following tables. Municipalities are categorized by urbanization level with a scale from 1 to 5. Level 1 and 2 represent urban municipalities, level 3 medium municipalities and level 4 and 5 are rural municipalities. The estimated response rates of municipalities in 2013 are shown in Table 4.1. The response rates are an extrapolation of the measured situation in 2011 (KplusV, 2011).

The values of all input parameters used in our calculation are presented in Table 4.2. Data sources and comments are also included in this table. The figures we use and the comments made provide reference for applying this calculation model to other cases.

Emission quantity is transferred to cost by a factor derived from carbon trading in Europe. The figure used is 20 euro per ton CO_2-eq. The CO_2-eq per kilogram diesel fuel is

Urbannization level	**Collection method**	**DIFTAR (kg/inhabitant)**	**No DIFTAR (kg/inhabitant)**
1	Curbside	-	-
1	Drop-off	-	3
2	Curbside	10	5
2	Drop-off	10	5
3	Curbside	12	6
3	Drop-off	8	6
4	Curbside	12	8
4	Drop-off	8	5
5	Curbside	12	8
5	Drop-off	8	5

Table 4.1: Expected response of collected plastic by urbanization level and taxation scheme for both source separated collection methods (kg/inhabitant)

represented in the GHG factor which is estimated to be 3.8 kg CO_2-eq/l diesel (Defra, 2012).

In post-separation, plastic waste is collected together with other residue waste. In the calculation, only the fraction of collection cost of plastics is counted. In the Netherlands, waste from post-separation municipalities is gathered and sent to four different separation centres. The distance to those centres is larger than the distance from municipalities to cross-docking sites. We do not reflect on those distances. Data on the composition of the waste is measured by each of the separation centres which are different from each other. We use the data collected from separation centres for calculating the percentage of plastics in the total waste. Details on the number of post-separation municipalities associated with each of the separation centres and their different composition of waste are presented in Table 3. Note that the costs of separation by the households are not taken into account, as well as the costs of separation in waste separation centres. After the collection phase, source separated waste from various municipalities is combined in storage centres, and post separated waste is combined in separation centres. After that phase, reprocessing takes place. The costs of these phases in the waste recovery network are described e.g. in Bing et al. (2012).

4.2.2 Model

The collection costs consist of vehicle cost, labour cost, container cost and emission cost. Vehicle cost is split into fixed and variable cost. This calculation is based on one municipality for the period of a year and per ton of plastic waste collected. Note that collection and transportation may lead to other environmental impact than global warming and also some external cost as noise or accidents but they were not included in the study.

4.2.2.1 Vehicle Cost

Variable vehicle cost

The cost for fuel (C_{veh_fuel}) and maintenance (C_{veh_main}) divided by the amount of waste per year (Q_{year}) form the variable vehicle cost per kg of waste (C_{veh_var}) (1). The total fuel cost in a year is calculated by summing up fuel cost of three activities, driving ($C_{veh_{d}ri}$), idling (C_{veh_idl}) and hauling (C_{veh_haul}) (1a). Fuel cost (C_{veh_fuel}) is calculated by the total fuel consumption times the fuel price (P_{fuel}). Driving means the activity between collection stops, idling means the collection stops and hauling is the activity driving to a location to unload the truck.

The fuel cost for driving is derived from the fuel consumption while driving (CS_{dri_fuel}) times the distance travelled (D_{dri_veh}) between stops times the fuel price (1b). The idling fuel cost is determined by the number of stops (n_{stops}), the fuel price and the fuel consumption while idling (CS_{idl_fuel}) (1c). Fuel consumption while hauling (CS_{haul_fuel}) times the distance travelled (D_{veh_haul}) to the unloading locations times the fuel price makes the hauling fuel cost (1d).

Total driving distance between stops (1e) is calculated by the (number of stops $n - 1$) times the distance between stops (D_{dri_stop}). It is an average distance between stops. We assume this distance only differs between municipality types.

The last element of the variable cost to describe is the number of stops (1f). Calculating the number of stops is the same for the curbside collection of the source separation system and the post-separation system and different for the drop-off collection at source separation. The number of stops at curbside collection of the source separation and the post-separation system is calculated by multiplying the number of households (n_{hh}) and the collection frequency ($freq_{col}$) divided by the number of households per collection point (hh_{con}). Note that we calculate the number of stop by assuming a fixed number of households served per stop. The drop-off collection at source separation is determined by the amount of waste per year (Q_{year}) divided by the capacity of a truck ($truck_{load}$).

	$C_{veh\ var} = (C_{veh\ fuel} + C_{veh\ main})/Q_{year}$	*(1)*
The total cost of fuel	$C_{veh\ fuel} = C_{veh\ dri} + C_{veh\ idle} + C_{veh\ haul}$	*(1a)*
Total fuel cost while driving during collection	$C_{veh\ dri} = CS_{dri\ fuel} \text{ x } D_{veh\ dri} \text{ x } P_{fuel}$	*(1b)*
Total fuel cost while idling	$C_{veh\ idl} = CS_{idl\ fuel} \text{ x } n_{\text{stops}} \text{ x } P_{fuel}$	*(1c)*
Total fuel cost while hauling	$C_{veh\ haul} = CS_{haul\ fuel} \text{ x } D_{veh\ haul} \text{ x } P_{fuel}$	*(1d)*
The total travel distance while collecting	$D_{veh\ dri} = (n_{stops} - 1) \text{ x } D_{dri\ stop}$	*(1e)*
The number of stops while collecting	$n_{stops} = \begin{cases} (n_{hh} \text{ x } freq_{col}) / hh_{con}, & \lvert curbside\ collection \\ Q_{year} / truck_{load}, & \lvert else \end{cases}$	*(1f)*

Fixed vehicle cost

The fixed vehicle costs per year are constituted from yearly capital cost (C_{veh_cap}), insurance cost (C_{veh_insu}) and tax cost (C_{veh_tax}) times the number of vehicles (n_{veh}). Fixed vehicle costs per kg of waste (2) are calculated by dividing the yearly fixed vehicle costs by the yearly amount of waste.

The first element, the annualized vehicle capital cost (2a) is determined by the difference between investment cost (C_{veh_inv}) and salvage cost (C_{veh_sal}) divided by the depreciation period (Dep) plus the average of the investment and salvage cost times the interest rate ($\%int$). The insurance and tax cost are fixed numbers.

The number of vehicles needed per year (2b) is calculated by the total time needed to collect waste ($Time_{veh}$) divided by the time one vehicle can be used in a year ($Time_{tyr}$) times the inverse of the percentage the truck is actually used ($Eff\%$). This number is not rounded up since we assume a vehicle can be used in multiple municipalities.

Time needed to collect waste (2c) is a combination of driving time between stops ($Timeveh_{col}$), idling time ($Time_{veh\_idl}$), and hauling time ($Time_{veh\_haul}$). The total collection time (2d) between all the stops is calculated by dividing the total driving distance by the average driving speed (V_{veh_dri}) between stops. The idling time (2e) is determined by the number of stops and the time for one stop ($Time_{stop}$). The total hauling time (2f) is derived from the total hauling distance (D_{veh_haul}) divided by the average hauling speed (V_{veh_haul}).

The total hauling distance (2g) consists of two times the average hauling distance (D_{dri_haul}) multiplied by the number of truck loads (n_{loads}). The number of drops (2h) are determined by the amount of waste per year divided by the capacity of a truck.

	$C_{veh\ fix} = (n_{veh} \text{ x } [C_{veh\ cap} + C_{veh\ insu} + C_{veh\ tax}]) / Q_{year}$	(2)
Vehicle capital cost	$C_{veh\_cap} = (C_{veh\_inv} - C_{veh\_sal}) / Dep + 0.5(C_{veh\_inv} + C_{veh\ sal}) \text{ x } \%_{int}$	(2a)
The number of vehicles	$n_{veh} = (1 / Eff_{\%}) \text{ x } Time_{\ veh} / Time_{\ tyr}$	(2b)
Time needed to collect waste	$Time_{\ veh} = Time_{veh\ col} + Time_{veh\ idl} + Time_{veh\ haul}$	(2c)
Total collection time between stops	$Time_{veh\ col} = D_{veh\ dri} / V_{veh\ dri}$	(2d)
Total idling time	$Time_{veh\ dri} = n_{stops} \text{ x } Time_{\ stop}$	(2e)
Total hauling time	$Time_{veh\ haul} = D_{veh\ haul} / V_{veh\ haul}$	(2f)
The total hauling distance	$D_{veh\ haul} = 2 \text{ x } n_{loads} \text{ x } D_{dri\ haul}$	(2g)
The number of drops at the unloading location	$n_{loads} = Q_{year} / truck_{load}$	(2h)

4.2.2.2 Labour Cost

Labour cost (C_{labour}) (3) included in this research is mainly the cost for the drivers and loaders of waste. The cost for the drivers and loaders are multiplied by the collection frequency and the number of vehicles. Labour cost of drivers (C_{driver}) (3a) or loaders (C_{loader}) (3b) are derived by multiplying their yearly wage (W_{driver}, W_{loader}) by the number of drivers (n_{driver}) or loaders (n_{loader}) for 1 vehicle times a factor. This factor constitutes of the time a vehicle is used in a year ($Time_{tyr}$) divided by the total hours a driver (hr_{driver}) or loader (hr_{loader}) are working in a year.

	$C_{labour} = (C_{driver} + C_{loader}) \text{ x } freq_{col} \text{ x } n_{veh}$	(3)
Driver's labour cost	$C_{driver} = W_{driver} \text{ x } n_{driver} \text{ x } Time_{\ tyr} / hr_{driver}$	(3a)
Loader labour cost	$C_{loader} = W_{loader} \text{ x } n_{loader} \text{ x } Time_{\ tyr} / hr_{loader}$	(3b)

4.2.2.3 Container and bag cost

Container and bag cost are different for source separation and post-separation. Also drop-off and curbside collection have different costs regarding containers and bags. For drop-off collection costs ($C_{cont\_drop-off}$) (4) investment cost (C_{cont_inv})and maintenance (C_{cont_maint}) are added together multiplied by the number of containers (n_{cont}). This number (4a) is calculated by dividing the total amount of plastic by the collection frequency ($freq_{col}$) divided by the capacity of a drop-off container ($Cont_{cap}$).

Investment cost of a drop-off container C_{cont_inv} (4b) consists of the investment cost ($Cont_{inv}$ divided by a depreciation period) and capital cost (investment of a container times the interest rate divided by two).

For curbside collection transparent bags are obligated. These bags are distributed by municipalities and are allocated special to the curbside collection system. It is stated each household will use one plastic bag each collection round. Therefore bag cost for curbside collection C_{bag},curbside (5) are calculated by the number of households (n_{hh}) times the collection frequency times the cost for one bag (C_{bag}).

Part of the investment cost of a 240 liter container for post-consumer residual waste is allocated to the post-separation system of plastic. The part allocated is the percentage of plastic within the residual waste separated by separation centres. The investment cost of a 240 liter container (C_{cont_post}) (6) is the number of households times the cost of one container (C_{240_inv}) divided by a depreciation period. The assumption is made one container is available for each household.

The cost of drop-off containers	$C_{cont,drop\text{-}off} = n_{cont}$ x $(C_{cont\_maint} + C_{cont\_inv})$	*(4)*
The investment cost of drop-off containers	$C_{cont\_inv} = Cont_{inv} / Dep + Cont_{inv}$ x $\%_{inv}$	*(4a)*
The number of drop-off containers	$n_{cont} = (Q_{year} / freq_{col}) / Cont_{cap}$	*(4b)*
The cost of plastic bags for curbside collection	$C_{bag,curbside} = n_{hh}$ x $freq_{col}$ x C_{bag}	*(5)*
The cost of post-separation containers	$C_{cont,post} = n_{hh}$ x C_{240_inv} / Dep	*(6)*

4.2.2.4 Emission Cost

Greenhouse gas emission costs (C_{GHG}) (7) are calculated by converting the total fuel use (F_{tot}) by a factor (GHG_{factor}) to the quantity of CO_2-eq emissions and then using a carbon tax (Ct_{co_2}) to further transfer the amount of emissions to cost. Total fuel use (7a) is the sum of fuel use while driving, hauling and making stops (idling). Driving fuel use is linear to the total distance travelled while driving between stops and hauling fuel use is linear to the distance from a collection area to an unloading location. The fuel utilized while making stops is calculated by multiplying the fuel consumption while idling with idling time.

The formulas are presented below (the values of the GHG factor and carbon tax are described in Section 2.1)

	$C_{GHG} = Ct_{co2} \text{ x } F_{tot} \text{ x } GHG_{factor}$	(7)
Total fuel use	$F_{tot} = CS_{dri\ fuel} \text{ x } D_{veh\ dri} + CS_{idl\ fuel} \text{ x } Time_{veh\ idl} + CS_{haul\ fuel} \text{ x } D_{veh\ haul}$	(7a)

The average distance travelled between collection points in each of the collection method is presented in Table 4. Table 5 presents the number of municipalities and the total amount of plastic collected by urbanization level and collection methods. Here we aggregate the five urbanization levels into three categories: urban (level 1 and 2), medium (level 3) and rural (level 4 and 5).

4.3 Results

We conducted the cost calculation for all the municipalities in the Netherlands. On average, the total collection costs per ton of plastic waste collected for source-separation municipalities are more than two times higher than that of post-separation municipalities. Within the source separation method there is a big difference in cost between curbside and drop-off collection. curbside collection is more than 2.5 times more expensive than drop-off collection and has a large deviation between municipalities. This is because plastic is a light weight material with a large volume. When plastic is collected separately in source-separation municipalities, the collection efficiency is much lower. For the same reason, the emission cost is also much higher than that in post separation municipalities (see Figure 4.2).

Comparing curbside and drop-off collection, we can see that drop-off collection has a higher percentage of fixed cost which results from the heavy lifting trucks used in drop-off collection to empty big containers at collection sites. Personnel cost is a major part of the total cost for both collection methods. It is relatively higher in curbside collection because in curbside collection, there is one driver with two loading persons for each truck, whereas in drop-off collection trucks, there is only one driver per truck. Drop off collection has container cost which is not in the curbside collection. In total, emission cost is less than 1% of the total cost. Emission cost of curbside collection is higher than that of drop-off collection. This indicates that while driving in curbside collection with frequent stops and short idling time generates more emission than driving to less spots with longer idling time. This difference is more obvious when the parameter of urban class of municipalities is added in the comparison (Figure 4.3). Urban municipalities have larger difference between the two collection methods as making frequent small stops for curbside collection in high population density area costs more.

TABLE 4.2: Values of input parameters

Input parameters	**Abbreviation**	**Curbside**	**Drop-off**	**Post separation**	**Unit**
Insurance cost / year [1]	C_{veh_insu}	2500	2500	2500	euro
Tax cost / year [1]	C_{veh_tax}	1000	1000	1000	euro
Depreciation period of a vehicle [1]	Dep	5	5	5	yr
Interest rate of the investment [1]	$\%_{int}$	0.05	0.05	0.05	%
% of use of a vehicle per year [2]	Eff%	0.8	0.8	0.8	%
Time one vehicle can be used per year [3]	$Time_{\_tyr}$	3000	3000	3000	hr
The average hauling speed [4]	V_{veh_haul}	60	60	60	km/hr
The average hauling distance [5]	D_{veh_haul}	18	18	54	km
Fuel price / litre [6]	P_{fuel}	1.4	1.4	1.4	euro/ltr
The average speed while collecting between stops [4]	V_{veh_dri}	25	40	15	km/hr
The number of households per curbside point [7]	hh_{con}	10	-	10	-
The average time per stop [8]	$Time_{\_stop}$	0.014	0.3	0.069	hr
The investment cost of a vehicle [1]	C_{veh_inv}	206000	250000	206000	euro
The salvage cost of a vehicle [1]	C_{veh_sal}	30900	37500	30900	euro
The average truck load per collection round [8]	$truck_{load}$	1800	750	7200	kg
The total maintenance cost of the vehicle / year [1]	C_{veh_main}	3000	4000	3000	euro
Fuel consumption for vehicle / km while driving [1]	CS_{dri_fuel}	0.33	0.4	0.4	l/km
Fuel consumption for vehicle / hr while idling [1]	CS_{idl_fuel}	4	3	4	l/hr
Fuel consumption for vehicle / km while hauling [1]	CS_{haul_fuel}	0.25	0.25	0.33	l/km
The driver wage per year [8]	W_{driver}	30000	30000	30000	euro
The loader wage per year [8]	W_{loader}	25000	25000	25000	euro
The regular working hours of driver/year [8]	hr_{driver}	1650	1650	1650	hr
The regular working hours of loader/year [8]	hr_{loader}	1650	1650	1650	hr
The number of driver per vehicle [8]	n_{driver}	1	1	1	-
The number of loader per vehicle [8]	n_{loader}	2	0	2	-
The total cost of container maintenance per year [8]	C_{cont_maint}	0	250	0	euro
The investment cost of the aboveground container [8]	C_{cont_inv}	0	1500	0	euro
Depreciation Period of container [8]	Dep	0	15	0	yr
Capacity Container [8]	$Cont_{cap}$	0	100	0	ton
The investment cost of the container 240l [8]	C_{240_inv}	0	0	58	euro
Cost of a bag [8]	C_{bag}	0.055	0	0	euro
The average distance between stops [2]	D_{dri_stop}	dependent on municipality type			

[1] Derived from literature, backed up by experts and contractor

[2] Difficult to optain, based on own jugdement, backed up by expert

[3] Every day, eight hours a day

[4] Difficult to access but good rules of thumb excist

[5] Derived from a network optimization model described by Bing et al. (2012b)

[6] Well known figure

[7] Difficult to access, counted within own neighbourhood, backed up by experts

[8] Derived from experts and contractor

As we assume the same number of householders served by making each stop in curbside collection for all municipalities, this result implies that for urban municipalities, more householders aggregating their plastic bags for curbside collection can help reduce the collection cost. Curbside collection costs vary a lot with different urbanization of municipalities, while drop-off collection has almost the same cost for all municipalities.

Tax charges influence the total collection cost which can be seen in Figure 4.4. DIFTAR is

Table 4.3: Percentage of MSW collection cost allocated to the post-separation collection scheme

Number of Municipalities	**Separation centre**	**Total plastic separated (kg/household)**	**% of the total waste**
23	Groningen	10.55	4.60%
32	Leeuwarden	13.61	6.00%
1	Rotterdam	15	6.60%
68	Wijster	9	3.90%

Table 4.4: Average distances between stops

Urbanization level	Curbside	Drop-off
Urban	0.155	3
Medium	0.18	3
Rural	0.195	3

Table 4.5: Number of municipalities and amount of plastic collected by urbanization level and collection methods

Urbanization level	Tax system	Collection method	Number of municipalities	Amount of plastic collected (kg)
Urban	DIFTAR	Curbside	3	2,822,140
	DIFTAR	Drop-off	3	3,021,200
	No DIFTAR	Curbside	24	7,992,558
	No DIFTAR	Drop-off	42	19,635,469
Medium	DIFTAR	Curbside	15	7,421,184
	DIFTAR	Drop-off	1	1,146,992
	No DIFTAR	Curbside	41	8,898,960
	No DIFTAR	Drop-off	20	4,849,320
Rural	DIFTAR	Curbside	93	23,998,526
	DIFTAR	Drop-off	23	4,452,553
	No DIFTAR	Curbside	73	12,679,202
	No DIFTAR	Drop-off	35	3,424,486
Post-separation	-	-	124	39,754,334

*Some municipalities have a combination of systems

in general the tax charges that differentiate the waste separated and not separated which will result in a higher separation rate. For curbside collection, with a larger amount of plastic waste to be collected, the trucks have the same amount of stops but per stop trucks can load more plastics, therefore, the utility of trucks raised. The lower cost and less emission result from the higher truck utility. However in drop-off collection, the containers have to be emptied when they are full. This means that with more amounts of plastics into the containers, more driving rounds are needed in order to empty the containers even though the truck are not full after emptying containers. This compensates the economics of scale achieved by a higher plastic waste input.

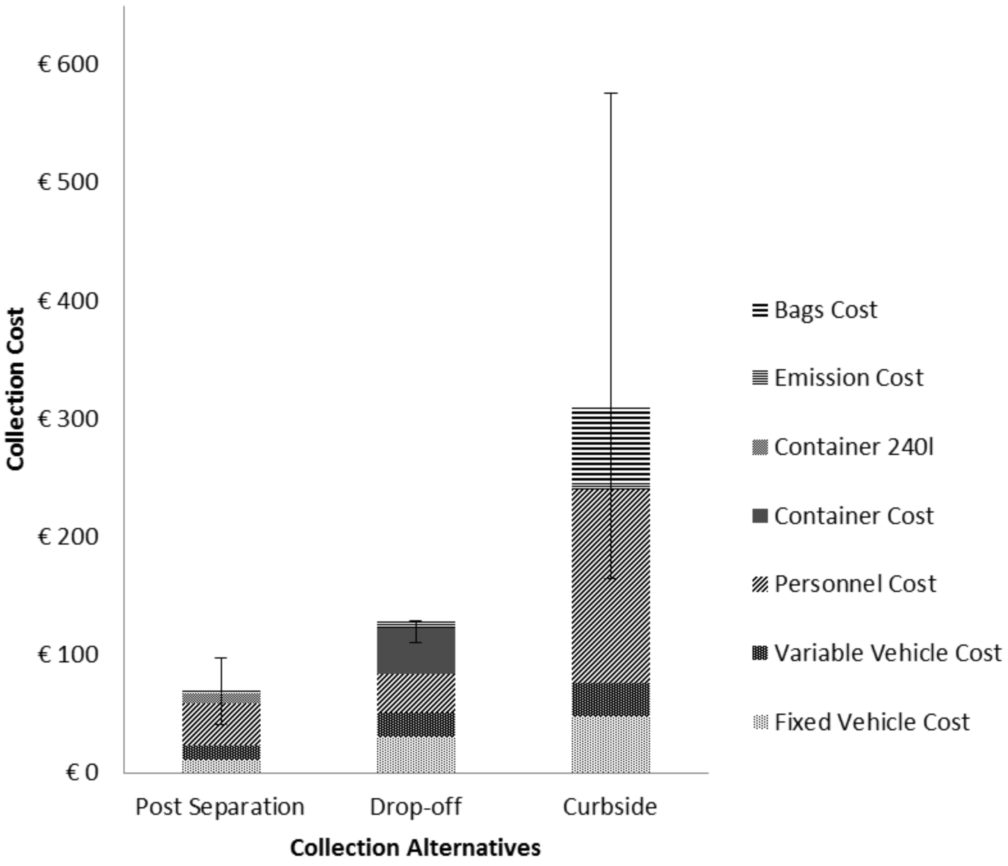


Figure 4.2: Collection cost of post separation and source separation municipalities, the latter split into drop-off and curbside collection, including min and max municipalities.

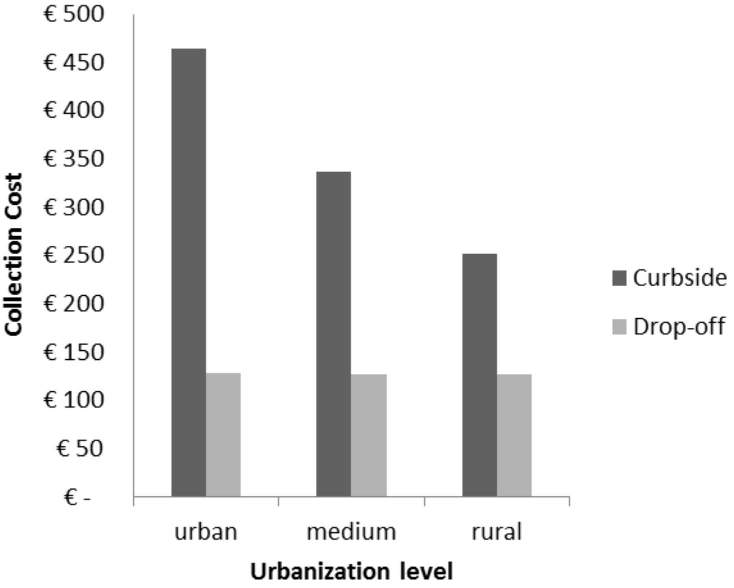


Figure 4.3: Average total collection cost per municipality type of curbside and drop-off collection (euro per ton)

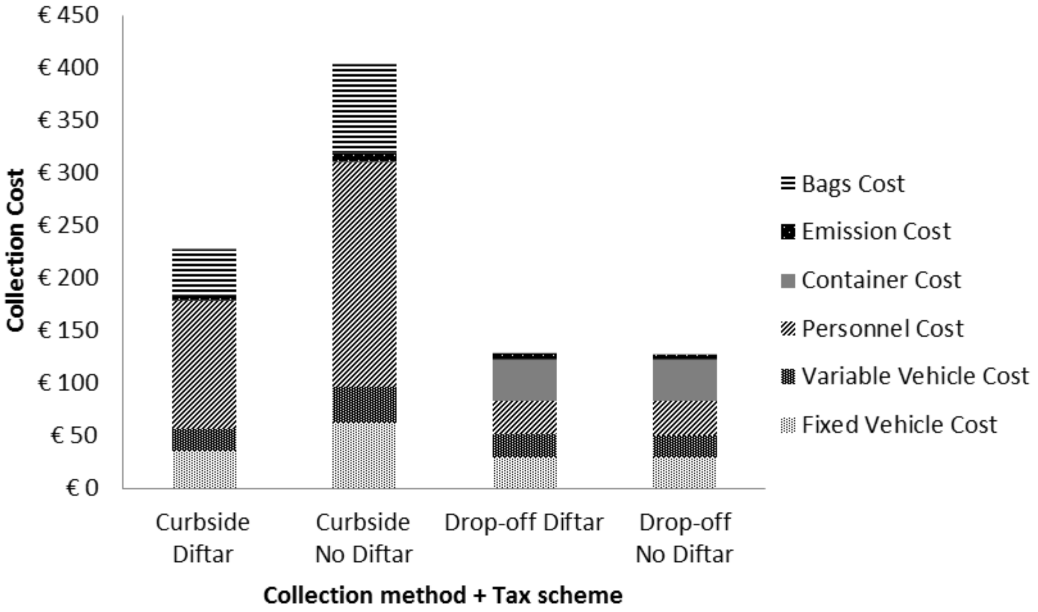


Figure 4.4: Average total collection cost per municipality of curbside and drop-off collection with different tax charges

4.4 Discussion

With some changes in the input parameters and assumptions, the calculation model proposed in this paper can further the insight into the collection system and provide decision support for making future changes in the collection. Also, we tested with our model the effect of different values for relevant input parameters, which are truck and container utility rates, fuel prices and carbon offset costs.

4.4.1 Utility of trucks and containers

In our case study, we made the assumption of a fixed truck utility and container utility, which is an average value from data we collected from waste collection companies. We analysed with our model the impact of a different utility rate of the trucks and containers on the total cost, without changing investment costs. The results are shown in Figure 4.5.

The collection truck has the same maximum capacity of 3000 kg for both drop-off collection and curbside collection. For drop-off collection, as explained before in the result section, there is no difference in cost between DIFTAR and No-DIFTAR. The average total collection cost per municipality of curbside and drop-off collection with different utilities of a collection truck shows to achieve a relatively low cost by each of the collection method, the utility of the truck should be around 1500 kg. In other words, the collection trucks should be at least about half full, so that the collection can be cost-effective. For the utility rate of drop-off containers, we observe a sharp decrease of total cost when containers are filled from 0% to 50%. After 50%, the decrease of cost slowed down. The result indicates that, in general, the fuller a container is filled, the less total cost is. If the utility rate falls below 50%, the collection can be very in-efficient. Furthermore, the result of container utility rate above 100% indicates that over filling a container (sometimes containers are full and some plastic waste bags are placed around the container) brings a very limited cost reduction.

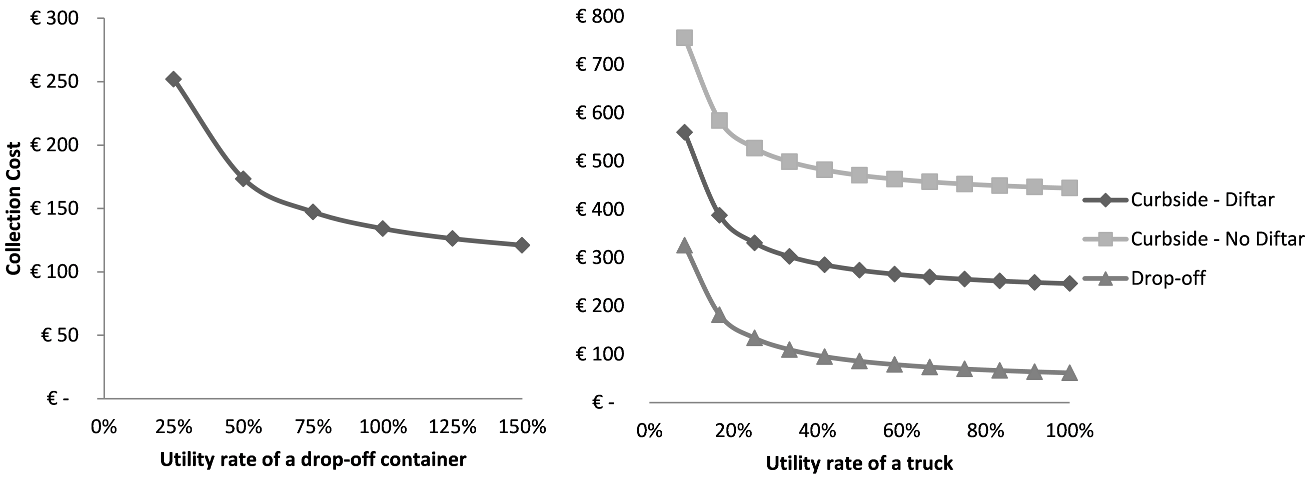


FIGURE 4.5: Average total collection cost per municipality of curbside and drop-off collection with different utility rates of a container and collection truck

The proposed model can also help with providing decision support in analysing the future changes. With the pressure from the regulations as mentioned in the introduction section, a possible change in the future is the increase of plastic recycling and a better behaviour in separating plastics of householders. With this trend, there will be more plastics input in the source separated plastics. To investigate the impact of plastic waste input on the collection cost, we tested the collection cost changes with a decreased (down to -30%) and raised (up to $+100\%$) amount of source separated plastic by curbside collection. The result in Figure 4.6 shows that collecting more plastic by curbside collection can decrease the total cost due to the economics of scale achieved. The current collection trucks (with pressing function) have enough capacity in collecting more plastics. Doubling the current amount of source separated plastics, the total cost can drop by about 100 euro per ton. This result implies that a higher response rate can improve the efficiency of collection trucks.

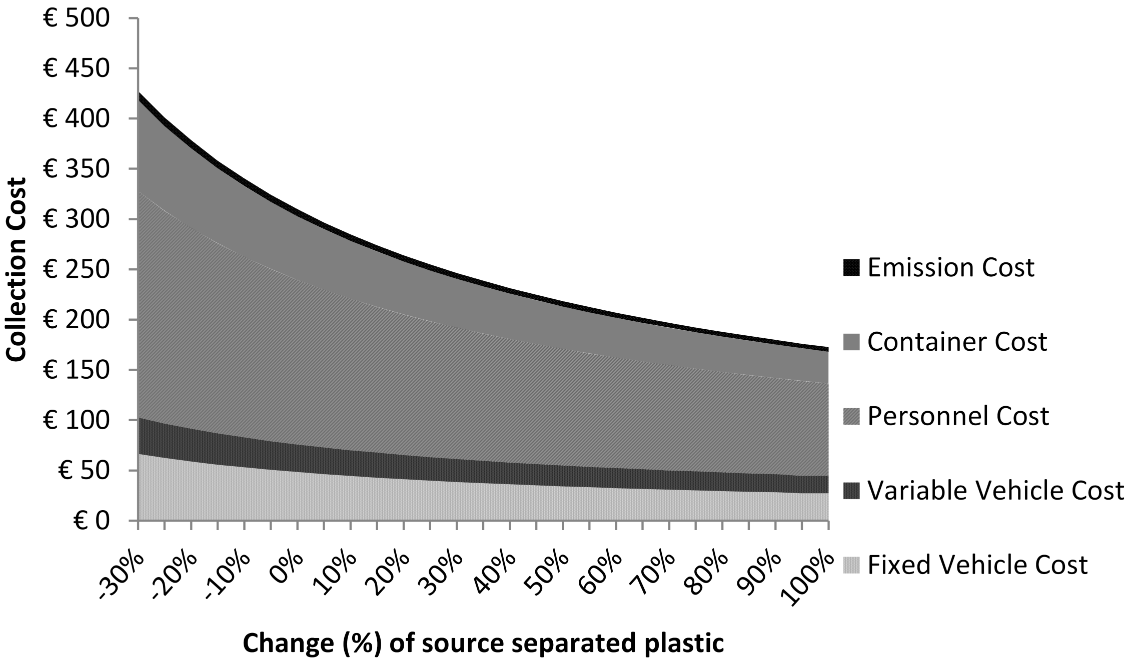


FIGURE 4.6: Average total collection cost by a change in the amount of source separated plastic by curbside collection

4.4.2 Fuel and carbon price

Another possible future change is the increase of fuel price and carbon cost. As presented in the result, both the fuel price and the emission cost are important factors in the total cost. Using the model, we tested the changes in total cost with these future trends. The results show that, doubling the fuel price would lead to an increase of total cost by 10% in source-separation and 15% in post-separation. While, doubling the carbon cost would make very limited change in the total cost.

4.5 Conclusions

This paper presents a comprehensive PPW collection cost model which takes into account carbon emissions from fuel consumption. The costs comprise fixed and variable costs per vehicle, personnel costs, container or bag costs as well as emission costs. Activity based costing is used to be able to calculate energy use and time elements needed for the determination of variable vehicle cost and personnel cost respectively. The calculation method takes into account the characteristics of municipalities and impacts of tax issues. It provides valuable insights into various plastic waste collection systems, which help the decision support of stakeholders in improving future plastic recycling schemes.

The model is used to compare costs of collection schemes within municipalities. The calculations for all municipalities in the Netherlands were conducted by using the proposed model. Results show that when PPW is collected as single material type in source-separation municipalities, the collection efficiency is much lower than collecting PPW together with other waste materials as happens in post-separation. Comparing curb side collection and drop-off collection, the driving with frequent stops and short idling times within curb side collection generates more emission than driving to less spots (where containers are located) with longer idling time as in drop-off collection. For urban municipalities, the collection costs can be reduced when households place their PPW collection bags at central places in their street (at a short distance from their house) for curb side collection. Curb side collection costs vary a lot with different urbanization degrees of municipalities, while drop-off collection sees almost the same cost for all municipalities. Taxation schemes have an impact of curb side collection but not drop-off collection.

Besides, the model can also help to investigate the impact of various input parameters on the total collection cost as well as predicting of the effect of possible changes to the system for a municipality. Our tests with the model show that the collection trucks and containers should be at least about half full to be cost-effective and as a consequence have a lower CO_2-eq exhaustion. A higher response rate can improve the efficiency of collection trucks due to economic of scale. Besides, the tests also showed that doubling fuel costs would lead to an increase of collection costs at 10% to 15%, depending on the collection scheme used. The impact of doubling the currently used carbon pricing on the total collection scheme costs is very limited.

For future research, this model can be extended to include other material types and collection schemes. This will enable a more integrated analysis of the efficiency of waste recycling management, because it can take into account incurred effects of changes in one material type to other recycling schemes In this research, the distances between stops are fixed. Future research can look into combining the presented model with an optimization model of collection distances. Another observation from our research is that the collection efficiency is relatively low when PPW is collected separately due to the low weight to volume ratio. This is most likely to be solved by technological progress in compressing the collected materials at household, drop-off or truck level. Furthermore, it was found that the total costs of post-separation are lower than those of source separation. However, it has been established by Thoden van Velzen et al (2013) that post-separated PPW has a higher contamination rate than source separation, leading to higher processing costs after sorting. A solution to this issue is worth further research.

Chapter 5

Sustainable Reverse Logistics Network Design for Household Plastic Waste

This chapter is based on the published journal article:
X. Bing, J.M. Bloemhof, J.G.A.J. van der Vorst (2014) "Sustainable reverse logistics network design for household plastic waste" Flexible Service and Manufacturing Journal, Vol 26, pp. 119-142

In this chapter we answer Research Question 3a:
What are the key issues that determine the sustainable performance of the regional network?

Abstract

Plastic recycling is a legal requirement and can yield environmental benefits. In the Netherlands, there is a complex network of various collection methods, separation centers, sorting centers and reprocessors. The first step of the recycling system, separating plastics from other waste, can occur within households (source-separation) or in separation centers (post-separation), making a difference in collection channel choice and technology requirements. The purpose of this paper is to provide decision support on choosing the most suitable combination of separation methods in the Netherlands. Decision support is given through optimized reverse logistics network design which makes the overall recycling system more efficient and sustainable, while taking into account the interests of various stakeholders (municipalities, households, etc.). A mixed integer linear programming (MILP) model, which minimizes both transportation cost and environmental impact, is used in this network design. The research follows the approach of scenario study; the baseline scenario is the current situation and other scenarios are designed with various strategic alternatives. Modeling is conducted by using a graphical optimization tool IBM LogicNet Plus 7.1. Comparing these scenarios, the results show that the current network settings of the baseline situation is efficient in logistics terms but has a potential to adapt to strategic changes, depending on the assumptions regarding availability of the required processing facilities to treat plastic waste. In some of the tested scenarios, a separate collection channel for Polyethylene Terephthalate (PET) bottles is cost efficient and saves carbon emission. Although the figures differ depending on the separation method choices of municipalities, our modeling result of all the tested scenarios shows a saving of more than 25 percent carbon emission compared to the current network.

Keywords: mixed integer linear programming, sustainability, network, plastics, household waste, reverse logistics

5.1 Introduction

Four percent of oil consumption in Europe is used for the manufacturing of plastic products (PracticalAction, 2010). High oil prices lead to rising virgin polymer prices which makes the use of recycled materials in manufacturing more profitable (WRAP, 2007). Virgin polymer prices are correlated with crude oil prices. Virgin high-density polyethylene (HDPE) prices, for instance, have almost doubled over the period from 2004 to 2008, which is in line with the increase of the price of crude oil during the same period (WRAP, 2007). According to Arena et al. (2003), technically, the production of 1 kg flakes of recycled PET instead of virgin PET saves roughly 30 MJ of energy (equivalent to the energy content of about one liter gasoline). A comprehensive life cycle inventory analysis of plastic recycling supply chains conducted by Wong (2010) also confirms that the recycling of post-consumer plastics has less environmental impact than the use of crude oil to produce virgin plastics. For example, CO_2 emissions due to the production of virgin polymer is 6 kg per kg of polymer, while it is 3.5 kg for that of recycled plastics (Wong, 2010). Besides, consumers' environmental concern puts pressure on manufacturing companies to produce environmental-friendly products (Kapetanopoulou and Tagaras, 2010). The cost savings and the environmental image of the products, which using recycled plastics instead of virgin polymer-based plastics in manufacturing brings, make plastic recycling environmentally and economically favored.

Besides the economic and environmental issues mentioned above, legislation on packaging waste put immense pressures on stakeholders regarding plastic recycling. According to EU Directive 2008/98/EC, by 2020, the preparing for re-use and recycling of plastic materials from households shall be overall increased to a minimum of 50 percent by weight (EU, 2008). Apart from European regulations, some EU member states also have national regulations and practices regarding the recycling of packaging waste. A well-known system is the Duales System Deutschland (DSD) for packaging waste, which was first applied in Germany in the 1990s. The DSD system is a privately organized channel which assures that primary packaging waste can be recycled through a material-specific channel. A green-dot label on packaging material gives the identification that the product belongs to the DSD system to be recycled (Buclet, 2002). Under the EU directive and national regulations, plastic collection practices vary in different countries, which has an impact on the network structure of reverse logistics for plastic waste.

Dutch regulation on packaging waste and paper waste, issued in 2006 and started in 2008, specified the goal of recycling 42% of plastic packaging waste in 2012 (Cramer, 2007a). Household plastic waste recycling in the Netherlands is characterized by various collection, separation and treatment systems. As the first step of recycling, separating plastics from other waste can occur in households (source-separation) or in separation centers (post-separation). Currently, both source-separation and post-separation systems exist in the Netherlands with source-separation dominating (88% of municipalities) as suggested by regulation. The overall collection rate, however, is not satisfying yet. In the Netherlands, there are 441 different municipalities varying a lot in population density (Poelman, 2009). Municipalities are in charge of choosing the collection methods of plastic waste. Currently, only the northern part of the Netherlands has post-separation facilities, therefore the post-separation system is adopted only in the North. Despite this current situation, most rural regions prefer source-separation. Large urban municipalities dislike applying source-separation, due to limited space at home for doing source-separation. The cost for a separate collection system of plastic waste and the investment in the collection facilities are quite high for municipalities.

Some of the EU member states apply economic instruments including taxes to create incentives for residents to separate recyclables from regular waste streams. A deposit-refund system provides one type of such incentives for ensuring the maximum reuse and recycling. Denmark implemented one of the oldest deposit-refund systems "Dansk Retursystem" for beverage bottles and mineral water bottles (ProEurope, 2009). The Netherlands also adopted a deposit-refund system for collecting PET bottles ($>$ 0.5L) with special collection machines in supermarkets. For PET bottle collection, a deposit-refund system is in place, meaning PET bottles are collected through a different channel. There is a trade-off between cost for using the refund collection system and the collection rate. Due to this trade-off, whether or not a separate collection channel is more efficient, in terms of transportation, than integrating the PET bottle collection into the normal plastic waste collection channels is worth investigation. Moreover, if a separate collection channel is used for PET bottles, whether or not to collect all the PET bottles through this channel is also an issue.

For an optimized network design, the choices of collection methods of municipalities should take into account the characteristics of the municipalities. This network design should provide decision support that both balances the interests of stakeholders and makes an overall efficient collection network for all household plastic waste types. Additionally, efficiency is not the only concern for the recycling system. Sustainability is also a crucial issue. Emissions from collection should be controlled by taking into account environmental parameters in the network design. The purpose of network design is not just to choose the most efficient way to deal with plastic waste, but also a sustainable one.

This research views plastic recycling as an application of reverse logistics. Reverse logistics is the process of planning, implementation and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain directions for the purpose of recovering value and proper disposal (Fleischmann et al., 1997a). This paper aims at designing a sustainable reverse logistics network for plastic recycling that is both efficient and sustainable, through building of a reverse logistics network model. The research issues we study in particular are 1) the choice between source-separation and post-separation and 2) whether or not to collect

PET bottles separately and if separately, whether or not to include PET bottles of all sizes in this channel.

In the following, Section 2 describes the theoretical framework and methodology with a literature review. Section 3 provides a system description of the network and the scenarios for analysis. Section 4 presents the mathematical formulation of the model, input data, the assumptions for all the scenarios as well as the modeling tool we use to solve the model. Section 5 shows the modeling results with sensitivity analysis and discussion. The last section gives a conclusion and points out the further research directions.

5.2 Theoretical Framework

A lot of research has been conducted on improving the understanding of plastic recycling. Astrup et al. (2009) focus on the accounting of greenhouse gas and the global warming contributions of plastic recycling. Ambrose et al. (2002) compare the quality of products made from recycled plastic materials with those from virgin plastics. Heng et al. (2008) work on increasing the participation of households to recycle plastics. Among these studies, Jahre (1995) points out that viewing waste collection themes as reverse logistics channels can also improve the understanding of the reverse system.

A review on the characteristics of the research on reverse logistics during the period of 1995-2005 shows that the majority of research focuses on the study of tactical and operational aspects like production planning and inventory management. Research on strategic aspects of reverse logistics is scarce (Rubio et al., 2008). Besides, very few attempts in the supply chain research area are made to study reverse and recycling supply chains (Wong, 2010). Some research in the management science fields focuses on reverse logistics of waste management. Pati et al. (2008) propose a mixed integer goal programming model to capture the inter-relationships among the economic, social and quality goals in the paper recycling industry. Bautista and Pereira (2006) establish a set covering problem for locating the collection points of urban waste in Barcelona and develop a genetic algorithm to solve the problem. In order to decide how to allocate the recycling containers for glass recycling, Gonzalez-Torre and Adenso-Diaz (2006) develop a two stage goal programming model to maximize the material collected and reduce the logistics costs. The allocation of bins is decided in the first stage and the route is planned in a following stage. These studies focus on a tactical and operational level by finding, among others, the optimized location of collection points and the routes. In our research we focus more on a strategic level then an operational level. That is, the impact of the choice of separation method on the channel choice in the network, the facilities required, the total transportation cost and emission. A comparison of network modeling results between the alternatives of separation strategies is the focus of this research.

Reverse distribution networks are not necessarily the symmetric picture of forward distribution. Most of them have a “many to few” (convergent) network structure instead of a “few to many” (divergent) structure (Fleischmann et al., 1997a). For plastic waste recycling network, there are a lot of municipalities as the source, however, only a few end users which reprocess the material. The structure of the plastic reverse network in this paper is a convergent multi-level network. Fleischmann et al. (2001b, 2004) develop a generic MILP network model for product recovery network design illustrated in by an example of paper recycling. This generic model provides a general approach to model convergent network. We follow this general approach and applied it to the case of plastic waste with an extension of taking into account environmental impact in the model. Besides environmental considerations, the special characteristic of plastic waste also distinguish our work from others. Plastic waste consists of various plastic types which need to be separated during the flow and shipped to different destinations for reprocessing. This is also a multicommodity-based problem. Geoffrion and Graves (1974) are among the first researchers who introduce multicommodity logistics network model for optimizing product flows. Lots of studies have been conducted on this type of network since then. For example, Arntzen et al. (1995) develop a multiperiod, multicommodity mixed integer model in order to optimize the global supply chain and Melo et al. (2006) propose a mathematical modeling framework for strategic supply chain planning of dynamic multicommodity capacitated facility location. Studying multicommodity network in a reverse supply chain setting is relatively new. Additionally, the implication of choosing separation strategy (source-separation or post-separation) on the network design is that, under such convergent network structure, the location where plastic is separated from other waste and the location where various plastic types, dirt and moisture are sorted out are places where waste separation happens. Opposite to the forward supply chain, in which products are assembled throughout the stages in the chain. This waste separation is similar to a process of product disassembly. Disassembly is a systematic method of separating a product into its constituent parts, components, subassemblies or other groupings (Taleb and Gupta, 1997). It may involve dismantling and/or demolition and/or reprocessing (Srivastava, 2007). Compared to the process of disassembling, waste treatment also involves separation and/or incineration and/or reprocessing. The major difference is that the separation of waste materials, as waste is a loose mix, is more stochastic than the disassembling process in which components of the objects are fixed (i.e. old cars). The separation will have an influence on the particular distribution channel choice. The point where separation happens could have an impact on the overall performance of the network. Consequently, this paper examines the impact of separation in plastic reverse logistics network by studying the difference in performance when choosing different separation point of PET bottles from other plastic waste.

Another trend in this research field is that environmental issues become an important parameter in logistics network design. The new concept of green supply chain management leads to a shift from minimizing cost to a balance between cost and environmental impact (Srivastava, 2007). Green supply chain management / logistics is an area that combines the concept of sustainability and logistics. Carbon footprint, as the weighted sum of greenhouse gas emissions and greenhouse gas removals of a process, a system of processes or a product system, expressed in CO_2 equivalents is a common measurement for environmental impact. Chaabane et al. (2012) introduce a mixed-integer linear programming based framework for sustainable supply chain design and demonstrate that efficient carbon management strategies can help to achieve sustainability objectives in a cost-effective manner. Environmental issues become an important parameter in logistics network design and the purpose is usually to get a balance between profit and environmental impact. Quariguasi Frota Neto et al. (2006) uses multi-objective programming (MOP) to apply this sustainability concept in the design of a sustainable logistics network. Krikke et al. (1999) use a multi-objective model to minimize cost, energy and residue waste. Cachon (2009) discusses how the objective of reducing carbon footprints affects supply chain operations and structures. In our research, we also take into account environmental issues in the modeling by calculating the logistics cost which embeds environmental cost.

A study on methodologies and initiatives of product carbon footprint of the European Commission shows that although very significant progress has been made in developing product carbon footprint methodologies, current methodologies still lack precision on some critical aspects like the end-of-life phase (Mugnier et al., 2010). Some research exists on post-consumer products, but rarely on the plastic sector. Chilton et al. (2010) undertook research on a life cycle assessment of the closed-loop recycling and thermal recovery of post-consumer PET to compare the environmental impact of different recovery options of PET bottles. Still, hardly any research studies the environmental impact with integrated household plastic waste types instead of focusing on a specific type.

To summarize, this paper studies the recycling of household plastic waste from a reverse logistics network design angle while taking environmental parameters into consideration, under a convergent multi-level network with multi-product and product split. The aim is to provide decision support on choosing the most suitable separation and corresponding distribution strategy with an optimized reverse logistics network which makes the recycling system more efficient and sustainable.

5.3 System description and research approach

5.3.1 System description

The Dutch network is presented in Figure 5.1. The scope of this research is limited to the trajectory of reverse supply chain from collection in Dutch municipalities to the reprocessors within Europe according to current practice. The 441 municipalities as suppliers and the few sorting plants form a convergent structure. In sorting centers, plastic is sorted into 6 different streams:

- PET (Polyethylene Terephthalate) : Water bottles and soda bottles, salad trays
- PP (Polypropylene) : Margarine tubs, microwaveable meal trays, ice-cream trays, detergent bottles
- PE (Polyethylene) : Milk bottles, bleach, cleaning agents and most shampoo bottles
- Film : Carrier bags, bin liners and packaging films
- Mix of hard plastic : PVC (polyvinyl chloride), PS (polystyrene), non-bottle PET and falsely sorted PE, PP and PET
- Non-plastic : Dirt and moisture, unsorted plastic due to inefficiency of sorting machines

Source-separation means that plastic is sorted from other waste at the household level. After that, plastic is transferred to regional cross-docking centers for baling up and then to the sorting centers where further sorting is conducted, so that each plastic type can continue to its processing plants and the non-plastic waste will be disposed. Other waste collected from municipalities[1] is transferred to incineration centers directly for energy recovery.

Post-separation means that plastic is not sorted from other waste at households. It is collected and transferred to separation centers together with other waste to be sorted. Afterwards, plastic waste is baled up and shipped to sorting centers where further processing is conducted. The remaining waste from separation centers is transferred to incineration centers directly. Source-separation requires the cooperation of householders and extra infrastructures, therefore, is more difficult and expensive to apply. Post-separation is easier to apply and results in a higher separation rate, as machinery separation is more efficient

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[1] separated collected waste at households (e.g. paper, glass, organic waste) not included.

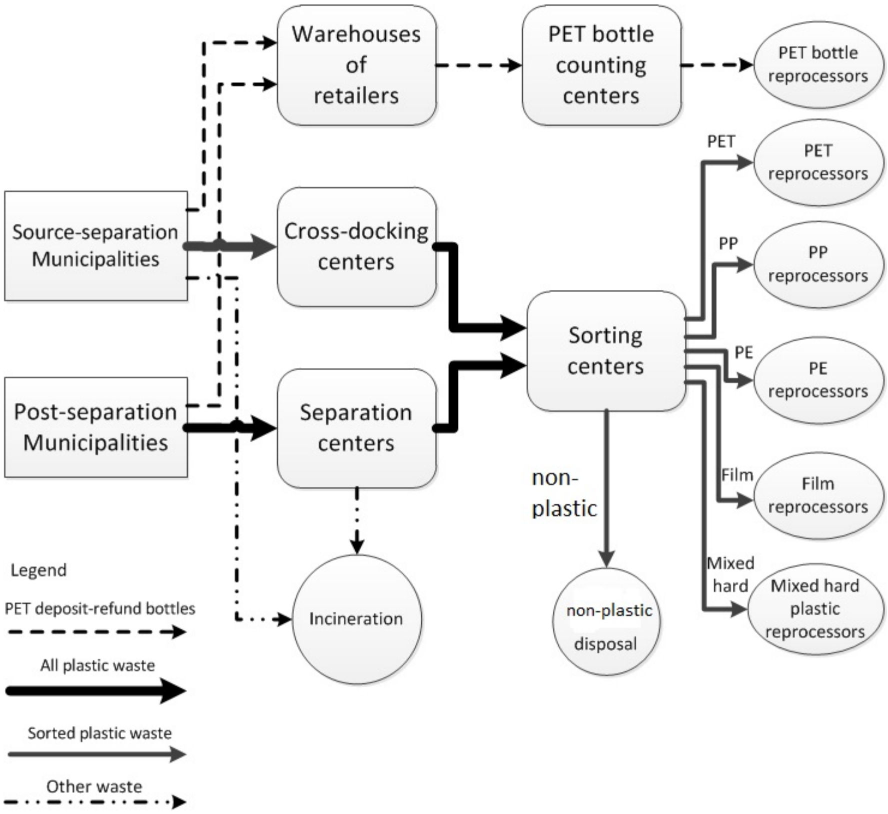


FIGURE 5.1: *Current Dutch household plastic waste collection network*

than householders' separation, meaning more plastic can be recycled in post-separation. However, since plastic waste is mixed with other waste, therefore, contaminated, the quality of the recycled material is lower than the material from the source-separation system.

The PET bottle is a special category of plastic waste. In the Netherlands, PET bottle (>0.5L) from all municipalities are collected through a channel that is specially for this type of plastic waste. The municipal collection is at the retailers by collection machines that have deposit-refund function. These deposit-refund PET bottles (DPET) are shipped to the warehouses of these retailers first. Then, they will be transferred to PET bottle counting centers before they go to the PET processing plants especially for processing PET bottles from the deposit-refund system.

From the description, it can be summarized that the household plastic waste recycling network in the Netherlands is a multi-product and multi-channel network. The channel choice is dependent on the choice of separation method used by municipalities, which has an influence on the total cost and emission of the network. Besides, there are also multiple stakeholders involved (householders, collection companies, municipalities, etc.), whose interests need to be considered in the network design.

5.3.2 Scenarios

This research follows the approach of scenario study by forming a list of scenarios first, then comparing the network modeling results of these scenarios. Scenarios are designed with research partners after the discussion with various stakeholders. In the scenario study, the baseline scenario is a representation of the current situation as presented in the previous sections. Since source-separation is dominating as suggested by legislation, more than 88% of the municipalities do source-separation. The 12% post-separation is conducted mostly in the northern part of the country because the only two currently available separation centers are both located in the North. DPET is collected through the special channel as described above. According to the scenario study approach, the scenarios used in the modeling are designed as described in Table 5.1. Based on the current situation (scenario 1), we investigate the impacts of various strategic alternatives.

- adopting a PET collection system that includes all sizes of PET bottles (Scenario 2)
- choosing a collection method according to the population density of the municipality (Scenarios 3 and 4)
- shifting to 100% post-separation (Scenarios 5 and 6)
- integrating PET bottle collection in the normal channel (Scenarios 4 and 6)

These strategic alternatives take into account the differences in the characteristics of municipalities and the alternative utility of the existing channels in order to search for balanced interests of stakeholders such as food companies, householders, municipalities, collection companies and policy makers. Adopting PET collection from other countries investigates the possibility to include more plastic bottles in the separate collection scheme as some other countries are doing, such as Switzerland. Integrating PET collection in the normal collection channel, on the contrary, investigates the results of removing the separate channel. Considering the difference in the characteristics of municipalities prioritizes the interests of householders while shifting to 100% post-separation takes into account the preferences of some of the municipalities. This scenario study includes building model according to scenarios with various strategic assumptions and comparing modeling results to provide decision support for making the choice of source-separation or post-separation and the choice of corresponding processing facilities. The purpose is to achieve the lowest overall transport cost from the municipalities to final processing facilities while taking into account emissions of transportation.

Table 5.1: key assumptions of the scenarios for modeling

	Collection channel for plastic waste		Collection channel for PET bottles
	Post-separation	Source-separation	PET bottle collection
Scenario 1	current situation: mainly in the North	current situation: rest of the country	recycling with refund through supermarkets*
Scenario 2	current situation: mainly in the North	current situation: rest of the country	*Recycling with no refund through supermarkets***
Scenario 3	*applied to urban municipalities*	itapplied to rural *municipalities*	recycling with refund through supermarkets
Scenario 4	*applied to urban municipalities*	*applied to rural municipalities*	*same as other waste no separate collection channel*
Scenario 5	*all municipalities*	−−	recycling with refund through supermarkets
Scenario 6	*all municipalities*	−−	*same as other waste no separate collection channel*

Description marked in italic format shows the changes in scenarios 2 to 6 in comparison with baseline scenario
* current collection method used for PET bottles (>0.5 L) with refund label
** adopting Swiss system in which PET bottles of all sizes are collected in the locations of supermarkets without refund

Mixed integer linear programming (MILP) is used in this network design. Modeling is conducted by using a graphical optimization tool IBM LogicNet Plus 7.1. Unlike the usual forward supply chain network model, we have all the plastic types and non-plastic as various "products" in the model. Municipalities are the supplier of these "products". The distinctive convergent structure is built in and the special feature of product disassembly during the flow is simulated. Contrary to normal distribution networks in which products are assembled at the source or during the flow, plastic waste is separated and sorted along distribution from the sources to the end processors. Many plastic fractions are collected together at the source, mixed with dirt and moisture and even other municipal solid waste, depending on the collection method. Along the flow, separation and sorting are conducted. The residual part out of each step of separation and sorting will be disposed; therefore, the quantity of plastics also reduces during distribution.

The objective of the MILP model is to minimize the overall transportation cost and environmental impact. In each scenario, different network layouts, assumptions on the choices of collection channels and the characteristics of municipalities define the quantity of the products, their flows and the availability of facilities in the network, which are constraints for the model. Additionally, PET bottles are a special category of plastic waste. They can have a unique channel of recycling in the network other than the normal plastic waste. The network design has to fit these features.

5.3.3 Data

Data collection for building up the model took place in cooperation with research partners through interviews, industrial reports and literature. A summary of the data used in the model and data sources is presented below.

Municipalities (population, quantity of plastic waste, location) Statistics are collected from the Central Bureau of Statistics in Netherlands, 2009. There are 441 municipalities in 2009, varying a lot in population. Municipalities are classified according to their population density into 5 classes where class 1 is the most populated municipality class and class 5 is the most rural one. Furthermore, we aggregated these 5 classes into 2 types of municipalities: urban (class 1, 2) and rural (class 3, 4 and 5).

Processing facilities (function, location, availability) Nedvang (Dutch packaging waste recycling agency) provided data on the locations and the functions of processing facilities in Netherlands. Processing facilities include cross-docking centers, separation centers, PET counting centers, incineration centers as well as all the processors in the network. Their locations, functions and some of their availability constraints are used in the model. The locations of all the facilities and municipalities are presented in Figure 5.2.

Plastic waste (components, quality) Total quantity and the quality of each component are provided by one of the research anchors of the Kenniscentrum Nascheiding (KCN), an expertise center located at Wageningen University that investigates the technological and economic feasibility, as well as the environmental impact, of new technologies for the treatment of plastics. Quality data is the reference for calculating the impurities mixed in the plastic waste.

Carbon equilibrant emission cost For the cost of transportation emission, we refer to the price of EU carbon allowances 2008 (Ellerman et al., 2010).

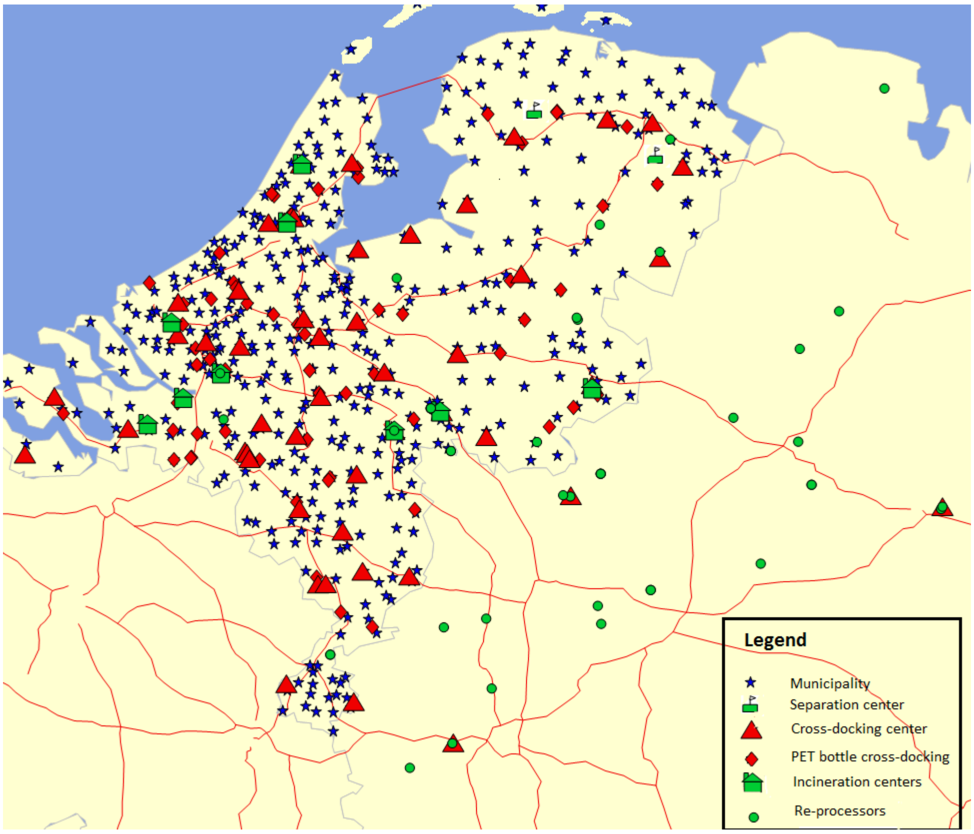


FIGURE 5.2: *Locations of municipalities and all facilities in the network*

5.4 Modeling

5.4.1 Assumptions

The key assumptions used in the baseline scenario (network flow as in Figure 5.1) are as follows.

- There is no mechanical efficiency difference between the same type of facilities (sorting centers, separation centers, etc.).
- There are 3 types of trucks used: small, medium and large. Small trucks are used from the municipality to the next location (separation center or cross-docking center). For the final transport to customers, large trucks are used. In the rest of the occasions, medium trucks are used. The unit cost of all types of truck is $c^t = 1\,\text{Euro/km}$. These 3 types of trucks have different capacities. A small one has a capacity of 9 ton. This is according to the statistics of average value for trucks in the Netherlands that travel less than 150 km for transportation. The medium one is 13-14 ton of overall average value. The large ones have a capacity of 18-19 ton,

which is according to the average loading weight of 40 foot high container trucks (PASI, 2007). Utilization rates are all 100%.

- Besides the transportation cost, we also consider environmental cost. It is calculated by the following formula

$$c^e = \frac{\text{price of EU carbon allowances (Euro/ton)}}{1000\text{(kg/ton)}} \times \frac{\text{carbon equivalent conversion factor (kg}CO_2\text{e/l)}}{\text{fuel efficiency (km/l)}}.$$

  For the initial input value for calculating, we use 20 Euro/ton (Ellerman et al., 2010) as the price of EU carbon allowances, 1.82 km/l (Rhoma et al., 2010) as the fuel efficiency of trucks and 2.67 kg CO_2e/l (DEFRA, 2012) as the carbon equivalent conversion factor. Therefore $c^e = 0.029\,\text{Euro/km}$.

- Total transportation cost per kilometer per ton is calculated as $c = c^t + c^e$. In the model, we use $c_{ij} = c * d_{ij}$ as the cost per ton, where d_{ij} is the distance between node i and j.

- We do not consider fixed cost of the existing facilities. As we only optimize transportation and transport emission cost, the fixed costs of facilities do not have impact on our results.

We interpret the current situation with the modeling settings by the following assumptions.

- Municipalities are "plants" and reprocessors are "customers".

- There are 7 types of products in the network: non-plastic, PE, PET, Film, mixed hard plastic, PP and DPET.

- Municipalities are the sources for the supply of "products" in the model. Each municipality is concentrated in a node in the model and the location is the geographical center of the municipality as a supply point. All the plastic waste within one municipality are collected and gathered at this central point to be transported to the next location.

- During the process, dirt, moisture and plastic that is not sorted out due to machinery inefficiency will be created and disposed. All these waste belong to the product category "non-plastic". We assume that this disposal only happens in sorting centers. we simulated the landfill activity to get rid of these waste at the site of sorting by creating virtual customers at the locations which are the same as the sorting centers with a "demand" for non-plastic waste.

- We include in our model the cost of the transport of PET bottles in the separated collection channel from supermarkets to the cross-docking locations, although it is operated by retailers by using the empty trucks that goes back from delivery of goods to supermarkets (if not for transport of PET bottles, this delivery return is still there, so the cost can be excluded from the PET bottle collection system). We make this assumption because this operation is not true for all scenarios. In Swiss system, supermarket operators are not in charge of transporting PET bottles. Therefore, we use the same system boundary for all scenarios by including this transport cost in our system.

5.4.2 Model formulation

The basic mathematic formulation of the MILP model for baseline scenario is presented in this section. Other scenarios are also built with some adaptions of the same model formulation. Adaptions are presented later in section 5.4.3.

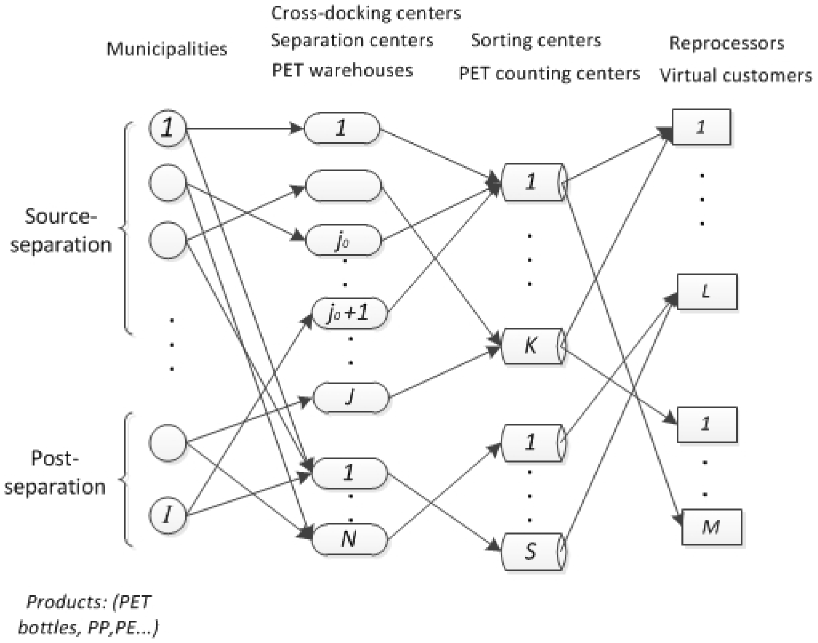


Figure 5.3: *Flow chart of reverse network for plastics waste*

Index sets used in the MILP problem are:

$i \in I$ set of sources (municipalities)

$j \in J$ set of warehouses (set of cross-docking sites$\{1, \cdots, j_0\}$; set of separation centers $\{j_0+1, \cdots, J\}$)

$n \in N$ set of deposit-refund PET bottle warehouses

$k \in K$	set of sorting companies
$s \in S$	set of deposit-refund PET bottle counting centers
$l \in L$	set of reprocessing plants
$m \in M$	set of virtual customers (for non-plastic disposal)
$p \in \{P, \bar{P}\}$	set of products (P set of products for collection at households {PET , PP, PE, Film, mixed hard plastic, dirt and moisture}; $\bar{P}$ set of products from deposit-refund collection {DPET})

Variables used in the MILP problem are:

$X_{ijp} \in \mathbb{R}^+$	quantity of product p transported from municipality i to warehouse j
$X_{inp} \in \mathbb{R}^+$	quantity of product p transported from municipality i to warehouse n
$X_{jkp} \in \mathbb{R}^+$	quantity of product p transported from cross-docking center/separation center j to sorting company k
$X_{nsp} \in \mathbb{R}^+$	quantity of product p transported from PET warehouse n to counting center s
$X_{klp} \in \mathbb{R}^+$	quantity of product p transported from sorting center k to reprocessing plant l
$X_{slp} \in \mathbb{R}^+$	quantity of product p transported from counting center s to reprocessing plant l
$X_{kmp} \in \mathbb{R}^+$	quantity of product p transported from sorting center k to customer m

where $\mathbb{R}^+ = \{x \in \mathbb{R} : x \geq 0\}$.

Parameters used in the MILP problem are:

$$t_i = \begin{cases} 1, & \text{if source } i \text{ is doing source-separation} \\ 0, & \text{otherwise} \end{cases}$$

c_{ij}	transportation and environment costs for transporting one unit product p from municipality i to warehouse j.
c_{in}	transportation and environment costs for transporting one unit product p from municipality i to PET warehouse n.
c_{jk}	transportation and environment costs for processing and transporting one unit product p from cross-docking/separation center j to sorting company k.
c_{ns}	transportation and environment costs for processing and transporting one unit product p from PET warehouse n to PET counting center s.
c_{kl}	transportation and environment costs for processing and transporting one unit

	product p from sorting company k to reprocessing plants l.
c_{sl}	transportation and environment costs for transporting one unit product p from PET counting center s to reprocessor l.
c_{km}	transportation and environment costs for transporting one unit product p from sorting center k to customer m.
$q_i \in \mathbb{R}^+$	quantity of total products collected at source i,
d_{mp}	demand of product p by customer m
d_{lp}	demand of product p by customer l
f_{ip}	fraction of product p in the total supply at i for post-separation
f'_{ip}	fraction of product p in the total supply at i for source-separation

The MILP problem is formulated as follows:

$$\begin{aligned}\text{Minimize} &\sum_{i=1}^{I}\sum_{j=1}^{j_0}\sum_{p=1}^{P} X_{ijp}c_{ij}t_i + \sum_{i=1}^{I}\sum_{j=j_0+1}^{J}\sum_{p=1}^{P} X_{ijp}c_{ij}(1-t_i) + \sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{p=1}^{\bar{P}} X_{inp}c_{in}t_i \\ &+ \sum_{n=1}^{N}\sum_{s=1}^{S}\sum_{p=1}^{\bar{P}} X_{nsp}c_{ns} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P} X_{jkp}c_{jk} + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{p=1}^{P} X_{klp}c_{kl} \\ &+ \sum_{s=1}^{S}\sum_{l=1}^{L}\sum_{p=1}^{\bar{P}} X_{slp}c_{sl} + \sum_{l=1}^{K}\sum_{m=1}^{M}\sum_{p=1}^{P} X_{kmp}c_{km} \end{aligned} \tag{5.1}$$

$$\sum_{j=1}^{J}\sum_{p=1}^{P} X_{ijp} = q_i \qquad \forall i \in I \tag{5.2}$$

$$\sum_{i=1}^{I}\sum_{p=1}^{P} X_{ijp} = \sum_{k=1}^{K}\sum_{p=1}^{P} X_{jkp} \qquad \forall j \in J \tag{5.3}$$

$$q_i f_{ip} t_i + q_i f'_{ip}(1-t_i) = \sum_{j=1}^{J} X_{ijp} \qquad \forall i \in I, p \in P \tag{5.4}$$

$$\sum_{j=1}^{J}\sum_{p=1}^{P} X_{jkp} = \sum_{l=1}^{L}\sum_{p=1}^{P} X_{klp} + \sum_{l=1}^{M}\sum_{p=1}^{P} X_{kmp} \qquad \forall k \in K \tag{5.5}$$

$$\sum_{k=1}^{K}\sum_{p=1}^{P} X_{klp} = \sum_{m=1}^{M}\sum_{p=1}^{P} X_{lmp} \qquad \forall l \in L \tag{5.6}$$

$$\sum_{i=1}^{I}\sum_{p=1}^{\bar{P}} X_{inp} = \sum_{s=1}^{S}\sum_{p=1}^{\bar{P}} X_{nsp} \qquad \forall n \in N \tag{5.7}$$

$$\sum_{n=1}^{N}\sum_{p=1}^{\bar{P}} X_{nsp} = \sum_{m=1}^{M}\sum_{p=1}^{\bar{P}} X_{smp} \qquad \forall s \in S \tag{5.8}$$

$$\sum_{k=1}^{K} X_{klp} \geq d_{lp} \qquad \forall l \in L, p \in P \cup \bar{P} \tag{5.9}$$

$$\sum_{k=1}^{K} X_{kmp} \geq d_{mp} \qquad \forall m \in M, p \in P \tag{5.10}$$

$$X_{ijp}, X_{jkp}, X_{inp}, X_{jnp}, X_{klp}, X_{lmp} \in \mathbb{R}^{+}. \tag{5.11}$$

The goal of the model is to identify the quantities shipped between various points that minimize the total transportation cost and environmental impact. Constraint (5.2) specifies that the total amount transported from a municipality equals the total supply. Constraint (5.3) balances the inflow and outflow in a cross-docking/separation center. Constraint (5.4) makes sure that the waste transported out of the source municipalities in the fixed fraction as produced, in other words, no separation happens before the products arrive at warehouse j. Constraint (5.5) balances the inflow and outflow in a sorting center. Constraint (5.6) balances the inflow and outflow in a PET bottle warehouse. Constraint (5.7) balances the inflow and outflow in a PET bottle counting center. Constraint (5.8) specifies that the total amount of all products transported to a customer should satisfy the demand of the customer. Constraint (5.9) specifies that the total amount of all products transported to a virtual customer should satisfy the demand of the customer.

5.4.3 Model adaption for scenarios

Other scenarios are also built accordingly, however, with different assumptions.

- For scenario 2, the only difference in the model is the quantity of PET and DPET. Since the Swiss system is used in this scenario, the quantity of DPET bottles increases, and consequently, the quantity of other PET reduces.
- In scenario 3, an extra parameter is introduced to the system, that is the municipal class. With a scale of 1 to 5, municipalities are defined by their population density. In this scenario, based on the scale, municipalities are further divided into 2 types, urban (class 1 and 2) and rural (class 3, 4, 5). Urban municipalities (U) perform post-separation and rural municipalities (R) perform source-separation.

$$t_i = \begin{cases} 1, & i \in U \\ 0, & i \in R \end{cases}$$

In this case, some municipalities changed from source-separation to post-separation compared to scenario 1. Since there is an increase of post-separation municipalities and they are not centrally located in the northern part of the country anymore, incineration locations are included as potential locations for the separation sites. There is a step of separation before incineration of waste, therefore, incineration centers have the function and existing capacity of separation which is why these locations are chosen to be the potential separation center. A binary variable is also used in this case to determine if an incineration center is used as separation site or not. The model will choose which incineration center to use during optimization.

- Besides the same assumptions as in scenario 3, the major difference of scenario 4 is in the flow of PET bottles. Because there is no separate channel for PET collection, all the PET bottles will go through the same channel as normal PET plastic waste. Consequently, the PET cross-docking stations and counting centers are no longer active in this scenario. However, the PET bottle reprocessors will still be there as a reprocessor for PET waste and the demand for these reprocessors are the same as when they function as PET refund bottle reprocessors.
- As there is no source-separation in scenario 5, post-separation is dominating ($\forall i, t_i = 0$). There need to be more separation centers. All incineration centers are used as locations for separation centers. There are only very limited numbers of post-separation reprocessors, therefore, the source separation reprocessors are kept as reprocessors in this scenario, so are the PET bottle reprocessors.
- The assumptions in scenario 6 are the same as in scenario 5, except that PET bottles from the deposit-refund channel go with normal plastic waste through post-separation channel, and the final reprocessors are not those for refund systems but the same as normal PET plastic waste reprocessors.

5.5 Results and Discussion

5.5.1 Results

The summary results of all plastic waste as in Table 5.2 shows that among all the scenarios, Scenario 3 has the best performance with the least transportation cost and emission. Scenario 3 introduces the strategy of differentiating urban and rural municipalities by assigning source-separation to rural municipalities and post-separation to urban ones. The difference in cost between scenario 1 and 3 is small. In comparison with scenario

1, which is the baseline scenario as a representation of current situation, this strategy saves transportation distance by 0.1%, with the assumption that locations of incineration centers are used as separation stations.

Table5.2 : Summary results for all plastic fractions

	Scenarios					
	1	2	3	4	5	6
Distance(km)	1,007,934	1,111,608	1,006,561	1,270,034	1,429,749	2,543,524
Total cost(€)	1,037,527	1,155,904	1,036,651	1,307,035	1,472,585	2,618,202
Cost per section(€)						
municipalities to cross-docking/separation	128,310	145,802	152,078	149,654	236,087	311,143
cross-docking/separation to sorting	410,700	440,574	384,013	718,527	722,174	1,294,537
sorting to reprocessing	498,517	569,528	500,560	438,855	514,323	1,012,522
Carbon emission(mtCO_2e)						
municipalities to cross-docking/separation	183	208	217	213	337	444
cross-docking/separation to sorting	586	628	548	1,025	1,030	1,846
sorting to reprocessing	711	812	714	626	734	1,444
total emission	*1480*	*1649*	*1479*	*1864*	*2100*	*3734*

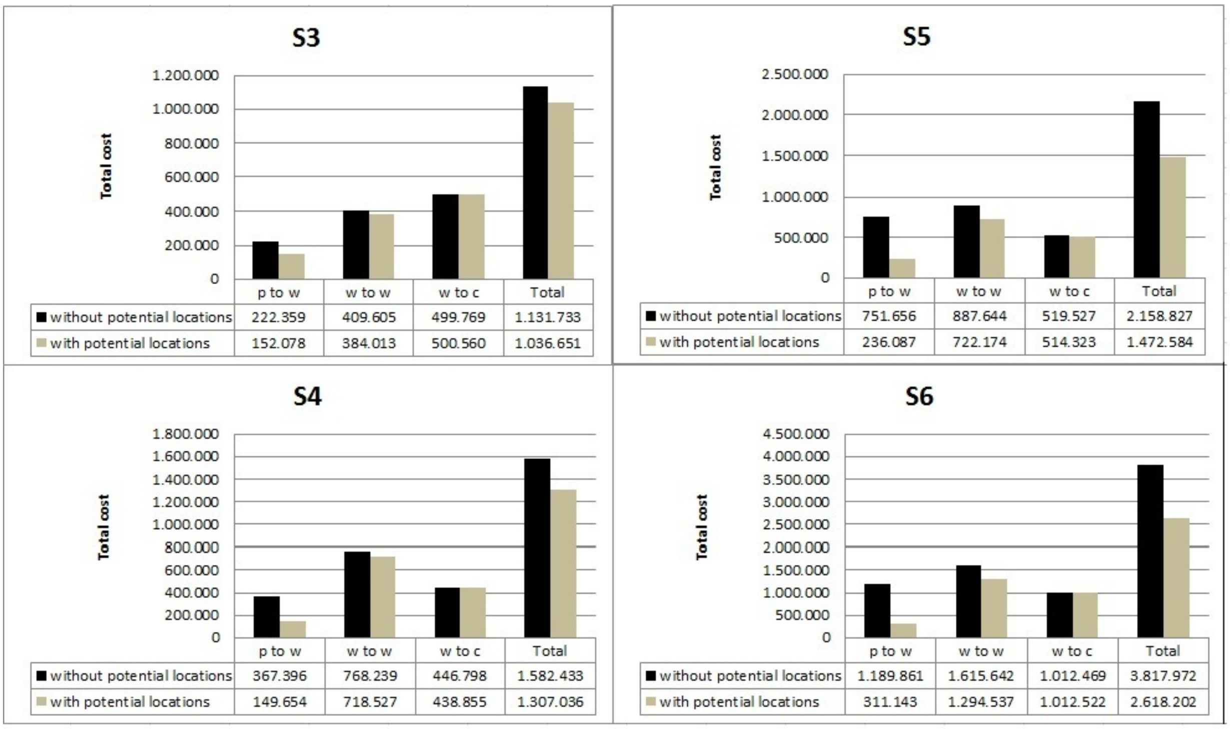
Applying post-separation to the whole country as in scenario 5, however, leads to a rise in total transportation cost and carbon emission. The increase in transportation kilometers and carbon emission is up to 65 percent. The difference lies in the part from plant to warehouses (municipalities to separation centers in this scenario) and the part from warehouses to warehouses (separation centers to sorting centers in this scenario). In this scenario, all the incineration centers (there are 11 locations in the model) are opened as separation centers. Still, compared to the large number of cross-docking centers (more than 50) as used in scenario 1, there is an increase in cost for these two parts, especially the part from separation centers to sorting centers in comparison with that from cross-docking centers to the sorting centers. The rise in cost of this part is up to 268 percent.

The Swiss system, in which the PET bottles of all sizes (not only bottles larger than 0.5 liter as in the current situation) are collected through deposit-refund channel, would bring an increase of transportation costs by 10 percent. The transport from the retailers to the warehouses of the retailers in the PET refund system has been included in these calculations. After adapting the choice of separation method according to municipal type, removing separate PET deposit-refund channel from the system would result in an increase of cost too. Comparing scenario 3 and 4, we can see that the difference is up to 26 percent. Comparison between scenario 5 and 6 confirms this observation. Scenario 6 also has much more cost than scenario 5, which represents an increase of 79 percent. Emission is calculated by traveling distance, therefore is linear to transport. The results shows the same difference as the transportation cost.

A separate PET bottle collection channel is a sort of product disassembly in the source of the network. The availability of facilities and their locations in the network in this case, play an important role on determining which separation point choice is better. The modeling results of scenarios 3 to 6 show that with the existing facilities for processing PET bottles, this separation at the source (separate collection) has less cost and emission than separation in a later stage (combined with normal plastic waste).

5.5.2 Sensitivity analysis

In the model assumptions for scenarios 3 and 4, the locations of incineration centers can be the potential locations for separation centers and in scenarios 5 and 6, all the incineration locations are opened as fixed locations for separation. We tested the results of using only the current locations of separation centers in these 4 scenarios and got the results as shown in Figure 5.4. For all these scenarios, the choice of separation centers does not have much influence on the transport between sorting centers and reprocessors. However, it is quite obvious that without the potential separation locations, there would be an increase in transportation for the other two sections. For scenarios 3 and 4, the differences are not as large as in scenarios 5 and 6. That is because, scenarios 3 and 4 still have a lot of municipalities performing source-separation which do not need separation centers. When the collection shift to post-separation for the whole country, the differences become much larger. With the only 2 current separation centers in the north, in scenarios 5 and 6, all the waste collected from the Netherlands is shipped to the northern facilities to get separated and transported to Germany for sorting (all the sorting centers are located in Germany). If we compare the total costs between baseline scenario and scenario 3 with the assumption that only the current 2 separation centers can be used, then scenario 3 leads to an increase of transportation cost by 9 % instead of having almost the same cost as baseline scenario when we make the assumption that potential locations can be used.



p to w (plant to warehouse): municipalities to cross-docking centers/separation centers
w to w (warehouse to warehouse) : cross-docking centers/separation centers to sorting centers
w to c (warehouse to customer) : sorting centers to reprocessors/disposal sites

Figure 5.4: *Sensitivity analysis: separation centers*

In the models of all scenarios, the assumption for truck utility rates (by weight) are all 100%. However, in reality, the utility rate might vary, especially on the part from municipalities to cross-docking centers/separations centers when a small truck with the capacity of 9 ton is used, as this is the same truck that is used for the collection within municipalities. The collection within municipalities could differ in truck utility due to different arrangement in each collection round from various municipalities. Plastic is also a quite light material which would result in a lower truck utility. Therefore, a higher variation of utility rate of trucks is expected in this section in comparison with the other two sections. We tested the model with different utility rates. The results, as shown in Figure 5.5, indicate a continuous decrease of total cost and emission with the rise of utility rate. With the increasing utility rate from 10% to 40%, both total cost and emission drop sharply. Between 50% and 100%, the reduction rate gets smaller. Scenario 5 is more sensitive to this utility change, as this scenario has a higher decreasing rate than the other two scenarios which we can observe from the bar chart. Scenarios 1 and 3 have similar performance.

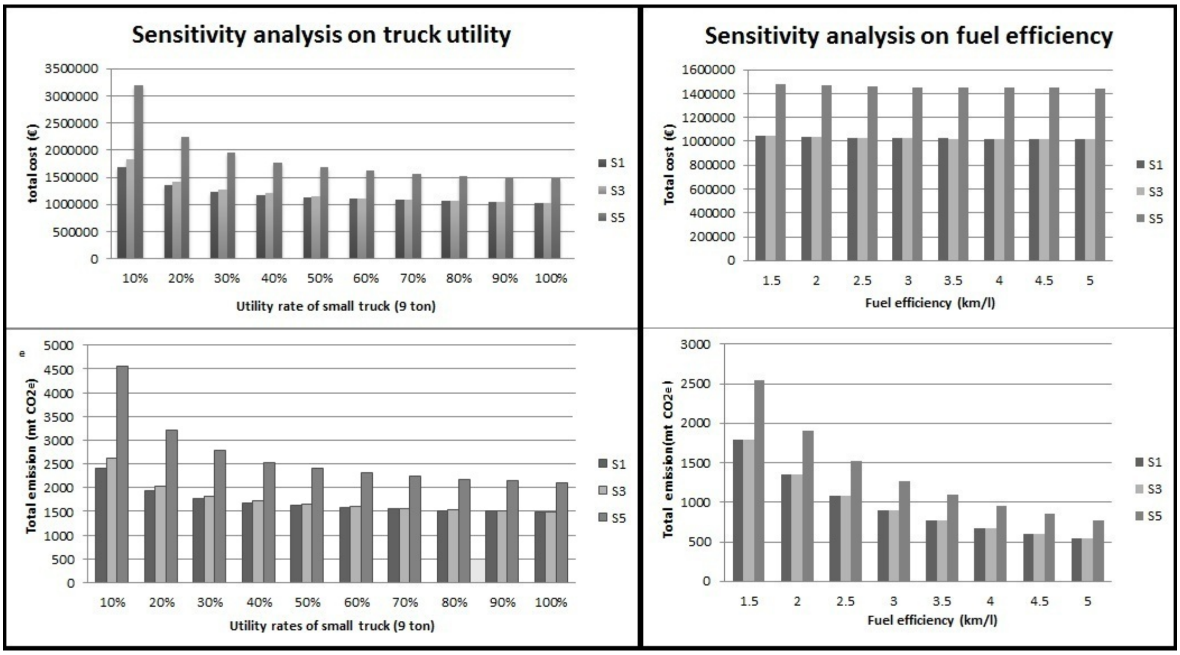


Figure 5.5: Sensitivity analysis: truck utility and fuel efficiency

Fuel efficiency is another factor that could influence the environmental performances of scenarios. The assumptions we make in the modeling gives an relatively low fuel consumption rate of 1.82 km/l (Rhoma et al., 2010). However, this value might vary depending on truck type and utility. We tested with scenarios 1,3 and 5, different values of fuel efficiency. The results show that total costs do not differ much with different values of fuel efficiency. Total emission values, however, experienced a steady decreasing trend with the rising value of fuel efficiency. Total cost do not differ that significantly as emission because emission cost only counts for a small part of total cost. Another observation is that, scenarios 1 and 3 also have stable similar performance with the change of fuel efficiency.

5.5.3 Discussion

Although scenarios 1 and 3 have similar performance, as there are currently only 2 separation centers both located in the North, if there are no new locations for separation centers for scenario 3, it would result in a lot more transportation from the urban municipalities to the north for post-separation. Adding new locations for facilities would bring extra cost in installation. However, if we consider the machinery efficiency of post-separation which is much higher than the separation rate of householders as in source-separation, the total quantity of plastic waste recycled would be increased. The quality of recycled material might be lower because of the contamination from post-separation, which indicates a trade-off between quantity and quality.

Post-separation scenarios have the highest costs and environmental impact. The post-separation scenario is also more sensitive to the input changes of truck utility and fuel efficiency. The main reason is the limited number of separation centers in comparison with the many cross-docking sites for source-separation. Considering the interests of stakeholders such as municipalities and householders, post-separation has its advantage in a higher separation rate and less installation cost, meaning lower set-up cost and less installation effort, such as putting collection bins, assigning separate collection routes and vehicles. Moreover, in this research, each municipality is a node as a source of waste production. The cost and emission from the collection within municipalities are not included. If we take the transport within municipality into account, post-separation might have lower overall cost, because of consolidated collection transportation in comparison with separated collection as in source-separation.

Comparing the results of all scenarios, it shows that this current network fits the baseline scenario quite well, meanwhile has the potential to be adjusted to fit the strategic change of the collection methods. The key issue is the availability of intermediate facilities and their locations. Although extra costs might be needed, benefit of more balanced interests of stakeholders and the potential higher recycling rate resulting from it by implementing strategic changes should be considered. The results from the modeling provides support in decision making by quantifying the difference, in terms of transportation cost and emission, would be if strategic changes are to be made.

The Swiss system, in which all PET bottles are transported through a separate channel, leads to more transportation in comparison with the baseline scenario. However, if we take into account that the PET refund bottles are transported in the empty trucks of retailers, which would have to drive back to the warehouses anyway after delivering goods to the retailers, meaning transportation in this section can be neglected from this system, the results might change. In general, a separate collection channel for PET bottles is beneficial when the municipalities' choices of performing source-separation/post-separation change as in scenarios 3 to 6. A separate channel also prevents PET bottles from contamination and ensures a high reaction rate by deposit, although the installation cost (e.g. collection machines) is relatively high.

5.6 Conclusion and Further Research

In order to improve plastic recycling system, decision support is needed on choosing the most suitable recycling collection method with the collection alternatives and separation possibilities in the Netherlands. This paper analyzes the strategic alternatives of reverse logistics network design by scenario study approach. Together with a baseline scenario of the current situation, scenarios with various strategic changes are modeled. The results show that for plastic waste, applying post-separation and differentiating urban and rural municipalities (by assigning post-separation to urban municipalities and source-separation to rural ones) has a similar result as the current situation with a slight reduction of overall cost with the assumption that additional facilities are available. In the model, all the incineration centers are set as potential separation centers. Without these potential locations, a lot more transportation would be generated by applying these strategic changes. In sensitivity analysis, this scenario also has similar stable performance as the baseline scenario. In general, increased truck utility reduces the total cost and emission. The rising fuel efficiency also brings such trend.

Post-separation scenarios have the highest costs and environmental impact. The main reason is the limited number of separation centers in comparison with the many cross-docking sites for source-separation. Post-separation has its advantage in a higher separation rate and less installation cost for municipalities and householders. It would be interesting for future research to include quality and separation rate as parameters in the model.

The Swiss system gives a slight rise in total transportation cost. After assigning post-separation to urban municipalities and source-separation to rural municipalities, PET bottles collection that has a separate channel should be kept because of the significant cost increase by integrating PET bottle collection into the normal plastic waste collection theme. Integrating PET collection in the normal collection channel results in more cost and emission. Post-separation scenarios are more sensitive to this integration than source-separation scenarios.

This model optimizes both transportation cost and environmental impact. Only emissions from transportation are considered. Other environmental influences such as the quality of material as the result of separation method choice and the emissions from each step of the processing in the network are not included in this research, but would be interesting for future research. Moreover, in this network model, the collection cost, distances, and environmental impact of collection additivity within municipalities are not considered , however, would also be interesting for further investigation.

Chapter 6

Multimodal Network Design for Sustainable Household Plastic Recycling

This chapter is based on the published journal article:
X. Bing, J. Groot., J.M. Bloemhof, J.G.A.J. van der Vorst (2013) “Sustainable reverse logistics network design for household plastic waste”,International Journal of Physical Distribution & Logistics Management, Vol. 43 No. 5/6, 2013 pp. 452-477

In this chapter we answer Research Question 3b:
What strategy can be used to re-design a regional supply chain to improve sustainable performance?

Abstract

This research studies a plastic recycling system from a reverse logistics angle and investigates the potential benefits of a multimodality strategy to the network design of plastic recycling. This research aims to quantify the impact of multimodality on the network, to provide decision support for the design of more sustainable plastic recycling networks in the future. A MILP model is developed to assess different plastic waste collection, treatment and transportation scenarios. Comprehensive costs of the network are considered, including emission costs. A baseline scenario represents the optimized current situation while other scenarios allow multimodality options (barge and train) to be applied. Results show that transportation cost contributes to about 7% of the total cost and multimodality can bring a reduction of almost 20% in transportation costs (CO_{2-eq} emissions included). In our illustrative case with two plastic separation methods, the post-separation channel benefits more from a multimodality strategy than the source-separation channel. This relates to the locations and availability of intermediate facilities and the quantity of waste transported on each route. This study applies a reverse logistics network model to design a plastic recycling network with special structure and incorporates a multimodality strategy to improve sustainability. Emission costs (carbon emission equivalents times carbon tax) are added to the total cost of the network to be optimized.

Keywords:

multimodal transport, mixed integer linear programming, sustainability, network design, plastic waste, reverse logistics

6.1 Introduction

Plastics currently represent 7% to 20% of household waste (WasteOnline, 2010, AgentschapNL, 2011). Statistics show that an average European inhabitant throws away 36 kg of plastic each year (PracticalAction, 2012). By 2020, waste generation will almost double if current practices do not change (WasteOnline, 2010). Plastic waste recycling, therefore, is promoted by regulations: according to EU Directive 2008/98/EC, by 2020, the preparation for reuse and recycling of plastic materials from households shall be increased to a minimum of 50% by weight (EU, 2008).

Dutch regulations on packaging waste and paper waste, which were issued in 2006 and took effect in 2008, specified the goal of recycling 42% of plastic packaging waste in 2012 (Cramer et al., 2007). To successfully achieve the target set by these regulations, a more sustainable and efficient way to handle the expected increased quantity of plastic waste is required. The growing market for recycled plastic as a result of high oil price also stimulates the recycling of plastic products (Bing et al., 2012). High oil prices lead to rising virgin polymer prices which makes the use of recycled materials in manufacturing more profitable (WRAP, 2007). Moreover, there are also social and technical issues which require an improvement of plastic waste collection and handling systems. Current waste treatment technology provides two options for the recycling of plastic waste; one option is to separate plastic waste from other waste at households (source-separation), the other option is to collect plastic together with other waste and to separate them later in a separation center (post-separation). For source-separation, a study conducted in the Netherlands indicates that householders' performance in treating plastic waste is related to how waste is handed in the reverse chain. If the waste is well handled throughout the chain, households are more willing to participate in waste recycling (Thoden van Velzen et al., 2012). For post-separation, separation facilities require a sufficient input of waste material in order to operate efficiently.

The recycling network should be able to meet the future demand of handling waste logistics in a more sustainable and efficient manner. This research investigates the recycling network by viewing plastic recycling as an application of reverse logistics (McLeod et al., 2008), illustrated by the case of the Dutch household plastic packaging waste recycling. The results of this research will also provide decision support to the relevant stakeholders for the evaluation of the two separation options: source-separation and post-separation.

Plastic waste from households consists mainly of plastics from packaging. Estimated plastic packaging waste (PPW) input of all Dutch municipalities of the year 2013 is used in a network optimization model. We optimize the costs of collection, transportation, and all treatments (cross-docking, separation, sorting and re-processing), as well as a cost factor for air emissions. Strategic collection, treatment and transportation alternatives are compared to give decision support for the redesign of the reverse logistics network of PPW in the Netherlands in the future.

Incorporating multimodality in the network design is the major strategy we adopt to improve the sustainability of the network. Currently, most waste transportation in the Netherlands is by truck. Trains are used between only a few cross-docking stations and final treatment facilities. Apart from trains, barges are also an alternative to transport plastic waste as the Netherlands has a developed inland waterway system (Bloemhof et al., 2011). Currently however, using barges to transport plastic waste is not common practice. We study the potential of multi-modal transportation by modeling a modality shift and quantifying the economic and environmental impacts on the network.

The remainder of this paper is structured as follows. Section 2 describes the theoretical framework and methodology with a review of related research. Section 3 provides a case description, an overview of the network, and scenarios for further analysis. Section 4 includes the mathematical formulation of the model, input data, and the assumptions for each scenario, as well as a description of the modeling tool used to solve the model. Section 5 includes both the modeling results and a discussion thereof. Section 6 presents a sensitivity analysis of the model. The paper ends with some research implications in Section 7 and the conclusions and recommendations for future research in Section 8.

6.2 Motivation and Scientific Relevance

Reverse supply chain management is a growing research area in supply chain management (Grant, 2012). In comparison to forward supply chains, reverse supply chains are, in general, more supply driven (push) rather than demand driven (pull). Time related issues (i.e. order lead times, time to market) are not as crucial as in forward supply chains. In reverse supply chains, research focuses on multiple stakeholders, supply uncertainty, returns deposition decisions, facility locations, etc. (Srivastava, 2007). Nagurney and Toyasaki (2005) develop an integrated framework for electronic waste that focuses on multiple tiers of decision-makers (stakeholders) to achieve network equilibrium. Listes and Dekker (2005) address the uncertainty issue in the reverse supply chain for sand from demolition waste. They identified that in their problem context, the amount and quality of the returned flows are uncertain, because recycling channel choice is dependent on the initial quality mix of waste which is unknown. Min et al. (2006) addressed the problem of determining the number and location of reverse consolidation points where returned products from retailers or end-customers were collected, sorted, and consolidated into large shipments destined for repair facilities. In our case, we have a fixed existing network with a certain quality level of plastic waste generated in municipalities. The issue we focus on is sustainability, which is a new angle from which address the reverse supply chain network design problem (Srivastava, 2007). In reverse supply chains time pressures are less important, which enables the consolidation of waste products at intermediate stages of the supply chain. This gives opportunities for new multi-modal transportation strategies to improve the sustainability of our reverse supply chain.

Sustainable transport can be achieved by switching from uni-modal to multimodal transport (Buchari, 2009). According to the United Nations Economic Commission, the main features of multimodal transport are: the carriage of goods by two or more modes of transport within a single transport chain, under one contract, one document and one responsible party (UNECE, 2002). Some business cases in industry show the environmental benefit for using multimodal transport. For example, logistics company DB Schenker reports that integrating rail with road transport achieves CO_2 reductions of up to 75% compared to pure road transport (DBSchenker, 2008). Dutch beer company Heineken also reports a yearly CO_2 reduction of 30% after a modal shift from road to water on the connection to the port of Rotterdam (Anonymous, 2011).

In literature on multimodal transportation, quantitative research has focuses on issues related to the coordination of operations between parties in a supply chain. Moccia et al. (2011) describe a multimodal transportation problem combining several features, such as timetables, flexible-time transportation, and consolidation options, based on a case study of a freight forwarder service in Italy. Puettmann and Stadtler (2010) analyse the impact of stochastic demand on the coordinated plans of independent service providers in a multimodal transportation chain. Some qualitative research on multimodal transportation identifies four initial driving forces for multimodal logistics: economic globalization, speed-to-market product delivery, agile manufacturing and business practices, and integrated supply chain management (Rondinelli et al., 1998). With these driving forces, multimodal transportation has been promoted and infrastructure has been built rapidly in Europe over the last decade. The port of Rotterdam in the Netherlands, for example, combines multimodal transportation and logistics service centers to connect maritime shipping facilities with truck, barge, and rail. Stimulated by these driving forces and the development of infrastructure, multi-modality has also been considered for application to reverse logistics. In the literature, an early attempt to make the link between multi-modality and reverse logistics was made by Hirsch et al. (1998), who developed an environmental impact assessment tool for the logistics simulation of recycling networks, in which multimodal transport alternatives have been included.

Waste recycling logistics is a special category in reverse logistics. McLeod and Cherrett (2011) discuss a sustainable waste recycling problem in the context of reverse logistics. They identified the difference between reverse logistics of waste and that of other return goods, which is the channel structure. Often intermediate points exist in the reverse supply chain for the consolidation of waste which could be at regional distribution centers, transfer stations, or other locations, before transportation to the final disposal site. Our network structure is influenced by a particular feature of plastic waste, which is a mix of many types of plastic material. These types of plastic need to be separated and sent to various channels for appropriate treatment. For an intermediate facility in the network, the inbound flow of plastic waste will turn to a few outbound flows of separated waste to different facilities. Because of the co-existence of two separation methods, there are also two channels in the network that share some intermediate facilities. McLeod and Cherrett (2011) also stated that waste management processes may be improved through the use of innovative ideas in reverse logistics. Bouzembrak et al. (2010) design a sustainable multimodal supply chain for recycling waterway sediments based on a case of the French waterway system. CO_2 equivalent costs are considered along with the transportation costs of the various modes in the network, processing cost of sediments and the handling costs of the depots. This combination of CO2 cost and inter-modality is stated to be innovative in supply chain design.

In our network design, we include the costs of collection, transportation, intermediate transfer and all processing and treatment. Most importantly, the environmental costs of transport modes are also considered. Aramyan et al. (2011) consider the cost of emissions in the design of the supply chain network of the European pork sector to achieve sustainability. They optimize the network for three objectives separately: minimizing cost excluding the cost of emission, minimizing emission only, and minimizing cost including the cost of emissions. The results show that minimizing emissions without consideration of costs gives an unrealistic network result. Taking into account emission costs in the total cost gives a more balanced network design result. Therefore, in our research, a cost of CO_2 equivalents is calculated by multiplying emission quantity by a carbon tax, which is then added to the total cost to be optimized.

Mixed Integer Linear Programming (MILP) is used as a general mathematical optimization framework and has the advantage that it allows a "global perspective" on all the constraints (Jain and Grossmann, 2001). MILP method is used for the network optimization as this method allows computational analysis on different supply chain scenarios (Huang et al., 2012). MILP is also the most common modeling technique for green supply chain network design problem formulation (Srivastava, 2007).

6.3 System description and research approach

Case description

This research studies the Dutch household waste collection network. Two separation methods exist in the Netherlands: source-separation and post-separation (see Figure 6.2). With source-separation, separating plastics from other waste occurs in the household, while with post-separation this occurs later in separation centers, after the combined collection of plastic waste and other household waste. The two collection systems differ in channel choice and facility requirements. Currently, both source-separation and post-separation systems exist in the Netherlands with source-separation dominating (88% of municipalities) as this is preferred by regulation (Bing et al., 2012). There is a trade-off between source-separation and post-separation. In general, source-separation prevents contamination of plastic waste by separating it from other waste at the source. Less non-plastic is found in the plastic waste from source-separation than in the plastic waste from post-separation. This reduces the need for cleaning and drying plastic waste before further treatments. Post-separation normally has a higher separation rate than source-separation, as the efficiency of separating plastic from other waste is decided by machines instead of householders. Furthermore, post-separation requires fewer infrastructures (bins, trucks, etc.) for collection in the municipalities, as all the waste is combined in the same bin. From a reverse network design angle, we compare these two options to show their differences in transportation efficiency and air emissions when adopting multi-modality, using the estimated quantity inputs for 2013.

The system boundary of the reverse network is from the municipalities in the Netherlands to the re-processors of recycled plastic materials within Europe. Household plastic packaging waste does not include plastics from industry or PET bottles, which go through a different recycling channel by recycling machines in supermarkets. Plastic waste can influence the density and quantity of the remaining waste . In post-separation, plastic waste is mixed with other waste during transport for some parts of the network. Therefore, besides plastic waste, we also include the transportation of other waste in this research. The parties in this reverse chain are:

Municipalities: Waste is collected from households within municipalities, so all municipalities in the Netherlands (418) are included as the source of the waste in the reverse chain, or in other words, the suppliers in the network. In this paper, collection rounds conducted within municipalities are not modelled, but costs for the collection are provided by KCN and we use those as input for our model. Each municipality constitutes a source node in the network, which generates waste that goes through the system.

Cross-docking centers/separation centers: Depending on which separation method is chosen, waste collected from municipalities goes to different centers. For source-separation, plastic waste goes to cross-docking centers where it is baled up and transferred for further transportation. Other waste goes directly from municipalities to incineration centers. For post-separation, waste goes to separation centers where plastic waste is separated from other waste, before further transport.

Sorting centers: After cross-docking centers and separation centers, plastic waste goes to sorting centers to be sorted for each plastic type. After the plastics are sorted, contamination and plastics falsely sorted (due to inefficiencies of sorting machines) are dealt with through special facilities. Incineration centers: Other waste from source-separation municipalities and separation centers (remaining waste after plastic waste is separated) goes to incineration centers for energy recovery. The remaining waste goes to incineration centers. This includes plastic which is not separated due to an inefficiency of the separation process.

Re-processors: After sorting, plastic types are transported to various re-processors for processing. These re-processors are usually specialized in processing one or several types of plastic. The waste flows through the network are categorized as follows:

- PET (Polyethylene terephthalate)
- PP (Polypropylene)
- PE (Polyethylene)
- Film
- Mix of hard plastic (MKS2)
- Other waste (remaining waste after separated collected waste is taken out)
- Non-plastic (impurities and contamination of plastic waste, falsely sorted plastic waste due to inefficiency of sorting machines)

The first 5 categories are the sorted plastic types to be used in further re-processing. “Other waste” is the remaining waste that cannot be separately collected for recycling; this waste will be incinerated. The quantity of this waste category depends on the collection method. Less plastic waste is separated from source-separation than post-separation; so, the amount of other waste from post-separation municipalities is lower than that from source-separation municipalities. “Non-plastic” is mingled with plastic waste even after separation. In the sorting procedure, plastics will be cut in flakes and washed. “Non-plastic” will be transferred to and disposed of in special treatment facilities. The network of the current system is described as in Figure 6.1.

In post-separation municipalities, plastic waste is collected mixed with other waste. This mix is called municipal solid residue waste (MSRW). MSRW goes to separation centers, where plastic waste is separated from other waste. Other waste is then sent to incineration centers, while plastic waste goes on to sorting centers. In separation centers, part of the film fraction of plastic waste is sorted out and sent to processors. Afterwards, plastic waste is sorted into the 5 types as mentioned earlier. Non-plastic is sorted out and disposed through specialized facilities. Each of the plastic types is then transferred to its specialized processors. Plastic waste from source-separation municipalities is not mixed with other waste. Therefore, after collection, plastic waste is transferred to cross-docking centers and other waste goes directly to incineration. Plastic waste, after cross-docking, is further transported to sorting centers where sorting procedures happen. Afterwards, all the plastics are sent to their specialized processors, as well as the non-plastic. Currently, trucks are the major transportation mode utilized throughout the network. However, MSRW from a few post-separation municipalities in Gelderland (east province) and from all the post-separation municipalities in Limburg (south province) are gathered at Apeldoorn and Maastricht and sent by train to a separation center in Wijster. Trucks are used to transport MRSW from the municipalities to Apeldoorn and Maastricht. From these two locations to Wijster, the train is used. There is no current existing barge transport in the network.

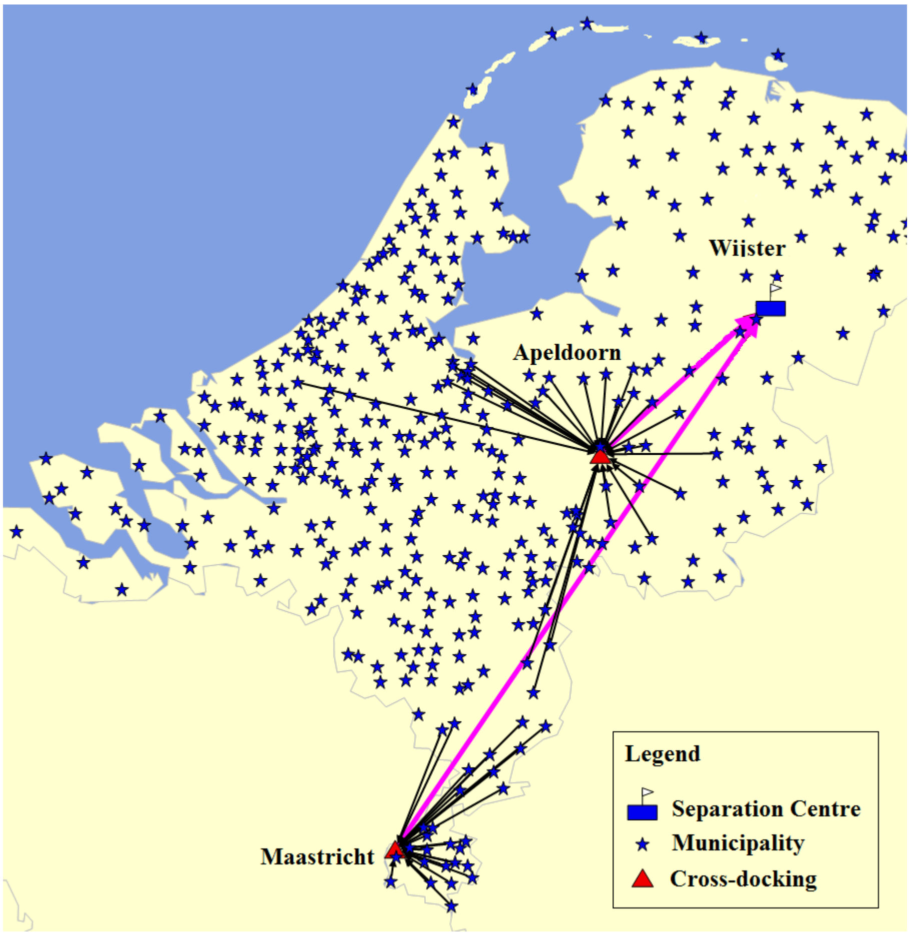


FIGURE 6.1: Existing train connections in the network

Scenario study

Our research follows a scenario study approach. Scenarios are based on the near future of 2013 when plastic quantity is expected to rise and the facility locations are fixed. The aim is to achieve future sustainability through multimodal transport of plastic waste.

Together with our industrial partners we defined the relevant scenarios for modeling and analysis as given below:

- Scenario 0 : Current network with estimated input for 2013 (benchmarking scenario)
- Scenario 1: Optimized network with estimated input for 2013 (baseline scenario)
- Scenario 2: Scenario 1, with multi-modality for source-separation channel
- Scenario 3: Scenario 1, with multi-modality for post-separation channel
- Scenario 4: Scenario 1, with multi-modality for both source-separation and post-separation channels

Scenario 0 is our benchmark scenario. This scenario is based on the current network with input of the recycled plastic quantity estimation for 2013. All flows are according to the current situation in practice, which means for all the connections between facilities, flows are fixed according to the real data (contracts made between parties). For example, a few municipalities have contracts with a separation center, so the MSRW from these municipalities will be shipped to this separation center. The flow is then fixed in the benchmarking scenario, regardless of whether or not this separation center is the closest. Scenario 1 is the baseline scenario, in which we relax the flow constraints (contracts) from Scenario 0, so that the model can optimize the network. The rest of the setting is the same. In these two scenarios, the current train connections to Wijster are not included in order to make a clear comparison between scenarios with and without multimodal options. This exception is investigated later in the sensitivity analysis section (Section 6). With the future trend of inland water transport possibilities, it is interesting to add the option to use barge for transportation if possible. In Scenario 2, barge and train transport modes are added for source-separation municipalities on the connections from cross-docking centers to sorting centers, and the connections from sorting centers to re-processors. Modalities for post-separations are kept the same as in the baseline scenario. In Scenario 3, barge and train options are added for post-separation municipalities on the connections from cross-docking centers to separation centers, from separation centers to sorting centers, and from sorting centers to re-processors. Modalities for source-separations are kept the same as in the baseline scenario. In Scenario 4, all the modality changes in scenarios 2 and 3 are combined and applied to the baseline scenario settings.

This scenario study approach includes building a quantitative model according to scenarios and comparing modeling results to provide decision support for making future changes to the plastic recycling network. We design these scenarios to investigate

- The potential of the network for further improvement by comparing scenarios 0 and 1.
- The difference between post-separation and source-separation when adopting multimodality by comparing scenarios 2 and 3.
- The impact of applying multimodality to the whole network by comparing scenarios 1 and 4.

For the benchmarking Scenario 0, we apply a comprehensive calculation method with the estimated input. We calculate all the collection, processing, transportation and emission costs of the network to be compared to our modeling results of other scenarios. For the rest of the scenarios, we use the same data and apply the method of mixed integer linear programming for the optimization of the network design. The purpose is to achieve a comprehensive optimized total cost of the network while taking into account emissions of various transportation modes. Modeling is conducted by the network optimization tool IBM LogicNet Plus 7.1.

Data
Municipalities (population, quantity of plastic waste, location): Statistics are collected from the Central Bureau of Statistics in the Netherlands. There were 418 municipalities in 2011, varying a lot in population (CBS, 2011). Quantity of PPW recycled is estimated for the year 2013. This estimation is based on the current collection data combined with the future trend. Estimation is conducted and results are provided by Kenniscentrum Nascheiding (KCN) (Thoden van Velzen et al., 2012). This collection cost estimation is based on the allowance municipalities get from government to cover the collection of waste. For source-separated plastic waste, the cost is 486.77 €/ton (Nedvang, 2012) and for MSRW, the cost is 72 €/ton (KPMG, 2010). *Processing facilities (function, location, availability, costs):* Nedvang (Dutch packaging waste recycling association) provided data on the locations, functions and costs of processing facilities. We have a cost input for each of cross-docking, separation, incineration, sorting, non-plastic disposal and re-processing. These are 25 €/ton, 350 €/ton, 88 €/ton, 135 €/ton, 88 €/ton, and 280 €/ton respectively (Thoden van Velzen et al., 2012). The cost for non-plastic disposal is the same as the incineration cost because the handling of other waste is usually through incineration in some special facilities.

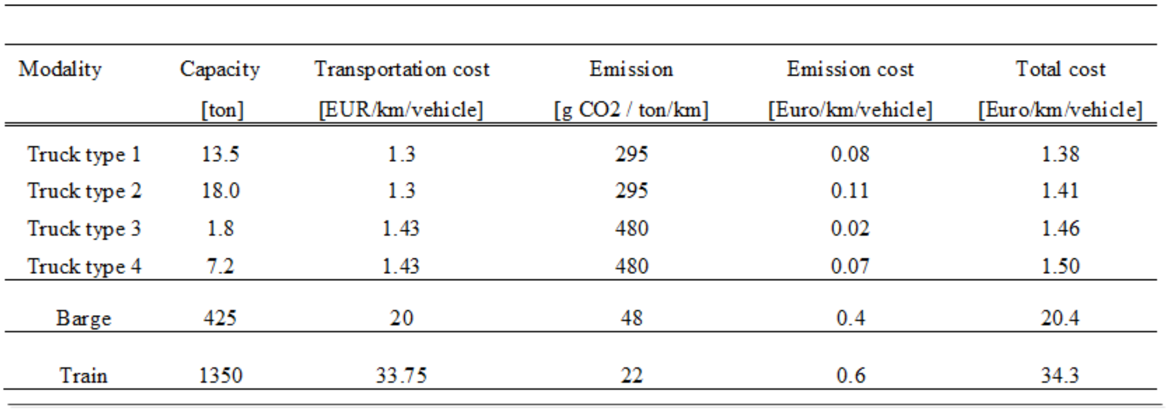
Current connections in scenario 0: The flow of plastic waste through the network is defined by the actual situation (contracts made between parties) in the baseline scenario.

The information on the flow details is provided by KCN.

Multimodal connections: In scenarios 2, 3, and 4, we add multimodal connections to the current situation. To estimate the potential to use other modalities than trucks between two facilities (e.g. between a cross-docking center and a sorting center), we first check, using Google Maps, whether there is a canal for barge transport or a train station within 3 km of the location. Then we make a decision on the modality possibility by comparing the connection information of the two facilities. If both facilities have a connection to the same modality, we consider it possible to transport by using this modality. Note that if both barge and train are possible, we always prefer barge, as it has a lower cost and less emission than train (Bloemhof et al., 2011). The sections of the network where we allow other modalities in scenarios 2, 3 and 4 are for the source-separation channel: from cross-docking centers to sorting centers and from sorting centers to re-processors. The section from municipalities to incineration centers is kept with only trucks. That is because the distance in this section is not long whereas the quantity of waste is large. Full truck load for short distance transport is common in this section. In post-separation channels, as an assumption, we allow a modality shift point on the section between municipality and separation center. Cross-docking centers function as the modality shift points. The sections in the post-separation channel, on which multimodality options can be used, are from cross-docking to separation centers, from separation centers to sorting centers and from sorting centers to re-processors.

Transportation and emission costs: For road transportation costs of waste, we refer to the NEA, a Dutch organization for transport research and training. These transportation costs of trucks include fixed cost, variable cost, labour cost and managerial cost (NEA, 2008). We use four types of trucks for the transport (see Table 6.1) and assign those to different routes (see Figure 6.2). Data is based on results from interviews of Dutch municipalities and waste collection companies, provided by KCN. Capacity of each truck type is set to be the average actual tonnage of truck in transporting the type of waste in each route. Average utility and waste density is considered in these figures. For inland waterway transport of freight in the Netherlands, a barge type called "Kempenaar" is often used. It has a capacity of about 425 ton of plastic and for its transportation cost, we refer to information given by BVB, the Dutch inland navigation bureau (BVB, 2012). From publications of the European Travel Commission, we got data on the costs of freight transport by train (ETC, 2008). Emission data for these alternative modalities is collected through the EVO, the Dutch transport organization of entrepreneurs. These data include the fuel efficiency and emissions for each modality (EVO, 2011). For the cost of transportation emission, we refer to the price of EU carbon allowances 2008 (Ellerman et al., 2010). All details are presented in Table 6.1.

TABLE 6.1: Cost details for all modalities used in the modeling



Modality	Capacity [ton]	Transportation cost [EUR/km/vehicle]	Emission [g CO2 / ton/km]	Emission cost [Euro/km/vehicle]	Total cost [Euro/km/vehicle]
Truck type 1	13.5	1.3	295	0.08	1.38
Truck type 2	18.0	1.3	295	0.11	1.41
Truck type 3	1.8	1.43	480	0.02	1.46
Truck type 4	7.2	1.43	480	0.07	1.50
Barge	425	20	48	0.4	20.4
Train	1350	33.75	22	0.6	34.3

6.4 Modeling

Scenario 0 is the benchmark scenario which represents the current network without optimization. By excluding the contract-related connection constraint in scenarios 1 to 4, we apply a MILP model for the network optimization. In the following sections, assumptions and modeling formulation of the baseline scenario (Scenario 1) will be presented, followed by adaptations for the model for scenarios 2 to 4.

Assumptions
Assumptions used in the baseline scenario are as follows:

- Flows are defined and described in the case description section (see Figure 6.2).
- There is no mechanical efficiency or cost difference between any two facilities of the same types.
- Cost input of the "nodes" in the network include (1) collection costs in municipalities (2) processing costs in separation centers, cross-docking centers, and sorting centers (3) incineration costs, non-plastic disposal costs and re-processing costs. Emission costs of these "nodes" are not included in the model, as multimodality does not influence the emission of these facilities.
- Trucks are the major modality used in this scenario (see Figure 6.2). Four types of truck are used. Capacity and cost details can be found in Table 6.1.

- The train connections in the current network are not considered in the benchmarking and baseline scenario. This is to better compare the results between scenarios with multimodality options and without.
- Total unit cost per kilometre per ton for each modality is calculated by adding transportation cost and emission cost, so $c = c_t + c_e$. In this calculation, we assume that carbon equivalent emission has a cost. In the model, we use $c_{ij} = c * d_{ij}$ as the cost per ton, where d_{ij} is the distance between node i and node j.
- The model optimizes only costs in the model, not yields, as yields depend on the market of recycled materials which is not within our research scope.

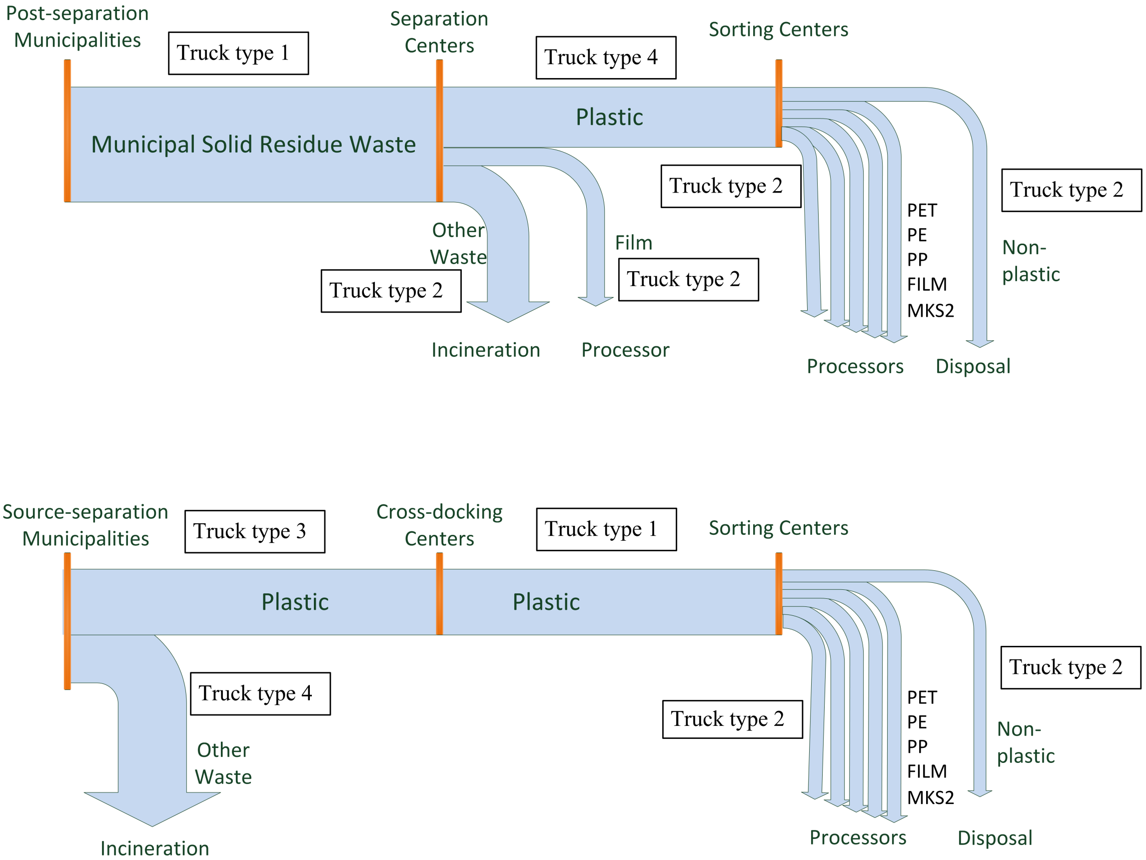


FIGURE 6.2: Modalities used in scenarios 0 and 1

Model formulation

The basic mathematical formulation of the MILP model for baseline Scenario 1 is presented in this section. The adaptions needed for other scenarios are presented in the next section.

Index sets used in the MILP problem are:

$i \in I$ set of sources (municipalities)

$j \in J$	set of warehouses (set of cross-docking sites$\{1, \cdots, j_0\}$; set of separation centers $\{j_0 + 1, \cdots, J\}$)
$k \in K$	set of sorting companies
$s \in S$	set of incineration centers
$l \in L$	set of re-processing centers
$m \in M$	set of destinations for non-plastic disposal
$p \in P$	set of products (PET, PP, PE, Film, mixed hard plastic, non0-plastic, other waste)
$v \in V$	set of modalities (truck types 1,2,3,4, barge and train)

Variables used in the MILP problem are:

$X_{ijpv} \in \mathbb{R}^+$	quantity of product p transported from municipality i to cross-docking center/separation center j using modality type v
$X_{ispv} \in \mathbb{R}^+$	quantity of product p transported from municipality i to incineration s using modality type v
$X_{jkpv} \in \mathbb{R}^+$	quantity of product p transported from cross-docking center/separation center j to sorting company k using modality type v
$X_{jspv} \in \mathbb{R}^+$	quantity of product p transported from separation center j to incineration center s using modality type v
$X_{jlpv} \in \mathbb{R}^+$	quantity of product p transported from separation center j to re-processing center l using modality type v
$X_{klpv} \in \mathbb{R}^+$	quantity of product p transported from sorting center k to re-processing center l using modality type v
$X_{kmpv} \in \mathbb{R}^+$	quantity of product p transported from sorting center k to non-plastic disposal m using modality type v

where $\mathbb{R}^+ = \{x \in \mathbb{R} : x \geq 0\}$.

Parameters used in the MILP problem are:

$$t_i = \begin{cases} 1, & \text{if source } i \text{ is doing source-separation} \\ 0, & \text{otherwise (post-separation)} \end{cases}$$

c_{ijv} transportation and environment costs for transporting one unit product p from

	municipality i to warehouse j when modality type v is used.
c_{isv}	transportation and environment costs for transporting one unit product p from municipality i to incineration s when modality type v is used.
c_{jkv}	transportation and environment costs for transporting one unit product p from cross-docking/separation center j to sorting company k. when modality type v is used
c_{jsv}	transportation and environment costs for transporting one unit product p from separation center j to incineration center s when modality type v is used.
c_{jlv}	transportation and environment costs for transporting one unit product p from separation center j to re-processor l when modality type v is used.
c_{klv}	transportation and environment costs for transporting one unit product p from sorting center k to reprocessor l when modality v is used.
c_{kmv}	transportation and environment costs for transporting one unit product p from sorting center k to non-plastic disposal m when modality type v is used.
C_i^p	cost of collection of all product p in municipality i
C_j^p	cost of handling one unit of product p in separation center/cross-docking center j
C_s^p	cost of handling one unit of product p in incineration center j
C_k^p	cost of handling one unit of product p in sorting center k
C_m^p	cost of handling one unit of product p in non-plastic treatment center m
C_l^p	cost of handling one unit of product p in re-processing center l
$q_i \in \mathbb{R}^+$	quantity of total products collected at municipality i,
d_{mp}	demand of product p by non-plastic disposal center m
d_{lp}	demand of product p by re-proccessor l
f_{ip}	proportion of product p in the total product collected at post-separation municipality i
f'_{ip}	proportion of product p in the total product collected at source-separation municipality i

The MILP problem is formulated as follows:

$$\text{Minimize} \sum_{i=1}^{I}\sum_{j=1}^{j_0}\sum_{p=1}^{P}\sum_{v=1}^{V} X_{ijpv}(c_{ijv}+C_j^v)t_i + \sum_{i=1}^{I}\sum_{j=j_0+1}^{J}\sum_{p=1}^{P}\sum_{v=1}^{V} X_{ijpv}(c_{ijv}+c_j^p)(1-t_i)$$

$$+\sum_{i=1}^{I}\sum_{s=1}^{S}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{ispv}(c_{isv}+c_{s}^{p})t_i+\sum_{j=j_0+1}^{J}\sum_{s=1}^{S}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{jspv}(c_{jsv}+C_{s}^{p})(1-t_i)$$
$$+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}sum_{v=1}^{V}X_{jkpv}(c_{jkp}+c_{k}^{p})+\sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{p=1}\sum_{v=1}^{V}X_{jlpv}(c_{jlv}+c_{l}^{p})+\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{klpv}(c_{klv}+c_{l}^{p})+$$
$$\sum_{l=1}^{K}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{kmpv}(c_{kmv}+c_{m}^{p})+\sum_{p=1}^{P}\sum_{i=1}^{I}c_{i}^{p} \tag{6.1}$$

Subject to:

$$\sum_{j=1}^{j_0}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{ijpv}+\sum_{s=1}^{S}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{ispv}t_i+\sum_{j=j_0+1}^{J}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{ijpv}(1-t_i)=q_i \qquad \forall i\in I \tag{6.2}$$

$$\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{ijpv}t_i=\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{jkpv} \qquad \forall j\in 1,...,j_0 \tag{6.3}$$

$$q_i f_{ip} t_i+q_i f'_{ip}(1-t_i)=\sum_{j=1}^{j_0}\sum_{v=1}^{V}X_{ijpv}t_i+\sum_{j=1}^{j_0+1}\sum_{v=1}^{V}X_{ijpv}(1-t_i)+\sum_{s=1}^{S}\sum_{v=1}^{V}X_{ipv}t_i \qquad \forall i\in I,p\in P \tag{6.4}$$

$$\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{ijpv}(1-t_i)=\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{jkpv}+\sum_{s=1}^{S}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{jspv}+\sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{jlpv} \qquad \forall j\in j_0+1,...,J \tag{6.5}$$

$$\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{jkpv}=\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{jkpv}=\sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{klpv}+\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{v=1}^{V}X_{kmpv} \qquad \forall k\in K \tag{6.6}$$

$$\sum_{k=1}^{K}\sum_{v=1}^{V}X_{klpv}+\sum_{j=1}^{J}\sum_{v=1}^{V}X_{jlpv}=d_{lp} \qquad \forall l\in L,p\in P \tag{6.7}$$

$$\sum_{k=1}^{K}\sum_{v=1}^{V}X_{kmpv}=d_{mp} \qquad \forall m\in M,p\in P \tag{6.8}$$

$$X_{ijpv},X_{jkpv},X_{ispv},X_{jspv},X_{klpv},X_{klpv},X_{kmpv}\in\mathbb{R}^{+}. \tag{6.9}$$

Constraints (6.2) specify that the total amount transported from a municipality equals the total supply. Constraints (6.3) make sure that the waste is transported out of the source municipalities in the fixed proportion as generated in municipalities, in other words, no separation happens before the products arrive at warehouse j. Constraints (6.4) balance inflow and outflow in a cross-docking site. Constraints (6.5) balance inflow and outflow in a separation center. Constraints (6.6) balance inflow and outflow in a sorting company. Constraints (6.7) specify that the total amount of all products transported to a re-processing plant should satisfy its demand. Constraints (6.8) specify that the total amount of all products transported to a non-plastic disposal destination should satisfy its demand. Constraints (6.9) are regular non-negativity constraints.

Model adaption for scenarios Scenarios 2, 3 and 4 are modeled in a similar manner, but, there are some different underlying assumptions.

- Multimodality is used in source-separation flow in scenario 2 and in post-separation flow in scenario 3. Scenario 4 uses multimodality in the flows of both source-separation and post-separation (Figure 6.3).
- Multimodality connections are selected following the method described in the data section.
- For post-separation flows, cross-docking center locations (with train connection possibilities to separation centers) are added to the flow between municipalities and separation centers to serve as a modality shift point.
- The fixed exceptional train route in scenario 1 is not considered in these scenarios. We let the model optimize the routes and the modality choices.

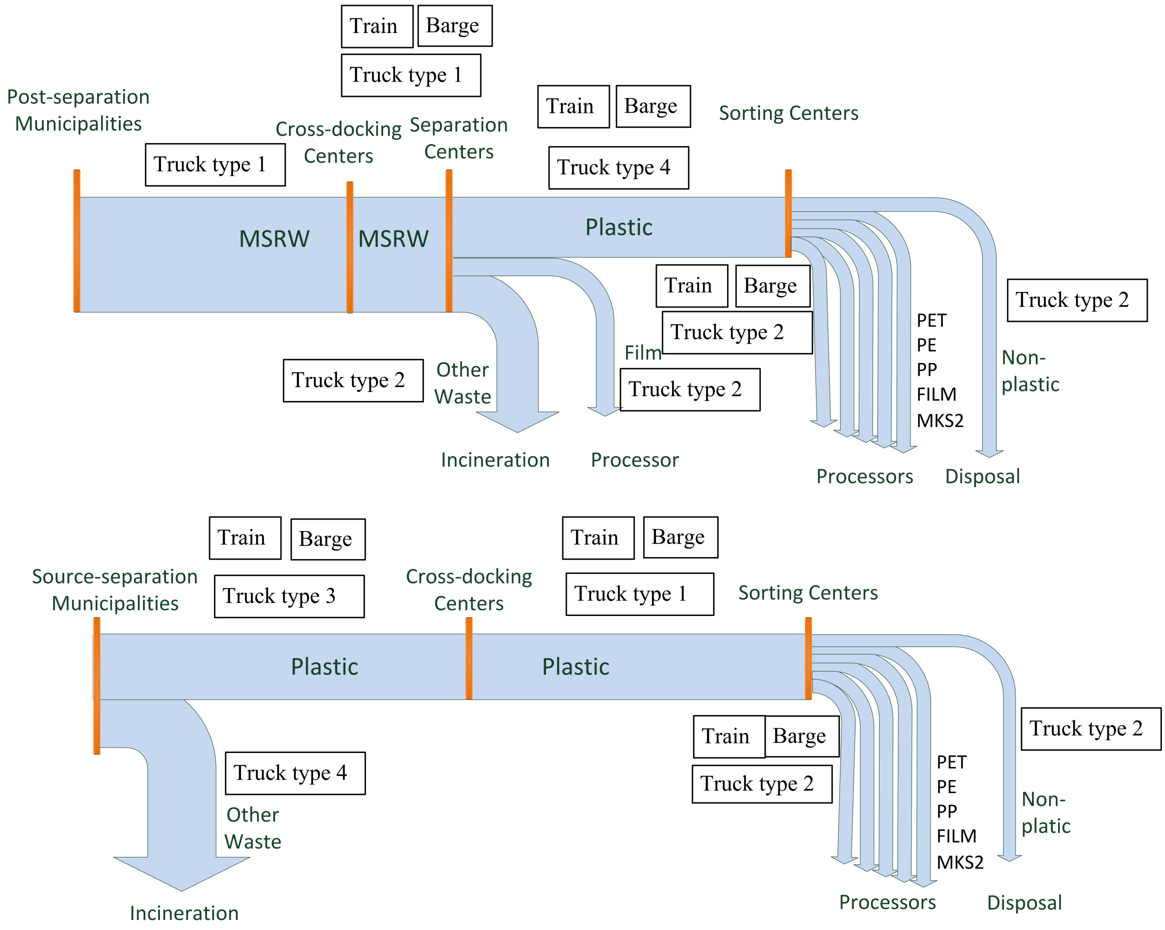


FIGURE 6.3: Modalities used in scenario 4

6.5 Results and Discussion

Using the estimated waste quantity of 2013 as an input, the results of the benchmark scenario show that transportation costs (including emission) contribute to about 6.6% of the total cost in the network. That is 50 million Euro in the total cost of 767 million Euro. By relaxing the constraints on the connections given by contracts, in the baseline scenario, optimization results show a reduction of approximately 17.5% of total transportation and emission costs. Total emission figures also show the same reduction. This result indicates that the current network for plastic recycling has a potential to be further optimized by changing some of the current connections between facilities. This change can be achieved by a better selection of partners in the network, although other factors besides transportation also decide how partners are selected.

Table 6.2: Results of all scenarios

	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Summary Results					
Total Costs (million €)	767.14	758.29	756.96	750.71	750.11
Transportation Costs (million €)	48.11	39.68	38.48	32.51	31.98
Emission Costs (million €)	2.39	1.97	1.84	1.56	1.49
Transportation and Emission Costs (million €)	50.49	41.65	40.32	34.07	33.47
CO2 emission (ton CO_2 eq)	119,319	98,251	92,149	77,868	74,568
Transportation and Emission costs					
% of total cost	6.58%	5.49%	5.33%	4.54%	4.46%
Reduction compared to Scenario 0	0.0%	-17.5%	-20.1%	-32.5%	-33.7%
Reduction compared to Scenario 1	-	0.0%	-3.2%	-18.2%	-19.6%

A multimodality strategy results in a decline of transportation and emission costs from 3% up to almost 20%. Comparing scenarios 2 and 3, it is obvious that the post-separation channel benefits more from multimodality options than does the source-separation channel. The realized cost saving in scenario 2 is 3.2%, while in scenario 3 it is 18%. Even though there are fewer post-separation municipalities, meaning less total waste in the post-separation channel of the network, adding multimodality options gives almost 6 times the cost savings in comparison with the source-separation channel. This difference results from the transportation of MSRW in the network. MSRW is large in quantity and the MSRW from post-separation channels needs to be transported from municipalities to separation centers to get plastic waste separated. This section of transport in the network has long distances (as separation centers are all in the north) and cross-docking centers can be used between municipalities and separation centers to function as modality shift points. Therefore, in the modeling result, the optimized solution shows that MSRW in the post-separation channel consolidates at a cross-docking center and switches to a train to be transported further north to the separation center. In case of source-separation, other waste is already separated from plastic waste in the municipalities. Although still in large quantity, other waste is directly transported to incineration centers from municipalities. In this section, there is no multimodality option in our model as there is no modal shift point between municipalities and incineration centers. All transportation in this section for other waste is by truck.

In scenario 1, only the four types of truck are used, while in scenario 4, barge and train options are added to both source-separation channel and post-separation channel. Figure 6.4 shows the quantity of waste that shifts to train and barge on each of the connections. In the connections where we allow train and barge options, modeling results show that at least about 50% percent of the waste is transported by train and barge. In the section from separation center to sorting center, no truck is used. In the total network, about 5% of all the waste transport (including other waste) shifts to train and 6.6% to barge.

The results depend on the assumptions we made in modeling. To decide whether it is possible to use a barge on a certain connection, we check for a canal near departure point and destination point. However, to facilitate barge transport, an inland waterway terminal has to be in place. There are also various handling costs involved. These costs are not included in the model. There is also no mechanical efficiency difference between facilities in the model of the same type. However, in reality, different efficiencies might occur depending on machine types and input waste quality. For example, sorting centers differ in sorting efficiency which decides what percentage of plastics can be sorted out and how much non-plastic waste is disposed of. With the same quantity of inbound flow, the outbound flow might differ between sorting centers. The efficiency difference could have an impact on the network and total cost. To validate some of the modeling assumptions, sensitivity analysis is conducted.

6.6 Sensitivity Analysis

Analysis on assumptions As always in modeling studies, the results depend on the assumptions that are made in modeling the system. Although our business partners have validated all assumptions made, there are still some aspects disputable. For example, in scenario 3, we use cross-docking centers between municipalities and separation centers as modality shift points for barge and train. To test this assumption, we compare the

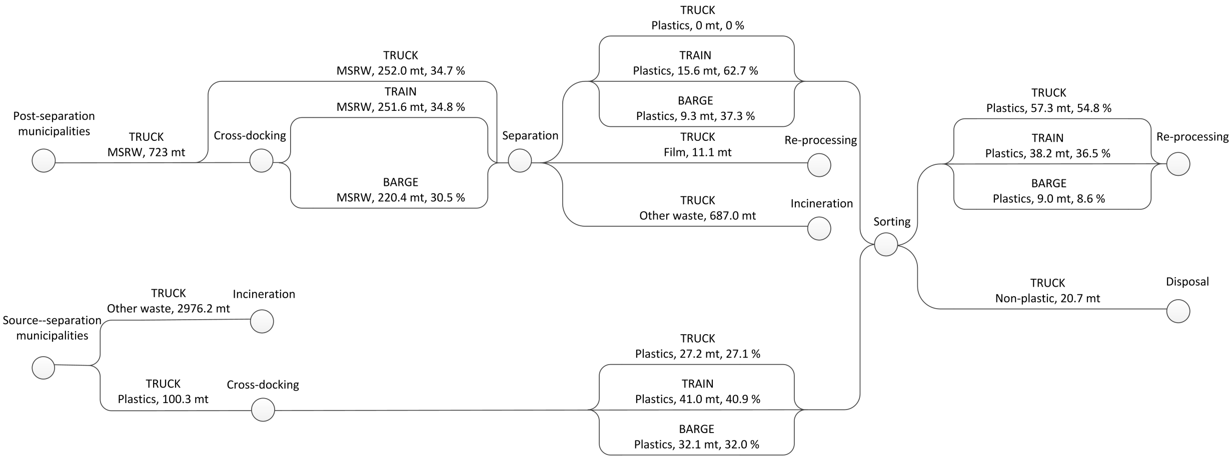


FIGURE 6.4: Modalities used and waste quantity of the network in optimization results of scenario 4

results of not using cross-docking centers for the post-separation channel to that with cross-docking centers. The results are shown in Table 6.3. When cross-docking functions in scenario 3 are not allowed, transportation from municipalities to separation centers can only be conducted by truck. The difference in total cost is 6.2 million Euro. Allowing cross-docking saves about 16,000 ton of CO_2eq.

TABLE 6.3: Sensitivity analysis on the availability of cross-docking centers in Scenario 3

	Scenario 3	No Cross-docking
Total costs (million Euro)	750.7	756.9
Transportation and emission costs (million Euro)	34.1	40.3
Transportation and emission costs in total costs	4.54%	4.46%
Emission (ton CO_2 eq)	77,868	93,936

We excluded any train connection of waste transport in our baseline scenario to compare scenarios without and with multimodality. In the sensitivity analysis, we include the one existing train connection from Maastricht and Apeldoorn to Wijster. As shown in Table 6.4, this modified scenario leads to a reduction of total cost by almost 5 million Euro. The CO2 equivalent reduction is 13 ton. This result indicates that using this existing train transport of waste from Maastricht and Apeldoorn to Wijster leads to a significant savings of total emission by 12,611 ton. The savings result from the long distance of this connection from the south of the Netherlands to the north (see map in Figure 6.1). The quantity of waste in this connection is also large, as it is MSRW. This result supports our strategy of applying multimodality in the network design.

Table 6.4: Sensitivity analysis on current train connection in Scenario 1

	Scenario 1	with train connection
Total Costs (million €)	758.29	753.45
Transportation and Emission Costs (million €)	41.65	36.80
% of Transportation and Emission Costs in total costs	5.49%	5.33%
Emission (ton CO_2 equivalent)	98,251	85,640

As plastic is a light material, the utility rate of trucks for plastic waste is usually lower than for other types of waste. We took this into account when assigning truck type and capacity to each connection. However, for barge and train, we do not have such data. In the model, we set the utility rate to 100%. In reality, it can be lower which is why we tested in scenario 4 barge and train with lower utility rates. The results can be found in Figure 6.5. A rise of cost as a result of reduced utility rate is observed. The increased cost comes from the modality shift back to trucks. If the utility rate for both train and barge is set at 10%, the cost is the same as in baseline scenario, which means no barge or train is used (see Figure 6.5). Comparing the results of changing utility rate of the train and changing the utility rate of barge only, it is obvious that the cost is more sensitive to the utility rate changes to the train than to the barge.

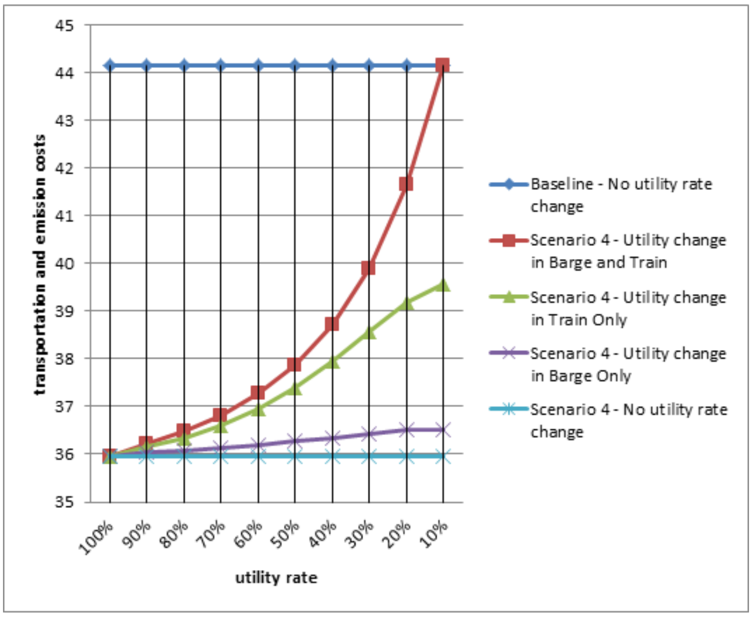
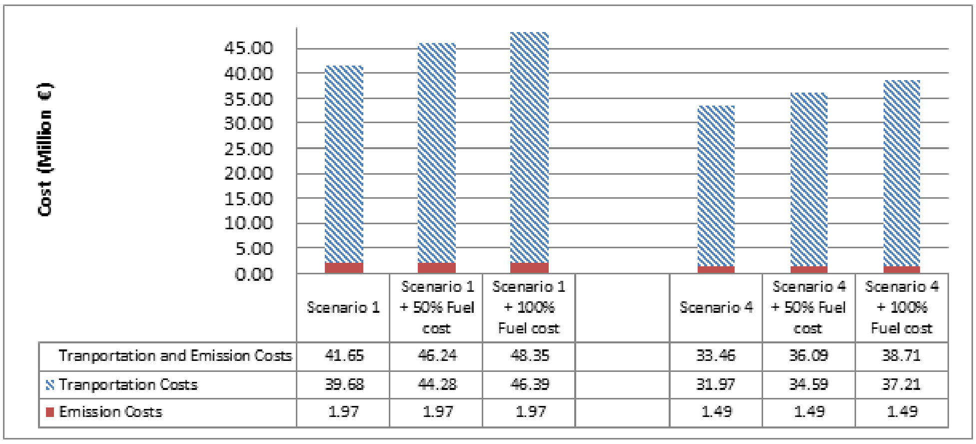


Figure 6.5: Sensitivity analysis on reduced utility rate of train and barge in Scenario 4

Analysis on input parameters The cost of each modality is the input parameter that influences the total transportation cost of the network. Among all the components of the total unit cost of each modality type, the cost of diesel is a key component. With a rising trend of energy price, the impact of diesel price on the total unit cost of each modality type differs. Therefore, a sensitivity analysis is conducted on diesel cost. Table 6.5 shows the contribution of diesel price in the total unit cost of each modality. In the total unit cost, fuel cost contributes to 15.4% and 17% for trucks. The percentage for barges is larger (40%). Trains in the Netherlands all run on electricity, so we assume the diesel price does not influence the total unit cost of trains.

TABLE 6.5: Cost calculations on fuel cost (Euro/km/vehicle)

Modality	Transport	% Fuel	Fuel	Fuel (+50%)	Fuel (+100%)	Emission	Total (+50%)	Total (+100%)
Truck type 1	€ 1.30	15.4%	€ 0.20	€ 0.30	€ 0.40	€ 0.08	€ 1.48	€ 1.58
Truck type 2	€ 1.30	15.4%	€ 0.20	€ 0.30	€ 0.40	€ 0.11	€ 1.51	€ 1.61
Truck type 3	€ 1.43	17.0%	€ 0.24	€ 0.36	€ 0.49	€ 0.02	€ 1.57	€ 1.69
Truck type 4	€ 1.43	17.0%	€ 0.24	€ 0.36	€ 0.49	€ 0.07	€ 1.62	€ 1.74
Barge	€ 20.00	40.0%	€ 8.00	€ 12.00	€ 16.00	€ 0.41	€ 24.41	€ 28.41
Train	€ 33.75	0.0%	€ -	€ -	€ -	€ 0.59	€ 34.34	€ 34.34



	Scenario 1	Scenario 1 + 50% Fuel cost	Scenario 1 + 100% Fuel cost		Scenario 4	Scenario 4 + 50% Fuel cost	Scenario 4 + 100% Fuel cost
Tranportation and Emission Costs	41.65	46.24	48.35		33.46	36.09	38.71
▨ Tranportation Costs	39.68	44.28	46.39		31.97	34.59	37.21
■ Emission Costs	1.97	1.97	1.97		1.49	1.49	1.49

FIGURE 6.6: Result of sensitivity analysis on increased fuel costs

We examine scenarios 1 and 4 with a rise in diesel prices of both 50 % and 100 %. The details of the cost calculations are presented in Table 6.5 and results are shown in Figure 6.6. Both scenarios have an increase in transportation and emission costs. Scenario 4 has a smaller increase in costs than Scenario 1. With 50% and 100% higher diesel costs, Scenario 4 is still around 20% cheaper than Scenario 1. This result indicates that the network with multi-modality options is less sensitive to fuel price rises, which demonstrates an advantage of this strategy.

Emission cost is another important parameter in our model. The cost of emissions is set to be 20 Euro per ton. The methods used to calculate the cost of carbon equivalent emissions, however, varies a lot (Lumbreras et al., 2008). There is also a possibility that the emission costs will rise in the future with increasing concern for the environment. It is then interesting to test the model with other emission costs. These results are presented in Table 6.6. It is obvious that the costs are not much influenced by the changes in emission costs tested, even though we tested with a cost that is up to 8 times of the original figure. This result indicates that emission costs, which are a very small portion of transportation cost, have a very limited impact on the total cost. Comparing the uni-modal scenario (Scenario 1) and the multi-modal one (Scenario 4), there is one difference that is worth noting. The emission level starts to change the transportation routes of the optimized solution in Scenario 1 when we raise the emission cost to 120 Euro/ton, whereas in Scenario 4, the change happens immediately when emission cost is doubled. The difference in emission quantity results from a change in the optimized solution (selection of routes, facilities and modality). Optimization leads to a solution which has lower emissions, which is due to the rising emission cost. Although, the change in the optimized solution is very small, it shows that the multimodal scenario is more sensitive to emission cost changes than the uni-modal scenarios. Although the two channels share part of the intermediate facilities, optimization results show that the small changes in optimization results started in the earliest section of source separation channel from municipalities to cross-docking centers, before the split of plastic types and the merging of the two channels.

TABLE 6.6: Sensitivity analysis on emission cost

Scenario 1								
Cost per ton CO2-eq	**20€**	**40€**	**60€**	**80€**	**100€**	**120€**	**140€**	**160€**
CO2 emission (ton)	98,251	98,251	98,251	98,251	**98,251**	**98,249**	98,248	98,248
Costs (Million Euro)								
Transportation	39.68	39.68	39.68	39.68	39.65	39.64	39.64	39.63
Emission	1.97	3.93	5.90	7.86	9.83	11.79	13.75	15.72
sum	41.65	43.62	45.58	47.55	49.48	51.43	53.39	55.35

Scenario 4								
Cost per ton CO$_2$-eq	**20€**	**40€**	**60€**	**80€**	**100€**	**120€**	**140€**	**160€**
CO$_2$ emission (ton)	**74,568**	**74,566**	74,566	74,564	74,561	74,559	74,559	74,549
Costs (Million Euro)								
Transportation	31.97	31.96	31.96	31.95	31.95	31.94	31.94	31.94
Emission	1.49	2.98	4.47	5.97	7.46	8.95	10.44	11.93
sum	33.46	34.95	36.43	37.92	39.41	40.89	42.38	43.86

6.7 Research Implications

This research shows how transportation can be improved through an optimization of transportation routes, a change in partners and the use of a multi-modality strategy. In practice, as there are several European countries involved in the supply chain, the differences between neighboring countries can influence the route and modality choice significantly. Politically, differences in national regulations may not allow a trans-border shipment of plastic waste. Other cross-border restrictions related to the use of railways and waterways also exist. These issues are not included in the model, which is a limitation of our proposed method. However, quantifying the economic and environmental benefits can potentially influence a greater harmonization of such policies.

Another policy related implication concerns emission costs. Incentives such as carbon taxes usually function as a tool to promote sustainable transportation. The sensitivity analysis results show that in the multimodality case, effectiveness of such incentive can be higher than in the uni-modal one, although current emission costs are too low to have significant impact on the total costs throughout the network. In this special network structure, the rising emission cost starts to have its impact on the beginning section of the source-separation channel.

The research findings also deliver a positive message regarding how improvements in sustainable reverse logistics can help balance resources. In Europe, on one hand, there is over capacity in processing plants in countries like Germany and the Netherlands; on the other hand, in eastern European countries, the landfill rate is still very high (EEA, 2009). Our research shows the feasibility of a more sustainable and cost efficient way of transporting waste, especially over longer distances. This can potentially help to bridge the gap in recycling rates in Europe, leading to a general improvement in the performance of waste treatment. In fact, an incineration plant in Rotterdam is planning to process the waste shipped from Naples, Italy. The waste would have been sent to landfill in Italy, but is now going to be converted to energy. In this way, approximately 160 kg CO_2 emission per tonne of waste can be saved (van Gansewinkel Groep, 2012).

Plastics, as a light material, have low transportation efficiency. The sensitivity analysis on the utility rates gives some indication of the relationship between the density of the waste material and the optimal modality choice. Barges and trains lose their advantage if the utility rate is too low, which indicates that a certain level of compression is needed in order to transport plastic waste more efficiently. The extent to which the plastic material is compressed constrains the options of sustainable transportation modalities. Sustainable reverse logistics of plastic waste can also contribute to the marketing of the recycled material. Especially when fuel pricing is rising, multimodality has the advantage in cost and emission savings. Lower logistics costs, lower emissions and larger quantities would help to make the price and quality of the recycled plastic more competitive in the market. An effort to increase the sustainability of the reverse network, once acknowledged by consumers, would stimulate a higher participation rate and improved plastic waste recycling behavior.

Currently, the research results show that post-separation is more sensitive to the modality change, which means more cost and emission reductions can be achieved in the post-separation channel. This could partly compensate for the higher emissions in the processing procedure, in comparison to the source-separation channel. Moreover, triggered by more sustainable reverse logistics of plastic waste, the potential change in consumer participation and technology might also influence stakeholders in choosing between these two systems.

6.8 Conclusion and Further Research

Network design of household plastic waste has to enable more waste to be recycled in a sustainable way. This paper investigates the impact of multimodality to achieve sustainability. We conducted a scenario study and model the network with estimated waste quantity input of 2013. Scenarios had been designed based on the two current existing channels of plastic waste separation and handling in the Netherlands, namely source separation and post-separation. Multimodality options were added to each of these channels. We developed a MILP model and use a graphical optimization tool IBM LogicNet 7.1 to solve the model. In the optimization, we minimized total costs of collection, separation, cross-docking, sorting, re-processing, incineration, transportation, and emission.

The benchmark scenario represented the current situation of the network with the input of 2013. As all the connections and flows were fixed according to contracts, we compared the costs of this network to optimization results of other scenarios. The baseline scenario was an optimization of the network of the current situation. A reduction of up to 17% of total transportation and emission costs can be achieved by a better selection of partners in the network.

This research showed that in the reverse logistics context, a multi-modality strategy could also save costs in a more sustainable manner. The model quantified the advantage of using multi-modality transport in the reverse logistics of plastic waste. Applying multimodality to the network reduced total transportation and emission costs by almost 20%. The difference was even larger if we compare to the benchmarking scenario. In coping with future changes such as the rising fuel price, the multimodal scenarios showed smaller cost increase than the baseline scenario, assuming that diesel price does not influence the unit cost of trains. Higher emission rates have limited influence on the total costs. Still, multi-modal scenario was more sensitive to the emission cost change than the uni-modal scenario.

As a special feature, this reverse network of plastic waste has a combination of two channels, which are separate chains in the initial section, but share the remaining part of the chain. The post-separation channel is more sensitive to the modality change than source-separation. This can be explained by the relatively long distances from municipalities to separation centers. Therefore, the modality shift to barge or train, permitting larger quantities to be shipped with reduced emission and transport costs, is more beneficial. Also sensitivity analysis on existing train connections confirms this observation. The availability of cross-docking sites plays an important role in deciding what emission cost reductions can be achieved in the post-separation channel. Source-separation channel is more sensitive to the change of emission costs than post-separation channel, as small changes start in the beginning section of this channel when we raise the emission costs in multi-modality scenario. The difference in our modeling results between source-separation and post-separation can provide decision support for stake holders in making future choices between these two methods.

The utility of barges and trains has a large impact on the savings that can be achieved by a modality shift. Sensitivity analysis on the utility rate of these two modalities shows that when reducing the utility rate from 100% to 10%, there is a modality shift back to truck. The transportation and emission costs of train transport are more sensitive to utility changes than the transportation and emission costs of the barge. This research result sheds a light on how plastic, as a light weight material, can be handled in a more efficient way in multi-modal transportation.

The added value of the proposed MILP model can be found in including the emission cost in transportation costs, together with comprehensive collection, treatment, and processing costs. Combining the various modalities across network connections can improve the sustainability of the network. The research results have a wide range of implications in the political agenda, as well as social, arenas. The use of incentives such as a carbon tax to promote sustainable transport in a reverse logistics context can be more efficient in a multi-modal network in comparison to a uni-modal one. To achieve an overall improvement in sustainable performance, national policies should be further harmonized to facilitate trans-border shipments. For further research, it is interesting to include the possibility of potential treatment facilities in the network together with the options of multimodality. In our current network, “nodes” are fixed. For instance, the separation centers are only located in the north which leads to a long distance transport for municipalities from the south. If there can be potential facility locations in the future a location allocation problem can be combined with the current multimodal network optimization. In the network model, the collection within municipalities is not optimized. Although cost for collection is considered, the allowance given by government cannot show the detailed differences in transport and emission costs for collection within municipalities. It is interesting, for further research, to conduct a separate study on collection logistics inside municipalities to be integrated with this research for a more comprehensive and detailed network logistics and emission cost analysis.

Chapter 7

Global reverse supply chain redesign for household plastic waste under the Emission Trading Scheme

This chapter is based on the submitted journal article:
X. Bing, J.M. Bloemhof, A. Chaabane, J.G.A.J. van der Vorst (2014) “Global reverse supply chain redesign for household plastic waste under Emission Trading Scheme”,Submitted to Journal of Cleaner Production

In this chapter we answer Research Question 4:
What strategy can be used to redesign a global supply chain to improve the sustainable performance?

Abstract:

Waste can be treated as a resource that can be managed globally. A reverse network for waste recycling needs to process all the waste with minimum cost and environmental impact. As re-processing of waste is one of the major sources of pollution in the recycling processes, a mechanism is needed to control the emission impact in the re-processing as a key to facilitate the globalized reverse supply chain and avoid spreading pollutants overseas. Emission Trading Schemes (ETS) can function as policy instruments for controlling emissions. The ETS introduces a trade-off between the economic efficiency and the environmental impacts. ETS has been implemented in Europe and is developing rapidly in China too. The aim of the research is to redesign a reverse supply chain from a global angle based on a case study conducted on household plastic waste distributed from Europe to China. Emission trading restrictions are set on both Europe and China on the processing plants. A mixed-integer programming model is used in the network optimization to decide location re-allocation of intermediate processing plants under such restrictions. The objective is to maximize the total profit under ETS. Results give an insight to the feasibility of building a global reverse supply chain for household plastic waste recycling and demonstrate the impact of ETS on the network design. The results also provide decision support for increasing the synergy between the policy of global shipping of waste material and the demand of recycled material.

Keywords: sustainability, reverse logistics, emission trading scheme, global supply chain, plastic recycling

7.1 Introduction

Recycled plastic can be used in industrial manufacturing to partly replace virgin plastics. The basic raw materials for plastic are petroleum and/or natural gas. Common ‘second life’ applications for recycled plastic packaging materials include fleece clothing, pipes wheeled, bins, pallets, kerbstones, garden furniture, etc. Driven by the huge demand of recycled material in the manufacturing sector in the Far East, a lot of waste is exported to the Far East, even under strict restrictions of waste trading from both Europe and Far East countries. Due to the cost-saving of using recycled plastics in recycling instead of virgin material in manufacturing, China drives the global waste trade. 200,000 Tonnes of plastic waste from Europe are sent 8,000 Miles to China each year for recycling (Jackson and Bertényi, 2006). Besides the economic motive, a report in Guardian UK stated that this trade is also driven equally by EU legislation forcing local authorities and businesses to recycle more. Landfill charges are rising steeply, making it relatively cheaper to send waste abroad. After export, migrant labours in China are often employed to sort and recycle plastic (Vidal, 2004).

In recent years, an argument on whether exporting waste from Europe to be recycled partly in the Far East should be allowed has raised quite some public attention. On the one hand, from an ethical point of view, the social conditions in the Far East are not comparable to European standards thus European waste is treated by companies that hardly comply with European social standards and working security (ProEurope, 2009). On the other hand, due to the imbalance of trade between China and the European Union, the majority of container ships heading back to China are empty and they are producing CO_2 emissions whether or not they carry cargo. Waste can be shipped by using these empty containers. Furthermore, according to Pro-Europe[1], waste recycling should be operated in a free market and systems are free to choose whichever end market best suits their needs in terms of price and quality - whether European destinations or third countries- depending on material demand (Proeurope, 2009).

Essentially, the key to the dilemma is that the supply driven reverse supply chain has also a strong demand driven mechanism. The demand for plastics is higher in manufacturing countries such as China, because that is where most products are manufactured and thereafter imported to Europe. Recycled plastics flow from Europe to China already exist. With the global trade driven by the demand from the secondary material market, the waste becomes a resource that needs to be managed globally. To re-allocate re-processing facilities to be closer to serve the market can potentially bring benefit for these processing companies.

The re-allocation decision is not simply the strategic decision of the processing companies, but is also highly dependent on regulations. Currently, shipping of waste material is under very strict regulation control. For example, China Environmental Protection Control Standard for Imported Scrap Material- Plastic scrap for raw material (GB 16487.12-1996) has specified the imported plastic waste standard. The contamination level should be less or equal than 0.1%. A study conducted by Thoden van Velzen et al. (2013) reported the re-processing (final processing step) yield in the Netherlands ranges from 67% to 90% (depending on plastic types), meaning the plastic waste after sorting (the step before reprocessing) would have a contamination level between 10% and 33%. This is much higher than the import limitation. To reach the purity requirement for import, an extra step of cleaning process is needed. This cleaning process is part of the re-processing

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[1] PRO EUROPE s.p.r.l. (PACKAGING RECOVERY ORGANIZATION EUROPE), founded in 1995, is the umbrella organization for European packaging and packaging waste recovery and recycling schemes

of plastic waste. Therefore, it is almost impossible to transport waste before reprocessing to China. This makes it difficult to re-locate processing facilities globally. The regulation used in China is dated back to 1996, and in recent years, there are cases showing how scientific research can foster regulation improvement. After the WEEE Directive was implemented in 2003, research studies have been carried out to give input to a review of this directive. They helped the European Commission generate full understanding of implementation of the Directive, to analyze the impacts of policy options particularly the development and simplification of the Directive in line with the Communication on better regulation. Issues covered are the producer responsibility obligations, the management of WEEE and the impacts on innovation and competition. Based on their results, a recast of the directive has ended with the publication of a new WEEE directive in 2012. This case shows that regulations with good intention of sustainability might lead to unwanted results and scientific research can help with evaluating impacts and proposing proper changes to improve the regulations.

The environmental impact of processing is one of the major concerns in the recycling of plastic waste. To control the emission of processing, a tool that balances environmental impact and economic efficiency is needed for such a recycling network. EU Emission Trading Scheme (ETS) is the first and the biggest international system for trading greenhouse gas emission allowances. Following this trend, China has shown a strong interest of experimenting with carbon market trading. The significant financial potential for new global or regional carbon markets to emerge motivates China to establish its domestic carbon trading system in a timely fashion. The coming years will be an intensive period of experimenting with carbon trading schemes. In November 2011 the Chinese National Development and Reform Commission ordered seven cities and provinces to set up pilot carbon trading systems in seven regions all over the country. At the same time, there have been also various proposals for sector-based carbon trading schemes targeting energy-intensive industrial sectors. The goal is to have pilot carbon trading at a regional level by 2014 and at a national level by 2016. During the pilot phase, local governments can decide upon the means of capping and select capped sectors themselves (Han et al., 2010). In 2008, Tianjing Climate Exchange was established as a first trial platform to facilitate the emission trading. Therefore, we see an opportunity of using ETS as an instrument for facilitating a global recycling network redesign for household plastic waste recycling.

In this paper, we investigate the possibility for the global relocation of re-processing plants in the recycling of plastic waste, based on a case of household plastic waste distributed from the Netherlands to China. This research proposes to allow market incentives play a role in the supply chain. Instead of restricting the trade of waste, a controlled export with an extended responsibility can be applied to design a global reverse supply chain for household plastic waste recycling. Processing plants are allowed to be re-located continuing to operate with the same technology and quality standard. The emission trading scheme is used to balance the environmental and economic impacts of re-processing phase in both Europe and China.

In the following, Section 7.2 discusses the scientific relevance of the paper. Section 7.3 presents the study case and the scenarios to be modeled. Section 7.4 shows the model assumptions, the data and data sources, as well as the mathematical formulation of the model. Results are presented in Section 7.5. Section 7.6 discuss results of sensitivity analysis. This paper ends with conclusion and future research in Section 7.7.

7.2 Scientific Relevance

Viewing waste recycling themes as reverse logistics channels can improve the understanding of the reverse system (Jahre, 2012). Reverse logistics is the process of planning, implementation and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain directions for the purpose of recovering value and proper disposal (Fleischmann et al., 1997c). Reviews on the reverse logistics network highlight the key aspects of reverse logistics network design, which are driving forces, type of returned products, processes involved, and actor strategies (Brito et al., 2005). The structure of the reverse logistics network is very much dependent on the type of returned product and the type of re-processing involved, thus can hardly be the same (Dekker, 2004). Plastic waste reverse logistics is initially driven by legislations regarding waste recycling. Market drivers have increasing impact on the reverse supply chain of plastic waste by diverting the flows towards the end market. Processes involved have also an impact on the network structure and product flow. A shared feature of reverse network is the convergent structure of the network from many sources to a few demand points (Ginter and Starling, 1978). The structure of the plastic reverse network is a convergent multi-echelon network, as processes including cross-docking, separation, sorting and re-processing are involved. Because plastic waste consists of various plastic types which need to be separated during the flow and shipped to different destinations for reprocessing, it is also a multicommodity-based problem (Bing et al., 2012). Besides the processes, actors involved and their strategies are essential for determining the network configuration of a reverse supply chain (Fleischmann et al., 1997). Thus, for such a reverse logistics network with specific driving forces, products and processes, our study investigates from the reprocessor (as one of the actors in the chain) strategy angle. The focus is on the redesign of the network by re-locating re-processors as one of the actors in the supply chain.

Redesign of reverse supply chain for plastic waste through relocation of the re-processors is a strategy that is in line with the concept of postponement in supply chain management. Postponement refers to a concept in which supply chain activities are delayed until a demand is realized. Final processing activities are performed from central locations in the international supply chain to include customer and country specific characteristics in the finished product based on final manufacturing, frequently followed by direct shipment to retailers or customers (van Hoek, 2001). Research suggests that postponement can be used to deal with large demand variety and improve responsiveness while reducing transportation expenditures, and product obsolescence (Lee and Billington, 1997). Veiga (2013) discussed the postponement strategy in the reverse logistics context and stated that in reverse logistics channels, postponing transformation activities have a greater impact than postponing transfer activities. Re-processing is transformation activity in plastic reverse supply chain and transfer activities refer to transportation. To serve the demand of the market for recycled material, we propose to apply a postponement strategy by relocating re-processing, as the final process step of plastic recycling, to the a location closer to the market. The proposed postponement strategy helps to reduce the barriers of market access, which is identified by Fleischmann et al. (1997c) as one of the major barriers in reverse supply chains.

Nowadays, environmental issues become an important parameter in logistics network design. Research in green supply chain management introduces the carbon footprint (the weighted sum of greenhouse gas emissions and greenhouse gas removals of a process, a system of processes or a product system, expressed in CO_2 equivalents) as a common measurement for environmental impact. Carbon emission is mostly used as a measurement of sustainable performance of the supply chain, which is then used as an objective for the network optimization. For example, Sheu and Chen (2012) formulated a linear multi-objective model that optimizes the operations of forward and reverse logistics in a given green supply chain and show how sustainable practices can contribute to increased profit. Aramyan et al. (2011) consider the cost of emissions in the design of the supply chain network of the European pork sector to achieve sustainability and proves that taking into account emission costs in the total cost gives a more balanced network design result. In general, these studies have shown the impact of environmental measurement on the overall improvement of sustainable supply chain performance. However, the impact of sustainable network design objectives on supply chain actors towards achieving such overall improved sustainable performance is not explicitly explained. There is an increased need for cooperation among partnering companies in sustainable supply chain management (Seuring and Müller, 2008). Therefore our paper takes into account the re-processor strategies in sustainable supply chain design.

Some recent studies have been using carbon pricing and ETS in supply chain modeling. ETS is a carbon management strategy involving actors in the supply chain and having a direct impact on their behavior related to sustainable performance. Supply chain actors need to establish strategic approaches in response to the carbon pricing schemes. Chaabane et al. (2012) are among the first researchers to introduce the Emission Trading Scheme into the modelling of supply chain networks. They build a mixed-integer linear programming based framework for sustainable supply chain design and demonstrate that efficient carbon management strategies can help to achieve sustainability objectives in a cost-effective manner. Diabat and Simchi-Levi (2009) develop an optimization model for carbon-capped supply chains, meaning that a specific level of emissions may not be exceeded. A number of parameters are considered in the model such as the through-put of the distribution centers and the storage capacity of the distribution centers together with carbon cap with emission trading mechanism. Carbon emission is embedded in the raw material and also associated to the fixed through-put of the opening facilities. The facility opening decisions are modeled as a binary variable, while the through-put of the facilities is not included as a decision variable. Fahimnia et al. (2013) firstly introduced carbon pricing to a closed-loop supply chain design, in which emission quantity is associated with the production in facilities, while the emission trading and emission cap are not included. By introducing carbon pricing into the closed-loop supply chain, they investigated how governmental policies can promote decarbonization of supply chains through subsidies of carbon cost. In our model, we implement both emission cap and emission trading mechanism in the reverse supply chain network design. Also the production (processing of waste) quantity and the facility openings are both modelled as decision variables, thus the emission quantity is embedded also in the production process and related to the variable through-put of each facility.

We also aim to provide insights for the governmental policy improvement. The focus is not on carbon related policies as Fahimnia et al. (2014) did, but on trading regulations for better facilitating a global reverse supply chain. Kannegiesser and Günther(2014) proposed a optimization framework targeting at the industry-wide modeling of sustainable global supply chains. They concluded that policymakers will gain a better understanding of sustainability relationships, trade-offs between conflicting objectives like costs and emissions and insight for making effective regulations for industry transitions towards a global sustainable development. Apart from the aim of investigating impact of global supply chains on policy improvement, another motivation of studying the global supply chain is that sustainable supply chain studies require a holistic view. They have to take into account a wider range of issues and, therefore, look at a longer part of the supply chain (Seuring and Muller, 2008).

Many of the models developed consider usually a "greenfield" situation, where the supply chain network and operations is to be designed from scratch. However, considering the dynamic changes in environment and the increasing environmental concerns, new performance measurements and requirements for supply chain development call for re-evaluating the network structure periodically. For successful improvement of the existing supply chain performance to adapt to new requirements, continuous re-optimization is a necessity. Therefore, we conduct the redesign of the reverse supply chain towards the improvement direction of globalization and decarbonization, based on the existing reverse supply chains. The results are meant to provide insights for decision makers as actors in the supply chain as well as policy makers to improve the sustainable global supply chain performance.

7.3 Case and Scenario Description

We conduct this research based on the case of plastics collected from Dutch households. To collect plastic waste, two alternatives exist in Dutch municipalities. Householders can either separate plastic from other waste at home (source-separation) or put plastic with other municipal solid residual waste (recyclable such as paper and glass are excluded) to be collected (post-separation). This mix of plastic with other waste will be transferred to a separation center to separate plastic from the mix (Bing et al., 2014). Plastics from source-separation go through cross-docking center towards the next step of sorting, and the separated plastic from separation center also go to the sorting procedure. In sorting centers, plastics are sorted by specific types as follows. The sorted plastics go to the re-processors where they are made to the materials which can be used in the manufacturing (Bing et al., 2013).

- PET (Polyethylene Terephthalate) : Fizzy drink, water bottles and salad trays
- PP (Polypropylene) : Margarine tubs, microwaveable meal trays, fibres and filaments for carpets and wall coverings, etc.
- PE (Polyethylene) : Milk bottles, bleach, cleaners and most shampoo bottles
- Film : Carrier bags, bin liners and packaging films
- Mix of hard plastic : pallets, crates, collection containers, marker posts

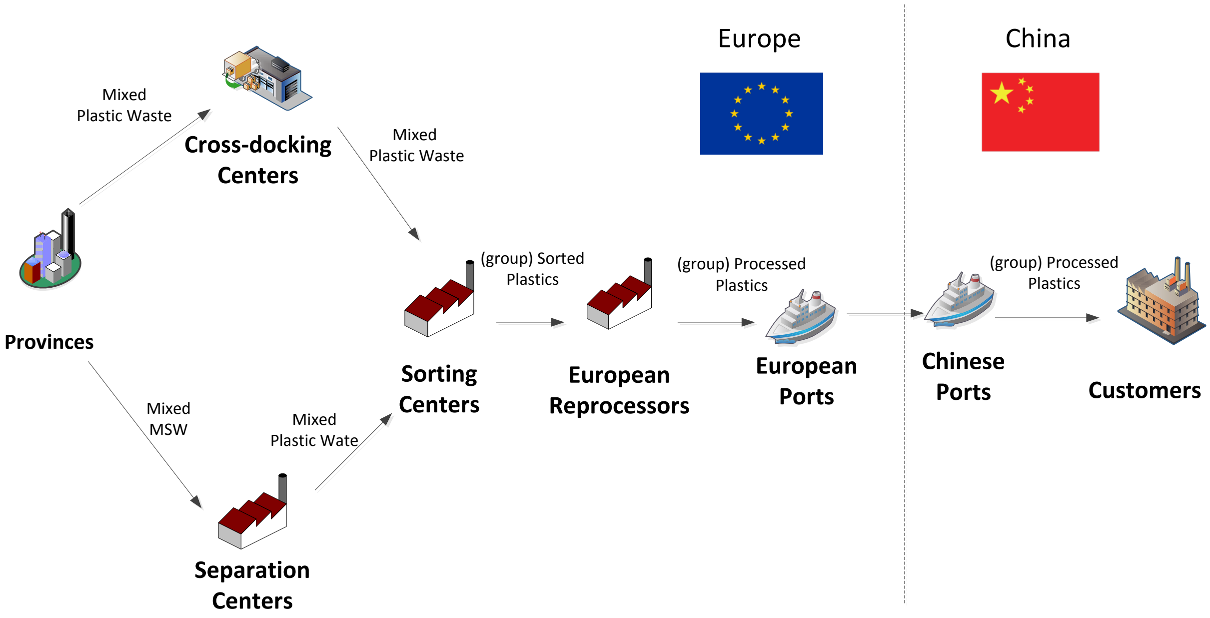

FIGURE 7.1: global network, all re-processing in Europe (Scenario 1)

In this research, a scenario study based on a mixed-integer programming model is used for the global network design for plastic waste recycling. The case study of plastic waste generated from the Netherlands handled by a supply chain with relocated reprocessing facilities to China is conducted. We take into account the complete reverse supply chain for the plastic waste recycling from provinces as source to the manufacturers as customers (who use the re-processed plastic). As manufacturing happens a lot in China and there is a large flow of recycled material to the Chinese market, the customers we consider in our case are all located in China. Besides the customers, all the other processing facilities are within Europe. We use this chain as our basic scenario (Figure 7.1).

Scenario 1: Global network, all re-processing in Europe

Based on this network, we explore the possibilities of relocating the re-processing facilities to China, by adding Chinese re-processors to the network and allow the flow of sorted plastics to be shipped to China to be processed.

As discussed before, a mechanism is needed to control the environmental impact, thus when allowing the flow of non-processed plastics to China, emission trading scheme is also introduced to both European re-processors and Chinese re-processors (see Figure 7.2). Accordingly, Scenarios 2 and 3 are introduced.

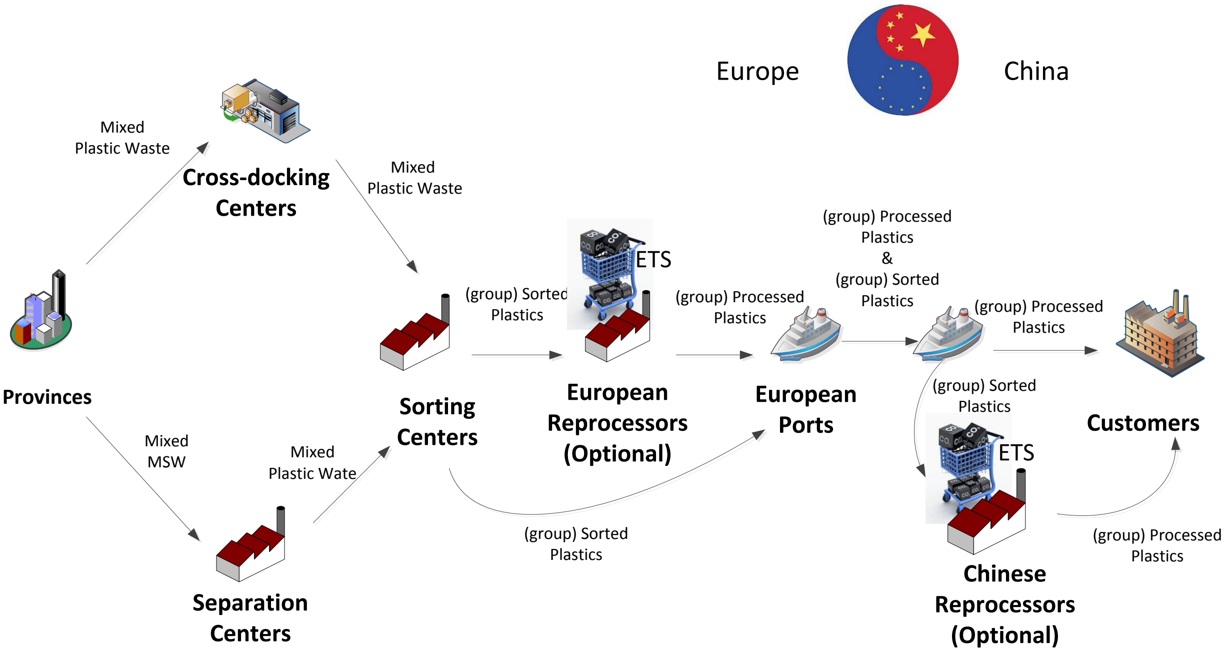

FIGURE 7.2: Global recycling, processing optional in Europe and China with ETS (Scenario 2 and 3)

Scenario 2: Global recycling, re-allocated re-processors to China **without** ETS

Emission trading is an incentive to reduce emissions, therefore we also test the effect of applying emission trading on the re-processors' decision on emission reduction. Under the 'cap and trade' principle, a cap is set on the total amount of greenhouse gases that can be emitted by all re-processors in zone Europe and zone China. Allowances for emissions are then allocated for free, and can subsequently be traded. If emission exceeds what is permitted by its allowances, a re-processor must purchase allowances from others. Trade can only happen between re-processors within the same zone.

Scenario 3: global recycling, re-allocated re-processors to China **with** ETS

We introduce in Scenario 3 a link between emission quality and the quantity of waste processed, assuming economics of scale/efficiency can be achieved when quantity is up to a certain level. As China has the potential of combining domestic generated waste into the re-processing, Chinese re-processors can have the opportunity of making less emission per unit of waste input. These two scenarios investigate if introducing emission trading can improve the overall sustainable performance of the network by inducing such improvement choices.

7.4 Modeling

7.4.1 Assumptions

The key assumptions used in the baseline scenario (network flow as in Figure 7.1) are as follows.

- There is no mechanical efficiency difference between the same type of facilities (sorting centers, separation centers, etc.).
- Chinese processors have 10% less cost than European processors(Anonymous, 2012)
- Re-processors in China have the possibility of aggregating the local generated waste, thus have the possibility of achieving the economies of scale and reduce the emission per kg of plastic waste processed.
- We do not consider fixed cost of the existing facilities because they already exist.

We interpret the current situation with the modeling settings by the following assumptions.

- Provinces are “sources” and manufacturers in China are “customers”.
- There are 5 types of end products in the network: End PE, End PET, End Film, End PP and End mixed hard plastic.
- Before making the end product in the re-processing plants, the component products are respectively PE, PET, Film, PP, and Mixed hard plastics. The five components

can be made from both plastic waste mix originated from source-separation or post-separated plastics out of separation centers. In the separation center, a mixed municipal solid waste is used as a component to make the plastic mix (group of the 5 types of sorted plastics).

- There are two types of emission "products" in the model, emission China and emission Europe. We use these two products to model ETS.
- Provinces are the sources for the supply of "products" in the model. Each province is concentrated in a node in the model, the location is the geographical centre as a supply point. All the plastic waste within one province is collected and gathered at this central point to be transported to the next location. Each province has a percentage of waste from source-separation and post-separation respectively.
- During the re-processing, dirt, moisture and plastic that is not sorted out due to machinery inefficiency will be created and disposed. We assume that this fraction is 10% of all sorted plastics. Landfill activity and incineration activities for the disposal of separated and sorted non-plastic waste are not considered int this model.
- We model emission in the re-processing facilities. Each re-processor has an assigned initial quota of emission quantity I_0, which is enough for re-processing waste up to the quantity of a_0. For processing a quantity larger than a_0, We assume the increased re-processing quantity would allow the re-processor to achieve a certain economies of scale. Re-processors achieve an "improved process" with 10% less emission needed per kg of waste processed. The initial quota has no cost for re-processors, however, the extra emission quanta needed has to be purchased from other re-processors.

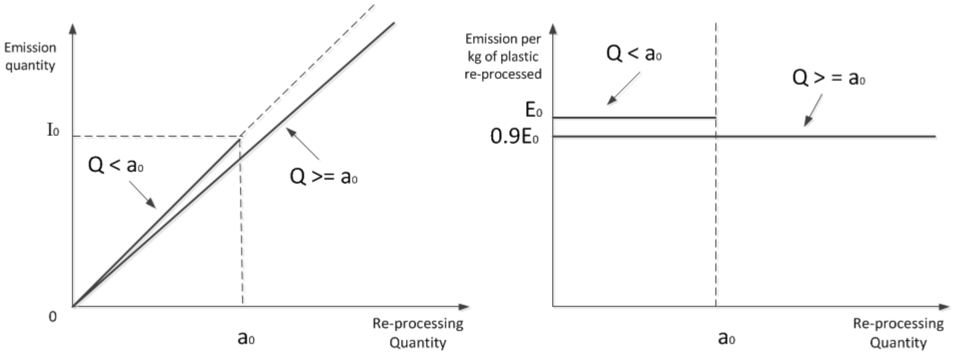

Figure 7.3: Emission setting in re-processors

- Emission trading, initial emission quota and emission quantity associated with re-processing output are modelled by using emission as "input" instead of "output" of the re-processing. In other words, emission is modelled as component required to make the end product. Initial assigned quota is then modelled as the initial inventory of the "emission component" and this component can be traded between re-processors.

- We model the choice of re-processors on whether or not to process more than a_0, thus achieve the economies of scale by creating an dummy "improved re-processor (dummy l)" at the same location as each re-processor(l). The difference between each pair of "re-processor" and dummy "improved re-processor" is that the improved re-processor use $0.9E_0$ as emission needed for processing each kg of waste. A facility opening constraint will be put on each pair of l and dummy l to allow at most only one of them to be open. Thus, the opening of dummy re-processor indicates the re-processor has achieved the economies of scale. This option is set for Chinese re-processors.

7.4.2 Data and data sources

Data collection for building up the model took place in cooperation with research partners through interviews, industrial reports and literature. A summary of the data used in the model and data sources is presented below.

Provinces (population, quantity of plastic waste, location)] Statistics regarding the geographical scope and number of Dutch provinces are collected from the Central Bureau of Statistics in Netherlands. for their choice of separation method (source- or post- separation), collection cost of municipalities within each province and quantity of plastic waste collected in each of the province by source-and post-separation throughout the year, we refer to the study on the collection cost of plastics applied to all Dutch municipalities conducted by Groot et al. (2013).

Processing facilities (function, location, availability) Nedvang (Dutch packaging waste recycling association) provided data on the locations and functions of processing facilities in Netherlands. Processing facilities include cross-docking centers, separation centers, as well as all the processors in Europe. Their locations, functions and the specified plastics types each European reprocessors produce are used in the model. Chinese reprocessor and customer locations refer to the existing areas of current plastic processing facilities in China as reported in China International Industry Fair (CIIF, 2014). Processing costs of separation and sorting are based on the previous network optimization study of Bing et al. (2013).

Plastic waste (components, quality) Total quantity and the quality of each component are provided by Kenniscentrum Nascheiding (KCN), an Expertise Center located at Wageningen University that investigates the technological and economic feasibility, as well as the environmental impact, of new technologies for the treatment of plastics. Energy consumption data is the reference for calculating the emission quantity in re-processing.

Emission Trading Price For the cost of emission trading emission, we refer to the average price of EU emission trading in European Energy Exchange (EEX) in Jan 2014 (5 euro per ton), and that of Tianjin Carbon Exchange (TCX), China in the same time period (equivalent to about 3 euro per ton) (EEX, 2014; TCX, 2014).

Market for Recycled Plastics For the five products: PP, PE, PET, Film, PO mix, we refer to the price offered on Alibaba, as one of the largest global business to business platforms in China (Alibaba, 2014).

Transportation For road transportation costs of waste, we refer to the NEA, a Dutch organization for transport research and training. The transportation costs of trucks include fixed cost, variable cost, labour cost and managerial cost (NEA, 2008). We use 4 types of trucks for the transport and assign those to different routes. Data is based on results from interviews of Dutch municipalities and waste collection companies. Details are consistent with the previous study of Bing et al. (2013). Shipping cost from Europe to China used in the model is 370 euro per TEU (Bloomberg, 2013).

7.4.3 Model formulation

The basic mathematical formulation of the MILP model is presented in this section. The adaption needed for other scenarios are presented in the next section. Index sets used in the MILP problem are:

$i \in I$ set of provinces

$j \in J$ set of warehouses; set of cross-docking sites$\{1, \ldots, j_0\}$;
set of separation centers $\{j_0 + 1, \ldots, J\}$

$k \in K$ set of sorting companies

$l \in L$ set of re-processing centers (set of European re-processing centers $\{1, \ldots, l_0\}$;
set of dummy European re-processing centers $\{l_0 + 1, \ldots, 2l_0\}$
set of Chinese re-processing centers $\{2l_0 + 1, \ldots, L - l_0\}$

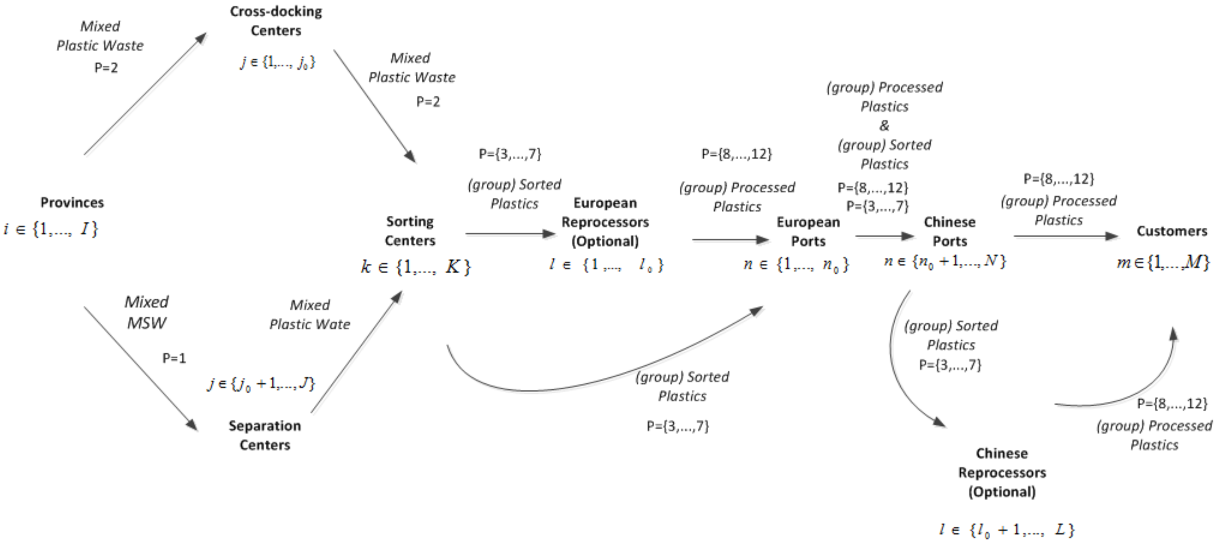

Figure 7.4: Indices used in the network model

set of dummy Chinese re-processing centers $\{L - l_0 + 1, \ldots, 2L\}$

$m \in M$ set of customers

$n \in N$ set of ports (set of European ports $\{1, \ldots, n_0\}$;

set of Chinese ports $\{n_0 + 1, \ldots, N\}$)

$p \in P$ set of products (see the index of products from Table 7.1)

Table 7.1: Product index

Products	$p =$	Products	$p =$
Mix MSW	1	Mixed hard plastic	7
Mix plastic waste	2	End PP	8
PP	3	End PE	9
PE	4	End PET	10
PET	5	End Film	11
Film	6	End Mixed hard plastic	12

Variables used in the MILP problem are:

$X^i_{jp} \in \mathbb{R}^+$ quantity of product p transported from province i to cross-docking center/separation center j

$X^j_{kp} \in \mathbb{R}^+$ quantity of product p transported from cross-docking center/separation center j to sorting company k

$X^k_{lp} \in \mathbb{R}^+$ quantity of product p transported from sorting company k to re-processing center l

$X_{kp} \in \mathbb{R}^+$ quantity of product p produced at sorting company k

$X_{lp} \in \mathbb{R}^+$	quantity of product p produced at re-processing center l
$X^k_{np} \in \mathbb{R}^+$	quantity of product p transported from sorting company k to port n
$X^l_{np} \in \mathbb{R}^+$	quantity of product p transported from re-processing center l to port n
$X^n_{n'p} \in \mathbb{R}^+$	quantity of product p transported from port n to port n'
$X^n_{lp} \in \mathbb{R}^+$	quantity of product p transported from port n to re-processing center l
$X^n_{mp} \in \mathbb{R}^+$	quantity of product p transported from port n to customer m
$X^l_{mp} \in \mathbb{R}^+$	quantity of product p transported from re-processing center l to customer m
$ET^e_{ll'}$	the European emission quota that is traded from reprocessor l to reprocessor l'
$ET^c_{ll'}$	the Chinese emission quota that is traded from reprocessor l to reprocessor l'

$$IN_l = \begin{cases} 1, & \text{if re-processing center } l \text{ is open} \\ 0, & \text{otherwise} \end{cases}$$

where $\mathbb{R}^+ = \{x \in \mathbb{R} : x \geq 0\}$.

Parameters used in the MILP problem are:

c_{ij}	transportation cost for transporting one unit product p from province i to warehouse j.
c_{jk}	transportation cost for transporting one unit product p from cross-docking/separation center j to sorting company k.
c_{kl}	transportation cost for transporting one unit product p from sorting center k to re-processor l.
c_{kn}	transportation cost for transporting one unit product p from sorting center k to port n.
c_{ln}	transportation cost for transporting one unit product p from re-processor l to port n.
c_{nm}	transportation cost for transporting one unit product p from port n to customer m.
c_{nl}	transportation cost for transporting one unit product p from
$c_{nn'}$	transportation cost for transporting one unit product p from port n to port n.
c_{lm}	transportation cost for transporting one unit product p from re-processor l to re-processor m.

c_{ip}	cost of collection of product p in province i
c_{jp}	cost of handling one unit of product in separation center/cross-docking center j
c_{kp}	cost of handling one unit of product in sorting center k
c_{lp}	cost of handling one unit of product in re-processing center l
c^{te}	cost for trading emission between re-processing centers in Europe
c^{tc}	cost for trading emission between re-processing centers in China
q_i	quantity of collected waste in province i,
d_{mp}	demand of product p by customer m
P_p	price of product p
$\alpha_{pp'}$	the quantity of p that are needed for producing one unit of p'
ϕ_1	the percentage of collected waste that is mixed MSWs
ϕ_2	the percentage of collected waste that is mixed plastic wastes
$\beta_{pp'}$	the quantity of p' that are produced together with one unit of p
EP^e_{lp}	the European emission factor that is required for producing one unit of p at re-processor l
EP^c_{lp}	the Chinese emission factor that is required for producing one unit of p at re-processor l
$ET^e_{ll'}$	the European emission traded from re-processor l to re-processor l'
$ET^c_{ll'}$	the Chinese emission traded from re-processor l to re-processor l'
I^e_l	the European emission quota that is assigned to re-processor l
I^c_l	the Chinese emission quota that is assigned to re-processor l
C^c_{ip}	the cost of collecting product p in province i

The MILP problem is formulated as follows:

Objective: Maximize Profit

$$Maximize \underbrace{\sum_{m=1}^{M} P^p_m * d_{mp}}_{\text{Revenue}} -(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P} X^i_{jp}(c_{ij}+c_{jp}) + \sum_{j=1}^{j_0}\sum_{k=1}^{K}\sum_{p=1}^{P} X_{jkp}(c_{jk}+c_{kp})+$$

$$\sum_{j=j_0+1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P} X^j_{kp}(c_{jk}+c_{kp}) + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{p=1}^{P} X^k_{lp}(c_{klp}+c_{lp}) + \sum_{n=1}^{N}\sum_{l=1}^{L}\sum_{p=1}^{P} X^n_{lp}(c_{nl}+c_{lp})+$$

$$\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{p=1}^{P} X_{lp}^{k}(c_{kl}+c_{lp}) + \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{p=1}^{P} X_{mp}^{l} c_{lm} + \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{p=1}^{P} X_{np}^{k} c_{kn} +$$

$$\sum_{l=1}^{L}\sum_{n=1}^{N}\sum_{p=1}^{P} X_{np}^{l} c_{ln} + \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{p=1}^{P} X_{np}^{k} c_{kn} + \sum_{n=1}^{N}\sum_{n=1}^{N}\sum_{p=1}^{P} X_{n'p}^{n} c_{nn} +$$

$$\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{p=1}^{P} X_{mp}^{n} c_{nm} + \sum_{p=1}^{P}\sum_{i=1}^{I} c_{ip}) - \underbrace{(\sum_{l_1=1}^{l_0}\sum_{l_2=1}^{l_0} ET_{l_1 l_2}^{e} c^{te} + \sum_{l_1=l_0+1}^{L}\sum_{l_2=l_0+1}^{L} ET_{l_1 l_2}^{c} c^{tc})}_{\text{Emission Trading Costs}}$$

Subject to:

$$\sum_{i=1}^{I}\sum_{j=j_0+1}^{J} X_{j1}^{i} = \phi_1 \sum_{i=i_0+1}^{I} q_i \tag{7.1}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{j_0} X_{j2}^{i} = \phi_2 \sum_{i=1}^{i_0} q_i \tag{7.2}$$

$$\sum_{i=1}^{I} X_{j1}^{i} = \alpha_{12} \sum_{k=1}^{K} X_{k1}^{j} \qquad \forall j \in \{j_0,\ldots,J\} \tag{7.3}$$

$$\sum_{i=1}^{I} X_{j2}^{i} = \sum_{k=1}^{K} X_{k2}^{j} \qquad \forall j \in \{1,\ldots,j_0\} \tag{7.4}$$

$$\sum_{j=1}^{J} X_{k2}^{j} \alpha_{23} = X_{k3} \qquad \forall kin\{1,\ldots,K\} \tag{7.5}$$

$$X_{kp} = X_{k3}\beta_{3p} \qquad \forall kin\{1,\ldots,K\}, p \in \{4,\ldots,7\} \tag{7.6}$$

$$\sum_{l=1}^{l_0} X_{lp}^{k} + \sum_{n=1}^{n_0} X_{np}^{k} = X_{kp} \qquad \forall kin\{1,\ldots,K\}, p \in \{4,\ldots,7\} \tag{7.7}$$

$$X_{lp} = \sum_{k=1}^{K} X_{l(p-4)}^{k} \alpha_{(p-4)p} \qquad \forall l \in \{1,\ldots,l_0\}, p \in \{8,\ldots,11\} \tag{7.8}$$

$$\sum_{p=8}^{11} X_{lp} EP_{lp}^{e} + \sum_{l'=1}^{l_0} ET_{ll'}^{e} \leq I_l^{e} IN_l + \sum_{l'=1}^{l_0} ET_{l'l}^{e} \qquad \forall l \in \{1,\ldots,l_0\} \tag{7.9}$$

$$X_{lp} = \sum_{k=1}^{K} X_{l(p-4)}^{k} \alpha_{(p-4)p} \qquad \forall l \in \{2l_0+1,\ldots,2L\}, p \in \{8,\ldots,11\} \tag{7.10}$$

$$\sum_{p=8}^{11} X_{lp} EP_{lp}^{c} + \sum_{l'=1}^{l_0} ET_{ll'}^{c} \leq I_l^{c} IN_l + \sum_{l'=1}^{l_0} ET_{l'l}^{c} \qquad \forall l \in \{2l_0+1,\ldots,2L\} \tag{7.11}$$

$$IN_l + IN_{l+l_0} = 1 \qquad \forall l \in \{1,\ldots,l_0\} \tag{7.12}$$

$$IN_l + IN_{l+(L-l_0)} = 1 \qquad \forall l \in \{2l_0+1, \dots, L-l_0\} \tag{7.13}$$

$$\sum_{n=1}^{n_0} X_{np}^{l} = X_{lp} \qquad \forall l \in \{1, \dots, l_0\}, p \in \{8, \dots, 11\} \tag{7.14}$$

$$\sum_{n'=n_0+1}^{N} X_{n'p}^{n} = \sum_{l=1}^{l_0} X_{np}^{l} + \sum_{k=1}^{K} X_{np}^{k} \qquad \forall n \in \{1, \dots, n_0\}, p \in \{4, \dots, 11\} \tag{7.15}$$

$$\sum_{l=l_0+1}^{L} X_{lp}^{n} = \sum_{n'=1}^{n_0} X_{np}^{n'} \qquad \forall n \in \{n_0+1, \dots, N\}, p \in \{4, \dots, 7\} \tag{7.16}$$

$$\sum_{n=n_0+1}^{N} X_{lp}^{n} = \sum_{m=1}^{M} X_{mp}^{l} \qquad \forall n_1 \in \{n_0+1, \dots, N\}, p \in \{4, \dots, 7\} \tag{7.17}$$

$$\sum_{m=1}^{M} X_{mp}^{n} = \sum_{n'=1}^{n_0} X_{np}^{n'} \qquad \forall n \in \{n_0+1, \dots, N\}, p \in \{8, \dots, 11\} \tag{7.18}$$

$$\sum_{l=l_0+1}^{L} X_{mp}^{l} + \sum_{n=n_0+1}^{N} X_{mp}^{n} \leq d_{mp} \qquad \forall m, p \in \{8, \dots, 11\} \tag{7.19}$$

$$X_{jp}^{i}, X_{kp}^{j}, X_{np}^{k}, X_{lp}^{k}, X_{np}^{l}, X_{np}^{n}, X_{mp}^{n},$$
$$X_{lp}^{n}, X_{mp}^{l} \in \mathbb{R}^{+}, IN_l \in \{0, 1\}. \tag{7.20}$$

The objective function maximizes the total profit. Total costs consist of transportation cost, collection cost at the municipalities, all the processing cost (at sorting, separation and re-processing centers), as well as the emission trading cost. Constraints (7.1) specify that all collected mixed MSW is transported to separation centers. Constraints (7.2) specify that all collected mixed plastic wastes are transported to cross-docking centers. Constraints (7.3) specify that all mixed MSW is separated into mixed plastic wastes and then obtained mixed plastic wastes are transported from separation centers to sorting centers. Constraints (7.4) specify that all mixed plastic wastes are transported from cross-docking centers to sorting centers. Constraints (7.5) and (7.6) together ensure that sorted products are produced together using the mixed plastic wastes. Constraints (7.7) ensure that sorted products are either transported to ports or transported to re-processing centers. Constraints (7.8) (resp. (7.10))specify the amount of end sorted products are obtained at reprocessing centers in Europe (resp. in China). Constraints (7.9) (resp. (7.11)) specify that the amount of European (resp. China) emission used or trade by re-processor

l cannot be more than the emission quota plus the amount of emission purchased from other re-processors. Constraints (7.11) and (7.12) ensure that the re-processing center and its dummy center cannot be open simultaneously. Constraints (7.14) specify that the end sorted plastics obtained in Europe are transported to Europe ports. Constraints (7.15) specify that all products at Europe ports are shipped to Chinese ports. Constraints (7.16) specify that all sorted products shipped to Chinese ports are transport to Chinese re-processing centers. Constraints (7.17) specify that all end sorted products obtained at Chinese re-processing centers are transported to destinations. Constraints (7.18) specify that all end sorted products at Chinese ports are transported to destinations. Constraints (7.19) specify that the supply of end products to customers cannot be more than their demands.

7.5 Results

The above presented model is used for all scenarios, whereas

- In scenario 1, no Chinese re-processor are introduced, thus only European re-processors are set as optional. The two "emission" products are not considered as well. Therefore, no transportation of sorted plastic waste are allowed to be transported to the port.
- In scenario 2, re-processors in China are set as optional as well, however, still "emission" products are not considered in the model, therefore, no initial inventory or trading of emission is considered.
- In scenario 3, all the parameters and decision variables and constraints presented in the formulation are included.

We program the model using LlamaSoft Supply Chain Guru 8.0. Fico Xpress Optimization solver is used to solve the model on a computer with Intel Core i5 CPU, 2.6 GHZ and 7.7G usable memory. The average optimization time is within 1 minute.

7.5.1 Impact of relocation

In Scenario 1, there is no optional China re-processor included in the network, meaning all the processes are conducted in Europe, while in Scenario 2, re-processors in China are added to the network, which create the additional option of sorted plastic waste to be transported directly to ports and shipped to China to be re-processed. By comparing the results of Scenario 1 and 2, the impact of global relocation of re-processing locations on the network can be observed.

Figure 5 shows the composition of total costs in Scenario 1. It is interesting to see that collection cost accounts for more than half of the total costs, and thus has the largest share (54%), followed by re-processing cost (25%). In the transportation sector, shipping cost is much lower than the cost of road transport by truck. comparing the total costs with the revenue calculated by the data we used, it is shown that the revenue covers only around 60% of the total costs, although in practice, collection cost is often largely covered by taxes and other sources of subsidies. As re-processing is one of the most costly activities in the network, it shows the value of looking into strategies of reducing such cost. The shift of re-processing facility locations in Scenario 2 leads to an increase of shipping cost (11%), but, total shipping cost takes only two percent of the total costs. Truck transportation costs more than shipping, and transportation cost in total is only 10% of the overall cost. Besides transportation cost, activities of sorting, cross-docking and separation are also no more than 10% of the total costs. The processes that contribute most to the total costs are collection (54% to 56%) and re-processing (23% to 25%). By relocating reprocessing to China, the re-processing cost in total drops 10% in comparison with Scenario 1, that is due to the 10% less cost per unit of waste processed in China.

As shown in Table 7.2, when re-processors in China are added to the network, all the re-processing shifts to China. The shift is due to the cost advantage of shipping together with the lower processing cost. It results in a reduction of total costs by 3% while satisfying all demand and getting the same revenue. In terms of emission, by adding the possibility of Chinese re-processors, scenario 2 has a slight reduction of emission amount by 17 ton. This emission reduction comes from the transport sector.

Table 7.2: Optimization Results of Scenario 1, 2 and 3

	Scenario 1	Scenario 2	Scenario 3
Total costs (Euro)	136,371,442	132,359,920	133,725,659
Total revenue (Euro)	86,824,912	86,824,912	86,824,912
Total transportation cost (Euro)	13,423,849	12,785,003	12,864,352
Total carbon cost (Euro)	0	0	94,729
Total emission (ton)	108,165	108,148	101,282
Re-processing emission (ton)	69,189	69,189	62,510
% re-processed in Europe	100%	0	35%
% re-processed in China	0	100%	65%

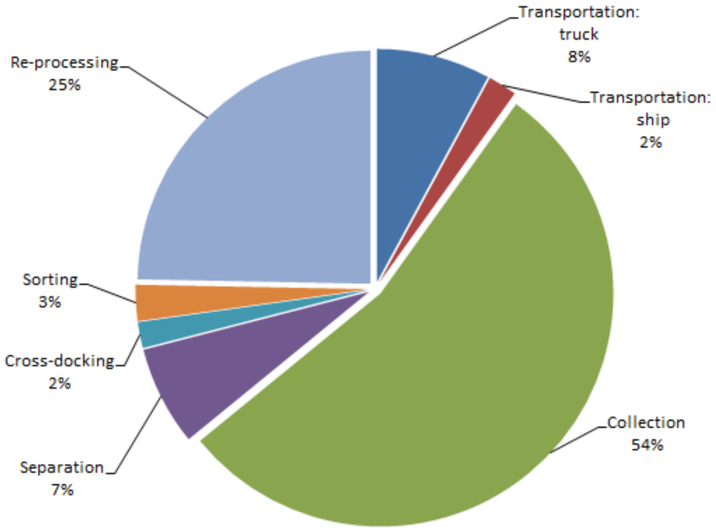

Figure 7.5: Composition of total costs in Scenario 1

7.5.2 Impact of ETS

In scenario 3, we further introduce the mechanism of carbon trading and carbon cap to the network. Initial emission is allocated to each of the facilities and trading of emission credits are allowed within Europe or China. Emission cap in both regions are set to be 60% of the total emission of processing all waste generated. As the purpose of the ETS is to create an incentive for processing companies to reduce the carbon emission, we allow the option of achieving an economies of scale when larger quantity are processed in one facility in scenario 3. The results are presented also in Table 7.2.

When ETS is added to the network, the trade-off between cost advantage of processing waste in China and the increased cost for extra emission quota is introduced. There is also a trade-off between re-processing with economics of scale in Europe and shipping waste to China. In comparison with Scenario 1, results show a cost saving of 2% and an emission saving of 6.4% in Scenario 3. Compared with Scenario 2, the cost increase is about 1%, which is smaller than the percentage of emission reduction achieved (6.4%). With a carbon cap, the re-processing takes place in both Europe and China. Processing happens both in Europe (35%) and China (65%) with China having a larger share of the total waste processed. The emission trading cost is less than 1% of the total costs. The result also shows that with the mechanism of ETS, several re-processors in both Europe and China have achieved the economies of scale with 10% emission saving. This result shows the effect of applying ETS on the actor strategy towards reducing carbon emission in processing.

Applying the emission trading scheme leads to a reduction of transportation emission in comparison with scenario 1. Re-processing emission is about 1.8 times the total emission in transportation. As some re-processors in Scenario 3 switched to a process with 10% less emission per ton of plastic waste, the total emission saving is 3,273 ton, which is about 5% of the total emission from re-processing. Total emission quantity also reduced by 6,866 ton. Based on the assumptions we made (regarding emission cap, transportation cost and processing cost, etc), these results indicate a positive effect of relocating re-processing plants to China and applying ETS on the sustainable performance of the network.

7.6 Sensitivity Analysis and Discussion

Emission Cap

The emission cap is one of the key factors that influence the sustainable performance of the network; therefore, we test different input values of emission cap and emission trading prices in the sensitivity analysis. In scenario 3, the setting of emission cap on both China and Europe is 60% of the total emission quantity of processing all the waste in the network. In order to show the impact of a total carbon cap from more than sufficient to insufficient for processing all the waste on the network, we choose the input value of 100%, 80%, 60% and 40% respectively. Carbon credits are assumed to be equally allocated among re-processors in the same region initially. The results are presented in Table 7.3.

TABLE 7.3: Sensitivity analysis result of emission cap(described by percentage of all the emission quota needed to re-process all waste generated)

	Cap Set on China and Europe			
	100%	80%	60%	40%
No. of re-processors used to process in Europe/China	0/4	15/4	25/4	18/4
No. of re-processors achieved economies of scale in Europe/China	0/3	7/4	18/4	12/4
No. of re-processors used only to trade emission in Europe/China	0/2	0/2	18/2	20/2
% of waste re-processed in Europe/China	0/100%	10%/90%	35%/65%	39%/61%
Transportation emission (ton)	38,878	38,275	38,772	18,484
Re-processing emission (ton)	63,422	62,571	62,263	51,909
Total Costs (euro)	132,416,239	132,606,326	133,725,659	109,176,983
Emission trading cost in Europe/China(euro)	0/55,467	3,728/61,412	47,174/47,556	88,480/27,735
Demand satisfied	100%	100%	100%	77%

When the emission cap is set to 100% for both regions, there are always enough emission credits to process, thus the optimization results are similar as in Scenario 2, in which reprocessing is shifted all to China. When the emission cap is reduced, the effect of sharing processing capacities between the two regions and the incentives for reducing emission per unit of waste processed start to show in the results. More and more European processors are used when the emission cap drops, as in our modeled case more European processors are available in the network than Chinese ones. When the cap drops from 100% to 60%, we observe an increase in number of re-processors used and an increase in emission trading quantity (in total there are 43 and 6 optional re-processors in Europe and China respectively). The emission trading is only happening in China when the cap is 100%, while at 60%, the difference in emission trading cost between China and Europe becomes much smaller. Further reducing the carbon cap to the level below the sufficient quantity to be used to process all the waste, we run the model by maximizing the total profit. Then the result shows that demand is not totally satisfied. It indicates that the emission cap should be carefully set to a level that is efficient to function as incentive to encourage re-processors to reduce emissions. When the level is too low, it will jeopardies the economic performance of the network. Note that in our network, only efficiency improvement through economies of scale is considered because of the possibility of re-processors further aggregating local waste when processing. Thus this result also implies that more options regarding improving individual actors' sustainable performance should be given in case of a low emission cap. Besides economies of scale, other methods such as technology improvement are also worth exploring.

Carbon Price

Carbon pricing is also an important factor in this model. The carbon market price is volatile, thus we test our model with different carbon price in order to see the impact of the carbon market on the decisions of actors. The initial input of carbon price in the scenarios are 5 euro for Europe and 3 euro for China. We test in the model the carbon price of 80 euro, 40 euro, 20 euro, 10 euro and 5 euro set in both China and Europe. Results are given in Table 7.4.

The first observation from the sensitivity analysis result is that with a higher carbon price, more re-processors have achieved economies of scale both in Europe and China. Reprocessors improve their efficiency (increase the quantity processed to achieve economies of scale) to compensate the emission cost increase. When the price is 80 euro per ton, there are 22 European processors (out of 43 available) and 6 Chinese re-processors (out of 6 available) that achieved the economics of scale. The numbers go down to 13 in Europe and 4 in China when the price is down to 20 euro per ton and below. All the facilities in China (6 in total) achieved to produce with lower emission needed per unit of waste processed, when the price is up to 40 and more. A higher emission trading cost does not lead to a reduction of total emission quantity, as to avoid emission trading, some more transportation is generated in order to make use of all the capacity of available re-processors. When the emission trading price is below 20 euro per ton, the emission credits traded in Europe and China are more or less equivalent, while above 20 euro, more emission is traded in China than in Europe. As emission cost is only about 1% of total costs, the 10% cost saving of re-processing in China and the cost advantage of shipping still out-weigh the emission cost increase, thus China still re-processes a larger amount of waste under the increased emission price. In the past few years, the carbon price in Europe has been fluctuating, but mainly within the range between around 5 euro per ton up to about 20 euro per ton, based on the the assumptions we made and the input parameter values. From the sensitivity analysis result, we can see that regarding emission trading quantity and percentage of waste re-processed, the share between Europe and China is more or less equivalent. The effect of encouraging the re-processors to improve the efficiency is also similar, with the same number of facilities achieving the economics of scale. In this price range, the difference in terms of total emission is also very small. More significant difference start to show when the price is higher, and in this case higher than 20 euro per ton.

Table 7.4: Sensitivity analysis on carbon price

	Carbon Trading Price				
	80 euro	40 euro	20 euro	10 euro	5 euro
Total costs (euro)	134,340,644	134,043,052	133,732,424	133,500,565	133,370,007
Total emission (ton)	102,218	101,962	100,934	100,794	100,778
Emission trading cost Europe/China (1000 euro)	419/0	304/122	211/200	120/139	63/69
Emission trading quantity Europe/China (ton)	5,242/0	7,608/3,055	10,541/9,988	12,030/13,867	12,691/13,867
No. of re-processors achieved economic of scale in Europe/China	22/6	15/6	13/4	13/4	13/4
% of waste processed in Europe/China	32%/68%	28%/72%	27%/73%	27%/73%	26%/74%

These results together have shown the potential advantages of postponing the re-processing of plastic waste (re-location of re-processors) in the reverse supply chain. With the postponement options, besides the cost reduction, there is also possibility of improving the environmental performance. The model we propose in this paper can function as an analytical tool to quantify cost advantage and resulting price for end products. Furthermore, when waste is aggregated near the end market, there is more freedom of storage and producing according to market demand. Of course, these possibilities are all under the assumption that there are supportive trade policies. Even with policies that give a strict constraint on the flow between continents, the model can still easily be extended to show the possibility under an extra flow constraint. More interestingly, the model can give decision support for policy improvement by quantifying the benefits when flow constraints are relaxed.

7.7 Conclusion and Further Research

This paper redesigns a reverse supply chain from a global angle based on a case study conducted on household plastic waste distributed from the Netherlands to China. The key decision is the relocation of re-processing plants. Emission trading schemes are used as a mechanism to control emission. Emission cap restrictions are set on both Europe and China on the re-processing plants while allowing emission trading within each region. A mixed-integer programming model is then used in the network optimization to decide location re-allocation of intermediate processing plants under such restrictions. The objective is to minimize the costs of the global chain (collection, transportation and processing, as well as carbon trading cost) under ETS.

Results show that relocation of re-processing centers to China leads to both a reduction of total costs and total transportation emission. ETS applied to re-processors further helps to reduce emissions from both re-processing and transportation. ETS encourages re-processors to switch to a lower emission production process, which leads to reduced emission in re-processing sector. Relocation possibilities improved the performance of the network which reduced the total costs and transport emission. ETS further created an incentive to reduce re-processing emissions by 5%. ETS applied to both Europe and China also creates synergy and cooperation of all re-processing facilities to process all the waste together. Sensitivity results show that a lower emission cap does not always lead to a cost reduction, nor an emission reduction. Hence, the carbon cap should be carefully set in order to be effective. Sensitivity analysis on carbon prices shows that a carbon price below 20 euro in our case setting makes has little impact on the performance of the supply chain network.

These results provide valuable insights for managing waste as a resource from a global perspective in a more sustainable manner. Overall, this research shows how postponement strategy with global re-location can be applied to waste recycling problems together with emission control mechanisms to ensure an improved performance both economically and environmentally. Practically, this paper also provides decision support for policy makers and actors involved in waste recycling by demonstrating the feasibility of decarbonizing the supply chain while globalizing it.

In the model assumptions, we apply the same energy use and carbon conversion factor in all processing facilities. A factor that can influence the environmental performance is the electricity generation mix (nuclear, hydroelectric, fossil fuels, etc.). This factor can be taken into account in the modeling for a more specific case study. One of the observations from modeling all the costs in the network is that the revenue is much less than the total costs of the network. As not all the cost are supposed to be covered by selling the end recycled product in the market, the collection of waste is largely covered by tax in most cases. With insights on cost break-down for plastic recycling, this research also can lead to a further study of cost and profit sharing between stakeholder in the chain such as producer, municipalities, transport service providers and processors.

This paper presented a case study based on plastic waste collected in the Netherlands and having an end market in China for recycled plastics, whereas, the application of this model is not limited to the counties involved. It is a model that can be applied to a globalized reverse supply chain for waste recycling in general. As the manufacturing industry is the major market for recycled plastics and in recent years, China is loosing its manufacturing cost advantage and other emerging markets are developing. This model can be generalized and applied to study a reverse supply chain problem for waste recycling when waste is generated at a place that is different than the end market for the recycled material on a global scale.

Chapter 8

Discussion and Conclusion

This thesis investigates plastic waste recycling from a sustainable reverse logistics perspective. Decision support is provided for the redesign of the plastic waste reverse supply chain at operational, tactical and strategic level. The aim is to improve the sustainable performance of the reverse supply chain, customized for household plastic waste.

Chapter 1 presented the research framework of this thesis. This framework consists of three decision levels, customized for plastic waste recycling, that are influenced by external factors and result in sustainable performance. Chapter 2 elaborated further on the framework, provided more insights in waste recycling, and identified research opportunities. Table 8.1 summarizes the research focus of Chapters 3-7, which correspond to the research framework in terms of the decision levels, the plastic waste characteristics and the external factors included. It shows that Chapters 3 and 4 focused on the operational decision level. Chapter 3 considered the characteristic of plastic waste (alternatives in collection and separation, low density) in the redesign of optimal collection routes. Chapter 4 evaluated the impact that taxes, in combination with these characteristics, have on the collection cost. Chapters 5 and 6 focused on tactical/strategic decision levels. Chapter 5 integrates the stakeholders' interests into the decision of network design. Chapter 6 explored the improvement opportunities for a more sustainable network performance. Chapter 7 focused on the strategic level and emphasis on a global strategic redesign, taking market incentives into consideration. The impact of emission control strategies on the global reverse logistics network performance was also evaluated.

		Ch. 3	Ch. 4	Ch. 5	Ch. 6	Ch. 7
Decision Levels	Operational: collection design	✓	✓			
	Tactical: waste flow allocation			✓	✓	
	Strategic: network design			✓	✓	✓
External Factors	Stakeholders			✓		
	Market incentives					✓
	Regulations	✓				
	Tax		✓			
System Characteristics	Drop-off and curbside collection	✓	✓			
	Source- and Post-Separation	✓	✓	✓	✓	✓
	Light material	✓			✓	✓
	Complex composition			✓	✓	✓

TABLE 8.1: Research focus of chapters 3 to 7

Looking from a geographical scale, we divided this research into municipal, regional and global level. Chapters 3 and 4 focused on providing decision support on municipal level. Key decisions were related to choices of separation method (source-/post-separation), collection method (curbside/drop-off collection), vehicle types and collection routes. Chapters 5 and 6 focused on providing decision support on regional level (within Europe). Key decisions analyzed included separation method, multi-modality choices, intermediate facility capacity and waste flow allocation (e.g. separate PET recycling flow or not).

Decisions on global level were analyzed in Chapter 7. In this chapter, the main decisions are related to the network configuration, the postponement of re-processing, and the emission trading scheme.

In the remaining part of this chapter, we elaborate the findings in Chapters 2-7 in order to answer the research questions. Integrated findings are then presented in line with the research framework. Scientific relevance and future research opportunities are discussed, followed by a summary of managerial insights.

8.1 Answers to the research questions

Findings RQ1: What are the research opportunities in modeling plastic recycling logistics?

Research question 1 is answered in Chapter 2. The aim of that chapter was to identify research opportunities in modeling municipal solid waste (MSW) recycling. To answer RQ1, we conducted a review of current practices in various EU countries and identified the characteristics and key issues of waste recycling from waste management and reverse logistics perspectives. We then conducted a literature review regarding the applications of operations research modeling methods. The identified issues and problems in practice are associated with the modeling methods used in literature. We identified research gaps and opportunities by comparing the findings from reviews of practice and literature. The three major opportunities that we identified for future research are as follows.

- MSW management cannot be viewed in a one-dimensional perspective, as there are many inter-related issues from various decision levels. The combined decisions on these inter-related issues are often too complex to be solved at once. Multi-dimensional problems often introduce different optimization objectives. Separating problems and pursuing the objectives on one decision level at a time will result in suboptimal solutions. It is only possible to obtain global optimal solutions by using an integrated approach that considers problems at different decision levels simultaneously. A multi-dimensional perspective on municipal solid waste management requires an integration of various disciplines in modeling MSW recycling. To improve sustainability performance, especially regarding environmental and social concerns, research opportunities can also be found with regard to integrating operations research modeling methods with methods from other disciplines such as life cycle assessment and technological studies.

- The export of waste between continents means that waste recycling is becoming a global issue. Solving issues such as over-capacity and valorisation, meeting the high requirement of waste recycling rates, and satisfying the increasing global demand of the recycled material requires a new perspective in research and practice to look into waste recycling. In other words, waste recycling must be considered as a procedure of retrieving waste as a global resource that is substitutable for raw material on a regional and a global scale. The existing theories and models of the global supply chain have to be applied in a waste recycling context to address the problem on a global scale. Uncertainties in the global market in terms of the demand of recycled material and currency exchange rates should also be integrated in the models.

- To meet future demands of improving the efficiency and sustainability of municipal waste recycling, solutions must be further tailored for individual waste types, and even sub-groups of waste types. Understanding the characteristics of different waste types and sub-groups of one waste type, such as the density (weight-to-volume ratio) difference, the quantity difference, and treatment procedure differences, can help tailor the network design for each type of waste in order to further improve recycling efficiency.

Findings RQ2a: What opportunities can be found from the comparison of the collection alternatives to improve the sustainable performance of the collection system?

In Chapter 3, municipal collection was modeled as a vehicle routing problem and improvement opportunities are investigated. The following two opportunities are identified.

- With the current input parameters, source-separation and drop-off collection of plastic waste can achieve the best performance in terms of eco-efficiency, provided that householders transport the waste from their homes to the nearby drop-off points in a sustainable manner. Furthermore, a higher response rate of source-separated plastic waste will make curb-side collection more favorable, although curbside collection still costs more than drop-off collection in general. Thus, improved behaviour of householders in terms of separating waste at home can potentially bring more convenience (drop waste at curb-side instead of a further drop-off location) to themselves.

- We applied different input parameters regarding vehicles in our proposed vehicle routing model for analyzing sustainable collection alternatives. The results indicate that hybrid (diesel-electric) collection vehicles can bring more significant improvements in sustainability performance. Emission costs account for approximately 1.5

percent of the total cost in curb-side collection scenarios, compared to around 3 percent in drop-off scenarios. Using hybrid trucks (a form of truck that uses hybrid electric vehicle technology for propulsion, instead of only a combustion engine) reduces emission costs significantly for all scenarios.

Findings RQ2b: What are the impacts of various collection and taxation alternatives on the performance of the collection system?

This research question is answered in Chapters 3 and 4. In these two chapters, we look into the impacts of various collection and taxation alternatives using two different methods. As identified in the answer to RQ1, the waste recycling problem should be given a tailored design. Therefore, at the municipal level, we started by researching plastic waste recycling problem in a specified area of Wageningen (Chapter 3). Then we extended the research scope by looking into plastic waste collection in all the municipalities with different taxation systems (Chapter 4).

Chapter 3 presented a vehicle routing model that is solved using a heuristics approach. The focus there is on testing various collection alternatives in the same municipality. In Chapter 4, we designed a comprehensive cost estimation model that can be applied to all municipalities, thereby enabling comparison between various municipalities with different taxation and collection choices. These models take into account collection alternatives and the characteristics of municipalities (including urbanization degree and taxation schemes). The results showed that post-separation collection generally has the lowest costs, while curb-side collection in urban municipalities without residual waste collection taxing schemes has the highest cost. These results were supported by the conducted sensitivity analysis, which showed that higher source-separation responses (more plastics separated at households) are negatively related to curb-side collection costs. Greenhouse gas emission costs are a significant part of the total costs when collecting post-consumer plastic packaging waste due to the low density-to-weight ratio of the materials collected. These costs can account for 15 percent of the total collection costs. The drop-off collection scenarios have better performance than curb-side collection scenarios, assuming householders take the waste to the drop-off points in a sustainable manner. Taxation schemes have an impact on curb-side collection but not on drop-off collection as the direct results of different taxation is a variation in response rate meaning the waste quantity difference in each of the collection point. Curb-side collection is more sensitive to the quantity change than drop-off collection, as driving in curbside collection with frequent stops and short idling time generates costs more than driving to less spots with longer idling time. For the same essential reason, curb-side collection costs vary greatly with the different urbanization degrees of municipalities, while drop-off collection costs do not vary as widely.

Findings RQ3a: What are the key issues that determine the sustainable performance of the regional network?

RQ3a is answered in Chapter 5, which analyzed the strategic alternatives of reverse logistics network design by a scenario study approach based on a mixed integer linear programming model. The decision to use the separation method (source-/post-separation) was investigated on the tactical/strategic level by testing the impact that the separation alternatives have on the network design. We also consider the preferences of various stakeholders while deciding which separation method to use. The results showed the impacts of these strategic changes. Furthermore, this research identified the key issues, at a regional level, that determine the sustainable performance of the network. The issues identified as being key to the sustainable performance of the network on a regional level are presented below.

- The function and availability of intermediate facilities are identified by the model on this level as the key factor that affects whether strategic changes of waste flow reallocation are feasible. Applying post-separation and differentiating urban and rural municipalities (by assigning post-separation to urban municipalities and source-separation to rural ones) has a similar result as the current situation, with a slight reduction of overall cost, assuming that additional facilities are available.
- After assigning post-separation to urban municipalities and source-separation to rural municipalities, the integration of PET bottle collection and other plastic waste collection results in higher total costs and emissions. Post-separation scenarios are more sensitive to this integration than source-separation scenarios. Given the current distribution of source-separations and post-separation municipalities as well as the function and availability of current facilities, a re-assignment of separation method choices among municipalities requires more available separation facilities in order to make it efficient. In other words, in our studied Dutch case, whether PET recycling channel should be separated from the collection channel of other plastic waste depends on the current distribution of source and post-separation municipalities as well as the number of separation centers available and their capacity.
- Truck utility and fuel efficiency are two areas in which the sustainable performance of the network could be improved. Collection within municipalities could differ in terms of truck utility due to different municipalities having different arrangements in each collection round. Plastic is a quite light material, which would result in a lower

truck utility. Therefore, a higher variation of utility rate of trucks is expected. We tested the model with different utility rates and the results indicate a continuous decrease of total cost and emission with a rise in the utility rate with a much sharper decrease before the utility reaches 50% than after. Consistent with earlier findings, test results on regional level also show that total costs do not differ greatly with different values of fuel efficiency. However, total emission values experienced a steady decreasing trend with the rising value of fuel efficiency. Total costs do not differ greatly because emission costs only account for a small part of the total cost.

Findings RQ3b: What strategy can be used to redesign a regional supply chain for improving sustainable performance?

We proposed multi-modality as a strategy to improve the sustainable performance of a regional network. The network model was further extended in Chapter 6. A strategy of multimodality was applied to show the impact that applying this strategy has on the improvement of sustainable performance of the regional network. The regional network model was extended with options for transport modality choices and more processing cost input is integrated into the model. A baseline scenario represented the optimized current situation, while other scenarios allowed multimodality options (barge and train) to be applied. With our input parameter settings, results showed that transportation costs contribute to approximately 7 percent of the total cost, and multimodality can help reduce transportation costs by almost 20 percent (CO_2-eq emissions included). In our illustrative case with two plastic separation methods, the post-separation channel benefits more from a multimodality strategy than the source-separation channel. This relates to the locations and availability of intermediate facilities and the quantity of waste transported on each route. In coping with future changes such as rising fuel prices, the multimodal scenarios showed a smaller cost increase than the uni-modal scenario, assuming that diesel price does not influence the unit cost of trains. Higher emission rates only have a limited influence on total costs. Still, the multi-modal scenario was more sensitive to the emission cost change than the uni-modal scenario.

Findings RQ4: What strategy can be used to redesign a global supply chain for improving sustainable performance?

The answer to RQ4 is presented in Chapter 7, which outlined a global network design problem. The aim of that chapter was to redesign a reverse supply chain from a global angle based on a case study conducted on household plastic waste distributed from Europe to China. The key decision was the relocation of re-processing plants. Emission trading schemes (ETS) were used as a mechanism to control emissions. In order to improve the sustainable performance of a global supply chain, we proposed ETS with the strategy of postponement by relocating re-processors globally. In a global network model, emission cap restrictions on the re-processing plants were set both in Europe and China while allowing emission trading within each region.

Results showed that relocation of re-processing centers to China leads to both a reduction of total cost and total transportation emission. ETS applied to re-processors further helps to reduce emissions from both re-processing and transportation. ETS encourages re-processors to switch to a lower emission production process, which is the reason for the reduced emission in re-processing sector. ETS applied to both Europe and China also creates synergy and cooperation of all re-processing facilities to process all the waste together. Re-processing is aggregated in a few facilities and other facilities are used for trading emissions more than processing waste. Sensitivity results proves a larger impact of emission cap compared to carbon price on the network configuration and performance. Lower emission cap does not always lead to a cost reduction, nor an emission reduction. Hence, the carbon cap should be carefully set in order to be effective. In general, re-processors' strategic decision of improving their individual sustainable performance is more sensitive to the carbon price change than the carbon cap change. These results provided insights into the feasibility of building a global reverse supply chain for household plastic waste recycling and demonstrate the impact of ETS on the network design.

8.2 Integrated findings

Plastic waste recycling involves a number of strategic, tactical, and operational decisions, such as the selection of the location of treatment sites, waste flow allocation to processing facilities, and routing of collection vehicles. Dealing with each of these aspects leads to solving several combinatorial optimization problems; therefore, computerized systems based on Operations Research techniques can help decision makers achieve performance improvements. However, because the problem involves also institutional, social, financial, economic, technical, and environmental factors, no single model is able to capture all the different aspects that need to be considered (Ghiani et al., 2014). Therefore, the research in Chapters 2 to 7 is conducted according to the framework presented in Chapter 1. A number of aspects are taken into account in each of the studies, which combined provide a more complete picture of the impacts of these aspects. Chapter 2 focuses on interpretation of the framework in the MSW recycling context and identifies research opportunities. Chapters 3 to 7 consider a range of external factors and plastic recycling system characteristics in modeling to provide decision support in different decision levels, as highlighted in Table 8.1.

Combining these studies shows that different models are required in order to tackle problems at different decision levels and different problem scales. At the tactical and strategic levels, network optimization models are used, while vehicle routing and collection cost models are developed at the operational level. Two types of model are used at the operational level as the scale of looking at the problem and issues taken into account are different. A vehicle routing model is used to investigate the influence of switching to a different collection/separation method for a given municipality and investigate the possibility of improving sustainable performance. To further demonstrate the impact of various taxation and compare the collection/separation alternatives among various types of municipalities, the vehicle routing model can be easily applied to one specific municipality. However, a lot more effort would be required for it to be applied to all municipalities in the Netherlands, and the results would include a level of details that is not necessary for this purpose. Instead, a comprehensive cost model is developed. The different modeling methods used in this research demonstrate that problems from various decision levels and problem scales often have diverse purposes to serve and different levels of details needed. Therefore different decision support models are used.

The complexity of problems necessitated the use of decision support models. The complexity was caused by internal and external factors. Internal factors are the characteristics of plastic recycling system, while external factors are related to regulation, legislation, and markets. One factor can have a different impact on different decision levels and some factors are more important on one decision level than others. Consequently, in our research we also show how one factor can be taken into account in various decision levels (i.e. post- and source separation) and have different and even contradictory results. Moreover, we also show which factors are taken into account in the decision support modeling process, at which decision level and in what way. Below, we elaborate on how sustainable performances, plastic recycling system characteristics, and external factors are integrated in the decision support approaches from different decision levels and their impacts.

Pathway to sustainable performance

We defined improved sustainable performance as the goal of our redesign of sustainable reverse logistics for plastic waste recycling. In this thesis, we showed that the improved sustainable performance can be achieved both by including eco-efficiency as key performance indicator and by applying strategic changes such as multi-modality and postponement. Eco-efficiency is defined as the key performance indicator in this research. In terms of modeling approach, the emission quantity is transferred to a cost factor, which is added to the total cost to be minimized as objective in both collection and network models. The total cost, which includes emission costs, is used to measure the performance of all scenarios. In the scenario study used in Chapter 3 and 5, the current situation is used as the baseline scenario and redesign is conducted by modeling with a new objective that takes environmental impact into account. In this measurement, the fuel cost and carbon costs are two important influential factors the impact of which we analyzed in the municipal collection (Chapter 4) and the regional network (Chapter 6). Fuel price has a larger impact on regional level than municipal level, as doubled fuel prize leads to total cost increase between 9 and 12 percent in municipal collection (Chapter 4) while in regional network, the increase is a bit higher, about 16 percent (Chapter 6). The results from municipal collection and regional network on the impact of carbon price in terms that carbon price, even set at its highest historical record, does not make the emission cost a large part in the total cost (e.g. less than 6% in Chapter 3). Nevertheless, the impact of the carbon price on the collection phase is higher than that from the regional network scale. Multimodal transportation network is more sensitive to carbon price change than uni-model network (Chapter 6). Furthermore, the carbon price change does make a difference optimization results. When carbon price is set to a difference value (Chapter 6), small changes in the optimization results started in the early section of the source-separation channel from municipalities to cross-docking centers (before split of plastic types). These results combined showed the impact of carbon cost is higher on the starting sections of the reverse supply chain for plastic waste than the later sections.

Apart from showing how sustainable performance is measured and used as an objective for supply chain redesign from the three decision levels, this thesis also demonstrates how sustainable performance can be improved strategically in the transportation and processing sector. A few strategies that aim to improve sustainable performance are also modeled. A recent literature review of operations research on MSW management suggested that the current literature is poor in such aspects as, multi-commodity and economies of scale (Ghiani et al., 2014). The present thesis covers these aspects. In the regional network presented in Chapter 6, multi-modality strategy is applied and, in the global network presented in Chapter 7, special attention is paid to the effect of emission trading scheme as a mechanism of influencing the re-processors' sustainable performance which takes economies of scale into account as an option for improving sustainable performance. Eco-efficiency performance improvement results provided valuable insights in analyzing future strategic changes. For example, the results in Chapter 7 showed a higher impact of carbon price than carbon cap on the global network performance, which can be taken into account in designing future environmental regulations.

This thesis also contributes in various ways to social sustainability. As concluded in Chapter 3, with a high frequency of waste collection in a residential area of city, a redesign that makes the collection more eco-efficient can not only reduce the emission quantity, but also other associated impacts (such as noise pollution, exposure to harmful odors, etc.). These impacts are difficult to quantify, but are still very important, especially for householders. The proposed global reverse logistics network redesign for plastic waste recycling in Chapter 7 can potentially help to reduce the possibility of migrant laborers being employed in the low-cost processing of waste that does not comply to safety regulations in manufacturing countries.

Cross-level decision support

Plastic waste recycling characteristics are taken into account in the decision making of different decision levels. Multiple collection and separation alternatives are taken into account by the scenario study research approach in the studies of all decision levels. Scenarios are made with a combination of alternative collection and separation methods. Models are applied to different scenarios in order to compare the differences between the alternatives. From each level, there is an obvious preferred choice between post-separation and source-separation. However, when these results from different decision levels are combined, they seem to conflict. In the collection phase, the average total collection costs per ton of plastic waste collected for source-separation municipalities are more than twice those of post-separation municipalities due to the frequent stops made and idling time at each stop. Within the source-separation there is a also large difference in cost between curb-side and drop-off collection. From the regional network perspective, post-separation scenarios have higher costs and environmental impact due to the limited number of separation centers compared to the numerous cross-docking sites for source-separation. It seems that combined results from different decision levels do not give a straight-forward preferred option. It is not only the municipalities' choices of separation and collection method, but also the locations of the different municipality with various choices on separation method and the locations of intermediate facilities and their capacity that combined determine the regional logistics cost. Nevertheless, these models help to quantify the differences and highlight the directions for improving performances on each alternative.

Plastics as a light material with a complex composition has made a large variation in truck utility depending on which type of waste is collected (plastics only or plastics mixed with other residual waste). In general, utility rate for collecting plastic waste is lower than that for collecting other waste types. We tested the impact of truck utility rate in municipal collection and regional collection in our studied case. Results in Chapter 4 showed that in municipal collection, although figure varies depending on the collection method, in general, the cost reduction is much faster when utility rate increase from 0% to around 30% than the increase after 30%. On regional level (Chapter 5), the tipping point is at around 50%. This result indicates the necessary of compressing plastic waste in both the collection phase and further transportation out of municipalities. The combined results also showed the need of having cross-docking centers available to perform baling of plastic waste in order to further improve the truck utility when transporting between facilities. As after each of the separation and sorting process in the network, for each of the inter-mediate processing facility the outbound plastic waste flow has usually lower density than the inbound flow. A certain level of compressing is needed when transporting the processed plastic waste out to the next processing facility in order to make the transportation more efficient.

Decision support through modeling methods can help decision makers. In practice, however, decisions are rarely made based solely on modeling results in practice. The measurements taken into account in the models do not cover all the factors that need to be taken into consideration when making decisions in reality. For example, a large extent of compressing the waste might make the transportation very efficient but make it more difficult to un-bale and further process the plastic waste. Therefore, the insights provided by these models can be taken into account by the decision maker to balance with other considerations(e.g. technical, political) in order to make an overall satisfactory decision.

Impact of external factors

In the introduction, we defined four external factors that influences the reverse logistics of plastic waste recycling: interests of stakeholders (e.g. existing local industrial recycling infrastructures, municipalities, transport service providers, householders), market incentives, regulations, and tax. This thesis has also shown how these factors are integrated in the models and their impacts.

- Recycling targets and differentiated taxation are taken into account at the operational level. EU regulation on waste recycling has been raising the recycling target to encourage recycling of waste. Improving the separation behavior of householders will result in an increased response rate of plastic waste in source-separation scenarios, which can lead to a reduced collection unit cost, as shown in our modeling results.
- Municipalities also can opt for different taxation schemes for household waste management, varying between a fixed fee or differentiated to volume/collection frequency; this is known as DIFTAR (means “pay as you throw” in English). Municipalities with DIFTAR have significantly lower curb-side collection costs than

those without DIFTAR, due to higher response rate (more plastic waste separated) induced by DIFTAR which increases the efficiency of collection. For drop-off collection, the difference is not so noticeable, as the extra return trip to empty trucks (trucks are more easily to be fully filled in drop-off collection than in curbside collection) compensates for the economies of scale achieved with increased utility.

- The interests of stakeholders are addressed in the scenario design on a tactical/strategic decision level. Assigning source-separation to rural municipalities and post-separation to urban ones takes the interests of householders into account. Scenarios with and without PET collection channels take into account the interests of collectors and producers of PET bottles. The results in Chapter 5 show that applying post-separation and differentiating urban and rural municipalities when choosing a separation method has a similar result as the current situation, with a slight reduction of overall cost with the assumption that additional separation facilities are available. Chapter 6 shows the population density of the municipalities has a larger impact on curbside collection than on drop-off collection.
- Market incentive is taken into account by strategically redesigning a global reverse network for plastic waste. Taking into account the market for recycled plastics, the valorization of recycled plastics is the motivation for applying a postponing strategy in the global network model. Location re-allocation of re-processors to be closer to the end market is tested in this model; the results showed a positive effect on cost reduction.

Overall, we can see that the external factors of recycling targets and taxation influence the redesign of the reverse supply chain at an operational level, resulting in a difference in collection cost. These factors can be taken into account in the modeling by settings in input parameters regarding waste quantity. Interests of stakeholders and market incentives as external factors provided the motivation for actors' strategic decisions on the reverse supply chain redesign. Stakeholders' interests have an impact on the municipalities in terms of the choice between source- and post-separation. Market incentives have an impact on the re-processors in terms of the choice of locations for re-processing facilities. These two factors are considered in modeling by the design and assessment of different scenarios.

8.3 Scientific relevance and further research

In this section, we elaborate the scientific relevance and contribution of this thesis to reverse logistics, modeling sustainable supply chains, and future research.

8.3.1 Reverse logistics

This research project applies the concept of reverse logistics on the network design of a plastics recycling system based on the case of the Netherlands. Characteristics of plastic waste are considered when developing the reverse logistics models for plastic waste recycling.

Our network structure is influenced by a particular feature of plastic waste; that is, a mixture of many types of plastic material. These types of plastic need to be separated and sent to various channels for appropriate treatment. Waste recycling logistics is a special category in reverse logistics. Fleischmann et al. (1997) noted that reverse distribution networks are not necessarily a symmetrical picture of forward distribution. Most of them have a “many-to-few” (convergent) network structure rather than a “few-to-many” (divergent) structure. In the case of Dutch plastic recycling networks, the many municipalities as suppliers and the few processing plants form such a convergent structure. We identified in Chapter 5 the intermediate processing plants, especially the separation plants are the key to the eco-efficiency of the network to decisions related to municipalities’ choice of their choices of separation method and the separate collection of PET bottles.

Furthermore, it is also a multi-commodity based network model. McLeod and Cherrett (2012) discussed sustainable waste recycling in the context of reverse logistics. They identified the difference between reverse logistics of waste and that of other return goods, which is the channel structure. Intermediate points often exist in the reverse supply chain for the consolidation of waste, which could be at regional distribution centers, transfer stations, or other locations, before transportation to the final disposal site. Unlike in a forward supply chain, in which product assembling happens in these intermediate points, in a reverse supply chain the product disassembles during each process step. In the plastic reverse logistics case, separation and sorting of plastic waste is “product disassemble ”. For an intermediate facility in the network, the inbound flow of plastic waste will turn to a few outbound flows of separated waste to different facilities. In the present study, this feature is modeled in all the network models and results in a different flow allocation after each disassemble process. The alternatives related to post-separation and source-separation, and PET channels are essentially the decision on the disassemble point. The impacts of these decisions are analyzed and results are summarized earlier earlier in subsection of answers to research questions.

In comparison to forward supply chains, reverse supply chains are generally more supply-driven (push) rather than demand-driven (pull) (van der Laan et al., 1999). In the case of plastic recycling, however, the growing demand on recycled plastic has triggered a flow of plastic waste overseas. Brito and Dekker (2003) stated that reverse logistics is conceptually different from waste management. Waste management assumes waste has no value to be recovered and deals with efficiently handling waste and its environmental and legal consequences. Reverse logistics focuses on products that have some value to recover. Therefore, in the modeling we take the demand into account by redesigning a global supply chain for plastic waste recycling.

Rubio et al. (2006) reviewed the characteristics of the research on reverse logistics and noted that the majority of research focuses on the study of tactical and operational aspects, such as production planning and inventory management. Research on the strategic aspects of reverse logistics is scarce. The present thesis deals with the interaction between available separation and collection methods. Through network planning and collection planning, our aim is to provide decision support for choosing the most suitable and sustainable recycling strategy from operational, tactical, and strategic levels.

8.3.2 Modeling sustainable supply chain

Environmental issues have become an important parameter in logistics network design. Srivastava (2007) reviewed green supply chain management from a reverse logistics angle. The new concept of green supply chain has led to a shift from minimizing cost to a balance between cost and environmental impact. The aim is not only to redesign a collection and treatment system that is cheap, but, more importantly, sustainable; that is, aim for economic, environmental, and societal improvement compared to the current situation. In the present study, eco-efficiency was used as the objective for redesign as a new angle with which to address the sustainable reverse supply chain problem for waste recycling. Eco-efficiency is used as the key performance indicator in the models. A total cost that includes emission cost is used in the objective function.

Real-life problems can be extremely complex and involve different system characteristics. Plastic waste recycling has several system characteristics. This thesis has demonstrated how these various issues are taken into account in the modeling process, by defining parameters, objective functions, and scenarios, as well as solution approaches. The complex composition of plastics has been interpreted in the models in two ways. First, the complex composition of plastic waste results in different types of plastics being treated in different ways. A separate channel for collecting and treatment of PET bottles is considered in the network models. Second, the complex composition of plastic waste means that there multiple end products result from the same component. Plastics are collected and sorted into five different product types in the models, which makes the network model a multi-commodity based model.

In the network modeling process, two commercial supply chain modeling tools are used to build and solve the network models: IBM Ilog logicNet and LlamaSoft Supply Chain Guru. The present study has shown how these tools developed for forward logistics setting can be used for exploring the frontier of scientific research in reverse logistics context while solving real-life problems. As most of these tools are developed based on forward logistics settings, this research has investigated how a reverse logistics problems can be modeled using such a tool. In Chapter 7, mathematical formulation of models are presented according to the way models are presented in the LlamaSoft Supply Chain Guru, which includes the use of dummy facilities, dummy by-products, and model emissions as components to make products, etc. These are not necessary elements from a theoretical point of view, but are key to fitting the reverse logistics problem into the framework of a forward supply chain modeling tool and integrating the new issues into the models.

8.3.3 Future Research

In Chapter 2, we summarized directions for future research. One of the identified directions is to view the waste recycling problem from a global angle. Chapter 7 presents a network design from the global angle, whereas there are also further possibilities to consider more issues in the global network design. For example, the fluctuation of market price and demand are not captured in the models in Chapter 7, but are worth consideration to be integrated. From reverse supply chain theory, it has been identified that reverse supply chain is more supply-driven (push) than demand-driven (pull). Adding the dynamic feature of demand into global reverse supply chain modeling could further demonstrate how reverse supply chain network design reacts to both pushes and pulls.

This thesis studied plastic waste recycling in specific by taking into account the features of plastic waste in the design. This is in line with the identified research direction of Chapter 2, that is to provide tailor made solution for specific waste types. After getting a clear picture on the recycling system plastic waste, it becomes interesting to look into the interaction between plastic waste and other waste types, especially in terms of sharing of facility. This thesis has only explored the interaction with other waste types regarding sharing collection facilities and intermediate locations in the network to a limited extent. Chapter 3 has included the other waste (remaining waste after recyclables are separated) to be incinerated in the network model. Future research direction can be to explore the possibilities of collection and transporting plastic waste together with other waste types, such as multi-compartment collection vehicle, shared drop-off bins, and shared cross-docking centers.

Environmental impacts have been quantified and included in the network models and collection models, while social impacts are considered and discussed, but not quantified. Therefore, for future research, it will be interesting to investigate measurements of social impact and include the quantified social impact into the objectives of models. As suggested in the conclusion of Chapter 2 that measurements from other research disciplines of social studies can be integrated with operations research methods to further explore the potential to model sustainable performance.

8.4 Managerial Insights

Decisions regarding what is the best and most efficient method of recycling are often impaired by a lack of insight. A clear view of best options is constrained by “the way it has always been done”, moral opinions about “doing the right thing”, and assumptions about the “correct” way of dealing with plastic waste. This research project of TIFN (Top Institute Food & Nutrition) is intended to provide scientific insights to the complex plastic recycling system. Research institutes, industrial organizations are collaborating in terms of gathering data for the research. As identified by Brandenburg et al. (2014), quantitative models could be employed to elaborate on the inter-play of regulatory decisions made by legal authorities and managerial decision making in firms, supply chains, or industries. The results of this thesis are intended to provide insights for the stakeholders involved. Hence, in this section, we have elaborated the managerial insights for various decision makers as an outcome of this research. Issues such as the allocation of collection points, the location and availability of processing facilities need to be taken into account simultaneously for decision making.

For municipalities and collection service providers
This research has provided valuable insights into the differences between the collection and separation alternatives. When making a decision on choosing collection and transportation alternatives, it is important for municipalities to consider this choice not only from a municipal level but also from a regional level. As the modeling results have shown no obvious “best way”, it is important to make the decision considering the choice of

other municipalities and the availability of the processing and supporting services on a regional level to balance the capacity, rather than focusing solely on each municipality.

For processors

The research findings also deliver a positive message regarding how improvements in sustainable reverse logistics can help balance resources. In Europe, on the one hand, there is over-capacity in waste processing and incineration plants in countries like Germany and The Netherlands. In Eastern European countries, on the other hand, the landfill rate is still very high (EEA, 2009). The research shows the feasibility of a more sustainable and cost-efficient way of transporting waste with multi-modality, especially over longer distances. This can potentially help to bridge the gap in recycling rates in Europe, leading to a general improvement in the performance of waste treatment.

Sustainable reverse logistics of plastic waste can also contribute to the marketing of the recycled material. Especially, when fuel prices are rising, multimodality has advantages in cost and emission savings. Lower logistics costs, lower emissions, and larger quantities would help to make the price and quality of the recycled plastic more competitive in the market. Relocation of waste re-processing plants can help to improve the valorization of various recycled plastic types. An effort to increase the sustainability of the reverse network, once acknowledged by consumers, would stimulate a higher participation rate and improved plastic waste recycling behavior. Re-location of re-processing facilities could potentially save transportation cost. Re-processors can also benefit from a location that is close to the end market in order to achieve better valorization of the recycled plastics. The modeling tool developed in this research helps quantify the potential benefits for decision makers to compare with the investment cost and other policy induced costs (such as licences) and constraints.

For policy makers

Processors' decisions on strategic changes cannot be feasible without supporting policies. A comprehensive measurement of the total cost in municipal collection and insights into the cost of all processes in the complete network presented in the global network study provide a clear estimation of the cost details in the reverse supply chain. These estimations provide fundamental information for policy makers on decisions related to waste recycling subsidies and for all supply chain actors on cost sharing.

This research has shown how transportation can be improved by optimizing transportation routes on a municipal and regional level and using multimodality and postponement strategies. In practice, as there are several European countries involved in the supply chain, the differences between neighboring countries can significantly influence the route and modality choice. Politically, differences in national regulations may not allow a trans-border shipment of plastic waste. There are also other cross-border restrictions related to the use of railways and waterways, as well as trading of waste. Quantifying the economic and environmental benefits can potentially lead to greater harmonization of such policies.

Another policy-related implication concerns emission costs. Incentives such as carbon taxes usually function as a tool to promote sustainable transportation. The sensitivity analysis results in this thesis show that, in the multimodality case, effectiveness of such incentive can be higher than in the uni-modal one, although current emission costs are too low to have significant impact on the total costs throughout the network.

Chapter 9

Summary/Samenvatting

Introduction

Recycled plastic can be used in the manufacturing of plastic products to reduce the use of virgin plastics material. The cost of recycled plastics is usually lower than that of virgin plastics. Therefore, it is environmentally and economically beneficial to improve the plastic recycling system to ensure more plastic waste from households is properly collected and processed for recycling.

Plastic waste has a complex composition and is polluted, thus requires a substantial technical effort to separate the plastics from the waste and to sort these into recyclable materials. There are several alternatives in the existing collection methods (curb-side and drop-off) and separation methods (source separation and post-separation). It is challenging to select a suitable combination of these methods and to design a network that is efficient and sustainable. It is necessary to build a suitable, efficient and sustainable recycling network from collection to the final processor in order to provide solutions for different future scenarios of plastics household waste recycling. Decision support is needed in order to redesign the plastic waste reverse logistics so that the plastic waste recycling supply chain can be improved towards a more sustainable direction. To improve the efficiency in the recycling of plastic packaging waste, insights are required into this complex system. Insights solely on a municipal level are not sufficient, as the processing and end market are important for a complete network configuration. Therefore, we have investigated the problem at three levels: municipal, regional, and global. Decision support systems are developed based on optimization techniques to explore the power of mathematical modelling to assist in the decision-making process.

This thesis investigates plastic waste recycling from a sustainable reverse logistics angle. **The aim is to analyse the collection, separation and treatments systems of plastic waste and to propose redesigns for the recycling system using quantitative decision support models.**

We started this research project by identifying research opportunities. This was done through a practical approach that aimed to find future research opportunities to solve existing problems (Chapter 2). We started from a review of current municipal solid waste recycling practices in various EU countries and identified the characteristics and key issues of waste recycling from waste management and reverse logistics point of view. This is followed by a literature review regarding the applications of operations research. We conclude that waste recycling is a multi-disciplinary problem and that research opportunities can be found by considering different decision levels simultaneously. While analyzing a reverse supply chain for Municipal Solid Waste (MSW) recycling, a holistic view and considering characteristics of different waste types are necessary .

Municipal Level

In Chapter 3, we aim to redesign the collection routes of household plastic waste and compare the collection options at the municipal level using eco-efficiency as a performance indicator. The collection problem is modeled as a vehicle routing problem. A tabu search heuristic is used to improve the routes. Scenarios are designed according to the collection alternatives with different assumptions in collection method, vehicle type, collection frequency, and collection points, etc. The results show that the source-separation drop-off collection scenario has the best performance for plastic collection, assuming householders take the waste to the drop-off points in a sustainable manner. In Chapter 4, we develop a comprehensive cost estimation model to further analyze the impacts of various taxation alternatives on the collection cost and environmental impact. This model is based on such variables as fixed and variable costs per vehicle, personnel cost, container or bag costs, as well as emission costs (using imaginary carbon taxes). The model can be used for decision support when strategic changes to the collection scheme of municipalities are considered. The model, which considers the characteristics of municipalities, including degree of urbanization and taxation schemes for household waste management, was applied to the Dutch case of post-consumer plastic packaging waste. The results showed that post-separation collection generally has the lowest costs. Curb-side collection in urban municipalities without residual waste collection taxing schemes has the highest cost. These results were supported by the conducted sensitivity analysis, which showed that higher source-separation responses are negatively related to curb-side collection costs.

Regional Level

Chapter 5 provides decision support for choosing the most suitable combination of separation methods in the Netherlands. Decision support is provided through an optimized reverse logistics network design that makes the overall recycling system more efficient and sustainable, while taking into account the interests of various stakeholders (municipalities, households, etc.). A mixed integer linear programming (MILP) model, which minimizes both transportation cost and environmental impact, is used to design this network. The research follows the approach of a scenario study; the baseline scenario is the current situation and other scenarios are designed with various strategic alternatives. Comparing these scenarios, the results show that the current network settings of the baseline situation is efficient in terms of logistics, but has the potential to adapt to strategic changes, depending on the assumptions regarding availability of the required processing facilities to treat plastic waste. In some of the tested scenarios, a separate collection channel for polyethylene terephthalate (PET) bottles is cost-efficient and saves carbon emission. Although the figures differ depending on the choices in separation method made by municipalities, our modeling results of all the tested scenarios show a reduction in carbon emissions of more than 25 percent compared to the current network.

Chapter 6 studies a plastic recycling system from a reverse logistics angle and investigates the potential benefits of a multimodality strategy to the network design of plastic recycling. The aim was to quantify the impact of multimodality in the network in order to provide decision support for the design of more sustainable plastic recycling networks in the future. A MILP model is developed in order to assess different plastic waste collection, treatment, and transportation scenarios. A baseline scenario represents the optimized current situation, while other scenarios allow multimodality options (barge and train) to be applied. With our input parameter settings, results show that transportation costs contribute to approximately 7 percent of the total costs, and multimodality can help reduce transportation costs by almost 20 percent (CO_2-eq emissions included). In our illustrative case with two plastic separation methods, the post-separation channel benefits more from a multimodality strategy than the source-separation channel. This relates to the locations and availability of intermediate facilities and the quantity of waste transported on each route.

Global Level

After the regional network redesign, Chapter 7 shows a global network redesign. The aim of this chapter was to redesign a reverse supply chain from a global angle based on a case study conducted on household plastic waste distributed from Europe to China. Emissions trading restrictions are set on processing plants in both Europe and China. We used a mixed-integer programming model in the network optimization to decide on location reallocation of intermediate processing plants under such restrictions, with the objective of maximizing total profit under Emission Trading Schemes (ETS). Re-locating facilities globally can help reduce the total cost. Once carefully set, ETS can function well as incentive to control emissions in re-processors. Optimization results show that relocating re-processing centers to China reduces total costs and total transportation emissions. ETS applied to re-processors further helps to reduce emissions from both re-processors and the transportation sector. Carbon caps should be set carefully in order to be effective. These results give an insight in the feasibility of building a global reverse supply chain for household plastic waste recycling and demonstrate the impact of ETS on network design. The results also provide decision support for increasing the synergy between the policy for global shipping of waste material and the demand of recycled material.

Conclusions

Chapter 8 summarizes the findings from chapters 2 to 7 and provides brief answers to the research questions. Beyond that, the integrated findings combine the results from different decision levels and elaborate the impacts of various system characteristics and external factors on the decision making in order to achieve an improved sustainable performance. Main findings are:

- Regarding the impact of carbon cost, the results from different chapters are consistent in terms that emission cost is only a small part of the total cost, even when carbon cost is set at its historically highest figure. When carbon price is set to a different value, impact of carbon cost on the change of optimization results is higher on the upstream of the reverse supply chain for plastic waste than the downstream.
- In Emission Trading scheme (ETS), carbon cap has a larger impact on eco-efficiency performance of the global network than carbon price.
- On one decision level, models can help to find the "best option". For example, in the collection phase, the average total collection costs per ton of plastic waste collected for source-separation municipalities are more than twice of the post-separation municipalities'collection costs due to the frequent stops made and idling time at each stop. From the regional network perspective, post-separation scenarios have higher costs and environmental impact than source separation due to the limited number of separation centers compared to the numerous cross-docking sites for source-separation. When combining decision levels, however, it is difficult to find one "best option" that fits all, as there are contradictory results when looking at the same factor from different decision levels. Through decision support models, we provided clear insights into the trade-offs and helped to quantify the differences and identify key factors to determine the differences.
- Population density differences in various municipalities influence the performance of curbside collection more than drop-off collection.

This information is valuable for decision makers to consider in the decision making process. Finally, managerial insights derived from sustainable reverse logistics for household plastic waste are summarized in Section 8.4.

Introductie

Voor het vervaardigen van plastic producten kan gerecycled plastic worden gebruikt om het gebruik van nieuw plastic te verminderen. De kosten voor gerecycled plastic zijn doorgaans lager dan die voor nieuw plastic. Het recycle systeem voor plastic is milieuvriendelijker en economisch voordeliger wanneer er wordt gezorgd dat er meer huishoudelijk plastic afval op de juiste manier wordt verzameld en verwerkt tot gerecycled materiaal.

Plastic afval heeft een complexe samenstelling en is vervuild. Er is daarom een substanti?le technische inspanning nodig om plastic van afval te scheiden en dit te sorteren in recyclebare fracties. Er bestaan verschillende alternatieven voor afval ophaalsystemen (ophalen aan de straat en wegbrengen naar een centraal punt) en afval scheidingsmethoden (bronscheiding en nascheiding). Het is een uitdaging om een geschikte combinatie te kiezen van deze systemen en methoden en zo een effici?nt en duurzaam netwerk te ontwerpen. Het is nodig om een geschikt, effici?nt en duurzaam netwerk te ontwerpen, van collectie tot de uiteindelijke verwerker, om oplossingen te bieden voor verschillende toekomst scenario's voor huishoudelijk plastic afvalrecycling . Bij het herontwerpen van de retourlogistiek voor plastic afval is ondersteuning bij de besluitvorming nodig zodat de supply chain voor gerecycled plastic zich in een meer duurzame manier kan ontwikkelen. Om de effici?ntie van het recyclen van plastic verpakkingsafval te verbeteren zijn inzichten nodig in dit complexe systeem. Inzichten op een gemeentelijk niveau alleen zijn niet voldoende omdat het verwerken en de uiteindelijke markt voor gerecycled plastic belangrijke aspecten zijn voor een complete configuratie van het netwerk. We hebben het probleem daarom onderzocht op drie niveaus: gemeentelijk, regionaal en wereldwijd. Beslissingsondersteunende systemen zijn ontwikkeld met behulp van optimalisatie technieken om om zo te onderzoeken wat de kracht is van wiskundige modelering als ondersteuning in beslisprocessen.

Dit proefschrift onderzoekt de recycling van plastic afval vanuit het oogpunt van een duurzame retourlogistiek. **Het doel is om de collectie-, scheidings- en behandelingssystemen van plastic afval te analyseren en om herontwerpen van het recycle systeem voor te stellen gebruik makend van kwantitatieve beslissingsondersteunende modellen.**

We zijn dit onderzoeksproject gestart met het identificeren van onderzoeksmogelijkheden. Dit is gedaan op een praktische manier met als doel om toekomstige onderzoeksmogelijkheden te benoemen waarmee bestaande problemen kunnen worden opgelost (Hoofdstuk 2). We zijn gestart vanuit een overzicht van de huidige inzamelpraktijken van huishoudelijk afval in verschillende EU-landen en hebben verschillende eigenschappen en kernpunten van afvalrecycling ge?dentificeerd vanuit een afvalmanagement en retourlogistiek oogpunt. Hierna is een literatuuronderzoek uitgevoerd met betrekking op de toepassingen van operations research in afvalrecycling. Hieruit hebben we geconcludeerd dat afvalrecycling een multidisciplinair probleem is en dat onderzoeksmogelijkheden gevonden kunnen worden in het beschouwen van het probleem op verschillende beslissingsniveaus tegelijkertijd. Wanneer de retourlogistiek voor huishoudelijk afval wordt geanalyseerd is een holistische aanpak nodig, evenals het onderscheiden van verschillende eigenschappen van verschillende afvalstromen.

Gemeentelijk niveau

In Hoofdstuk 3 hebben we tot doel de collectie routes voor huishoudelijk plastic afval binnen gemeenten te herontwerpen en collectie opties te vergelijken waarbij eco-effici?ntie als prestatieindicator wordt gebruikt. Het collectie probleem is gemodelleerd als vehicle routing probleem. Een tabu search heuristiek is gebruikt om de routes te verbeteren. Verschillende aannamen in collectiemethoden, voertuigtypen, collectiefrequentie, collectiepunten, enz. hebben geleid tot collectie alternatieven waarop scenario's zijn gebaseerd. De resultaten laten zien dat het 'bronscheiding wegbreng collectie systeem' het beste presteert, als aangenomen wordt dat huishoudens het afval op een duurzame manier wegbrengen naar de centrale collectie punten. In Hoofdstuk 4 wordt een uitgebreid kosten schattingsmodel gemaakt voor het verder analyseren van de impact van verschillende belastingheffing alternatieven op collectie kosten en milieu impact. Het model is gebaseerd op verschillende variabelen zoals vaste en variabele kosten per voertuig, personeelskosten, kosten voor de afvalcontainer of afvalzak, en ook emissiekosten (fictieve CO_2-heffing). Het model kan gebruikt worden voor beslissingsondersteuning wanneer er wordt nagedacht over strategische veranderingen in de collectie van afval in gemeenten. Het model, wat verschillende eigenschappen van gemeenten meeneemt, zoals mate van verstedelijking en het wel of niet toepassen van gedifferentieerde tarieven voor afval (DIFTAR), is toegepast in een Nederlandse casus. De resultaten laten zien dat het nascheidingssysteem over het algemeen de laagste kosten heeft. Het ophalen van afval aan de straat in grote steden zonder DIFTAR systeem zorgt voor de hoogste collectie kosten. Deze resultaten worden ondersteund door een gevoeligheidsanalyse die is uitgevoerd, waarin is aangetoond dat hogere bronscheiding negatief gecorreleerd is met de kosten voor het ophalen aan de straat.

Regionaal niveau

Hoofdstuk 5 geeft beslissingsondersteuning voor het kiezen tussen verschillende combinaties van afvalscheidingsmethoden in Nederland. Dit wordt gedaan aan de hand van een geoptimaliseerd netwerk ontwerp voor retourlogistiek dat het algehele recycling systeem effici?nter en duurzamer maakt, daarbij rekening houdend met de belangen van verschillende stakeholders (gemeenten, huishoudens, etc.). Een 'mixed integer linear programming' (MILP) model, dat transport kosten en de impact op de omgeving minimaliseert, is gebruikt om dit netwerk te ontwerpen. Het onderzoek volgt de aanpak van een scenariostudie; het basis scenario representeert de huidige situatie en andere scenario's zijn opgesteld aan de hand van verschillende strategische alternatieven . Wanneer deze scenario's met elkaar worden vergeleken kan worden geconcludeerd dat de huidige configuratie van het netwerk effici?nt is in termen van logistiek maar dat er potentie is om verbeterslagen te maken bij strategische veranderingen . Dit hangt wel af van de aannames omtrent de beschikbaarheid van benodigde verwerkingslocaties. In een aantal van de geteste scenario's blijkt een gescheiden collectiemethode voor Polyethyleentereftalaat (PET) kosten efficiënt te zijn en CO_2 emissie te besparen. Hoewel de afzonderlijke uitkomsten verschillen, afhankelijk van de keuzes die gemeenten maken met betrekking tot de scheidingsmethode, laten onze resultaten over alle geteste scenario's heen wel zien dat een reductie in de CO_2 emissie van meer dan 25% gehaald kan worden vergeleken met de huidige situatie.

In Hoofdstuk 6 wordt het plastic recycling systeem bekeken vanuit een retourlogistiek oogpunt waarbij de mogelijke voordelen worden onderzocht van het gebruik van multimodaal transport in het netwerk . Het doel was om de impact van multimodaliteit in het netwerk te kwantificeren om zo beslissingsondersteuning te bieden bij het ontwerpen van duurzamere plastic recycling netwerken in de toekomst. We hebben een MILP model ontwikkeld om verschillende scenario's te kunnen beoordelen met betrekking tot afval collectie, verwerking en transport. Het basis scenario representeert de huidig situatie en de andere scenario's zijn opgesteld aan de hand van verschillende multimodale toepassingen (binnenvaart en trein). Met onze parameter instellingen laten de resultaten zien dat transportkosten ongeveer 7% van het totaal uitmaken en met multimodale toepassingen tot 20% kunnen dalen (inclusief CO_2-equivalenten). In een illustratieve casus met twee scheidingsmethoden voor plastic, heeft de nascheidingsketen meer voordeel bij het gebruik van een multimodale strategie dan de bronscheidingsketen. Dit heeft te maken met de locaties en beschikbaarheid van tussenliggende faciliteiten voor tijdelijke opslag en overslag van het afval en de hoeveelheid afval dat vervoerd wordt op de routes.

Wereldniveau

Na het regionale niveau wordt in Hoofdstuk 7 een netwerk ontwerp op wereld niveau beschreven. Het doel van dit hoofdstuk is om een retourlogistiek netwerk vanuit een wereldwijd perspectief te ontwerpen. Dit is gebaseerd op een casus omtrent huishoudelijk plastic afval dat gedistribueerd werd van Europa naar China. Voor de verwerkingslocaties in Europa en China golden restricties op de emissiehandel. Een 'mixed-integer programming' model voor netwerk optimalisatie bepaalt de her-allocatie van tussenliggende verwerkingslocaties, met als doel om winst te maximaliseren bij het toepassen van het Emissiehandelssysteem (ETS). Het verplaatsen van faciliteiten op wereldniveau kan de totale kosten van het systeem omlaag brengen. Wanneer het zorgvuldig wordt toegepast kan het ETS systeem als prikkel werken om de emissies bij herverwerkers te beheersen. De resultaten van de optimalisatie laten zien dat het heralloceren van herverwerkers naar China de totale kosten en transport emissies reduceert. Het toepassen van ETS bij herverwerkers helpt om emissies verder te reduceren bij zowel herverwerkers en de transport sector. Streefwaarden voor CO_2 emissies moeten daarbij wel zorgvuldig worden ingesteld om effectief te zijn. Deze resultaten geven inzicht in de haalbaarheid van een globaal netwerk voor huishoudelijk plastic afval recycling en het demonstreert wat de impact is van het ETS op het netwerk ontwerp. De resultaten geven ook beslissingsondersteuning voor het versterken van de synergie tussen het beleid omtrent wereldwijd transport van afvalmateriaal en de vraag naar gerecycled materiaal.

Conclusies

Hoofdstuk 8 vat de bevindingen van Hoofdstuk 2 tot en met 7 samen en geeft beknopt antwoord op de onderzoeksvragen. Ook geven de bevindingen samen aanbevelingen op verschillende beslissingsniveaus en wordt de impact, van verschillende systeem eigenschappen en externe factoren op het maken van beslissingen, uitgewerkt om een duurzamere prestatie te bewerkstelligen. De belangrijkste bevindingen zijn:

- Met betrekking tot de impact van CO_2-kosten zijn de resultaten van de verschillende hoofdstukken consistent, in de zin dat emissiekosten maar een klein deel van het totaal uitmaken, zelfs wanneer CO_2-kosten ingesteld staan op het historisch hoogste niveau. Wanneer de CO_2-kosten op een ander niveau ingesteld staan is de impact op veranderingen in optimalisatie resultaten groter'upstream' dan 'downstream' in de retourlogistieke keten voor plastic afval.
- Bij het Emissiehandelssysteem (ETS) heeft de streefwaarde voor CO_2-emissies een grotere impact op eco-efficiënt presteren op globale schaal dan de CO_2-prijs.
- Op één beslissingsniveau kan model len helpen om een 'beste optie' te vinden. In de collectie fase zijn de gemiddelde totale collectie kosten van plastic afval bij bronscheidingsgemeenten meer dan twee keer zo hoog dan bij nascheidingsgemeenten bijvoorbeeld. Dit komt doordat er frequenter wordt gestopt wat (arbeids-)tijd kost. Op het regionale netwerk niveau hebben nascheidingsscenario's hogere kosten en grotere milieu impact dan bronscheidingsscenario's doordat er, in tegenstelling tot het aantal cross-docking sites voor brongescheiden materiaal, maar een beperkt aantal nascheidingslocaties is. Wanneer beslissingsniveaus echter gecombineerd worden

dan is het lastig om één 'beste optie' te vinden omdat er tegenstrijdige resultaten zijn wanneer er gekeken wordt naar dezelfde factor op de verschillende niveaus. Met beslissingsondersteunende modellen geven we inzicht in de afwegingen en helpen we verschillen te kwantificeren en de belangrijkste factoren te identificeren om de verschillen te bepalen.

- Bevolkingsdichtheid in de verschillende gemeenten be?nvloedt de prestaties bij het ophalen van het afval aan de straat meer dan bij het wegbrengen naar een centraal punt.

Deze informatie is waardevol voor besluitvormers om afwegingen te kunnen maken in het beslisproces. Als laatste zijn de bestuurlijke inzichten, afgeleid van duurzame retourlogistiek voor huishoudelijk plastic afval, samengevat in Sectie 8.4.

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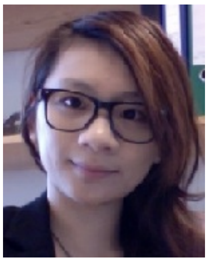
About the Author



Xiaoyun Bing was born on 26 Dec. 1985, China. She conducted her PhD research in the Operations Research and Logistics group at Wageningen University between 2010 and 2014. She worked in the project on post-consumer plastic packing waste recycling funded by Top Institute Food and Nutrition, the Netherlands. Her main fields of research interests are supply chain management, reverse logistics, logistics network design, transport planning and sustainability.

In 2013, with a junior research grant from WASS, she conducted a research visit to ÉTS, Canada for further advancing modelling skills. Between 2013 and 2014, she also worked as a researcher in Wageningen Food and Biobased research, specializing in supply chain management. She worked for multiple international projects at a time from strategic level to operational level for clients from industry and governmental organizations. Before working in Wageningen, she obtained her MSc. in Logistics and Transport Management from Gothenburg University, Sweden.

One of her publications, titled “Multimodal Network Design for Sustainable Household Plastic Recycling” won the TIFN 2013 Publication Prize. She was also awarded a bonus from TIFN for finishing her thesis within 48 months of her PhD period.

Xiaoyun Bing
Wageningen School of Social Sciences (WASS)
Completed Training and Supervision Plan

Name of the course	**Department / Institute**	**Year**	**ECTS (=28 hrs)**
I. Project Related Competencies			
Heuristic Methods in Operations Research	LNMB	2011	6
Combinatorial Optimization 1a	LNMB	2010	1
Summer School Zaragoza Logistics Center	MIT-ZLC	2013	2
Food Supply Chain Management	WUR	2010	2.5
II. General Research Related competencies			
Introduction course	WASS	2011	1
Techniques for Writing and Presenting a Scientific paper	WGS	2011	1.2
Information Literacy including EndNote Introduction	WGS	2010	0.6
Scientific writing	WGS	2011	1.8
Teaching methodology and skills for PhD candidates	ESD/WUR	2011	1.8
III. Personal Development			
'Sustainable Reverse Logistics Network Design for Household Plastic Waste'	ALIO/EURO Workshop on Applied Combinatorial Optimization, Portugal	2011	2.0
'Sustainable Municipal Collection for household Plastic Waste'	INFORMS International Conference, Beijing, China	2013	2.0
Writing research proposal	WASS	2011	6
Supervising Master thesis	WUR	2012	2.0
Supervising Bachelor thesis	WUR	2011	2.0
TOTAL			31.9

The studies presented in this thesis were performed within the framework of TI Food and Nutrition.