Resources, Conservation and Recycling 85 (2014) 79–87

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

A comprehensive waste collection cost model applied to post-consumer plastic packaging waste

Jim Groot[a,*], Xiaoyun Bing[a,b], Hilke Bos-Brouwers[b,1], Jacqueline Bloemhof-Ruwaard[c,2]

[a] TI Food and Nutrition, Food Chain Sustainability and Dynamics, Nieuwe Kanaal 9A, 6709PA, Wageningen, The Netherlands
[b] Wageningen UR Food & Biobased Research, Fresh Food and Chains, Bornse Weilanden 9, 6700AA, Wageningen, The Netherlands
[c] Wageningen University, Operations Research and Logistics, Hollandseweg 1, 6706KN, Wageningen, The Netherlands

ARTICLE INFO

Keywords:
Municipal waste collection
CO_2-eq cost
Post-consumer packaging waste
Plastic recycling
Cost model

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 centre 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.

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

* Corresponding author at: Wageningen UR Food & Biobased Research, Fresh Food and Chains, Bornse Weilanden 9, 6700AA, Wageningen, The Netherlands. Tel.: +31 317483827.
E-mail addresses: jim.groot@wur.nl (J. Groot), xiaoyun.bing@wur.nl (X. Bing), hilke.bos-brouwers@wur.nl (H. Bos-Brouwers), jacqueline.bloemhof@wur.nl (J. Bloemhof-Ruwaard).
[1] Tel.: +31 317480137.
[2] Tel.: +31 317484726.

0921-3449/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.resconrec.2013.10.019

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 organizing 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 (differentiated tariffs. 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) analyzed 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, sensitivity analysis is performed with discussions of findings. The paper ends with conclusions stated in Section 5.

2. Material and method

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

2.1. Data available

In this research the cost breakdown is made for all 418 municipalities in the Netherlands (Fig. 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 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 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.

Table 1
Expected response of collected plastic by urbanization level and taxation scheme for both source separated collection methods (kg/inhabitant).

Urbanization level	Collection method	DIFTAR (kg/inhabitant)	No DIFTAR (kg/inhabitant)
1	Curb side	–	–
1	Drop-off	–	3
2	Curb side	10	5
2	Drop-off	10	5
3	Curb side	12	6
3	Drop-off	8	6
4	Curb side	12	8
4	Drop-off	8	5
5	Curb side	12	8
5	Drop-off	8	5

Emission quantity is transferred to cost by a factor derived from carbon trading in Europe. The figure used is €20 per tonne CO_2-eq. The CO_2-eq per kilogram diesel fuel is 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. (2012a,b).

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 tonne 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.

2.2.1. Vehicle cost

2.2.1.1. 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_dri}), 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 $n-1$) × 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

Table 2
Values of input parameters.

	Abbreviation	Curbside	Drop-off	Post separation	Unit
Insurance cost/year[a]	C_{veh_insu}	2500	2500	2500	Euro
Tax cost/year[a]	C_{veh_tax}	1000	1000	1000	Euro
Depreciation period of a vehicle[a]	Dep	5	5	5	Yr
Interest rate of the investment[a]	$\%_{int}$	0.05	0.05	0.05	%
% of use of a vehicle per year[b]	$Eff\%$	0.8	0.8	0.8	%
Time one vehicle can be used per year[c]	$Time_{\_tyr}$	3000	3000	3000	h
The average hauling speed[d]	V_{veh_haul}	60	60	60	km/h
The average hauling distance[e]	D_{veh_haul}	18	18	54	km
Fuel price/litre[f]	P_{fuel}	1.4	1.4	1.4	Euro/l
The average speed while collecting between stops	[d]V_{veh_dri}	25	40	15	km/h
The number of households per curbside point[g]	hh_{con}	10	–	10	–
The average time per stop[h]	$Time_{\_stop}$	0.014	0.3	0.069	h
The investment cost of a vehicle[a]	C_{veh_inv}	206,000	250,000	206,000	Euro
The salvage cost of a vehicle[a]	C_{veh_sal}	30,900	37,500	30,900	Euro
The average truck load per collection round[h]	$truck_{load}$	1800	750	7200	kg
The total maintenance cost of the vehicle/year[a]	C_{veh_main}	3000	4000	3000	Euro
Fuel consumption for vehicle/km while driving[a]	CS_{dri_fuel}	0.33	0.4	0.4	l/km
Fuel consumption for vehicle/hr while idling[a]	CS_{idl_fuel}	4	3	4	l/h
Fuel consumption for vehicle/km while hauling[a]	CS_{haul_fuel}	0.25	0.25	0.33	l/km
The driver wage per year[h]	W_{driver}	30,000	30,000	30,000	Euro
The loader wage per year[h]	W_{loader}	25,000	25,000	25,000	Euro
The regular working hours of driver/year[h]	hr_{driver}	1650	1650	1650	h
The regular working hours of loader/year[h]	hr_{loader}	1650	1650	1650	h
The number of driver per vehicle[h]	n_{driver}	1	1	1	–
The number of loader per vehicle[h]	n_{loader}	2	0	2	–
The total cost of container maintenance per year[h]	C_{cont_maint}	0	250	0	Euro
The investment cost of the aboveground container	[h]C_{cont_inv}	0	1500	0	Euro
Depreciation Period of container[h]	Dep	0	15	0	yr
Capacity Container[h]	$Cont_{cap}$	0	100	0	tonne
The investment cost of the container 240l[h]	$C_{240\text{-}inv}$	0	0	58	Euro
Cost of a bag[h]	C_{bag}	0.055	0	0	Euro
The average distance between stops[b]	D_{dri_stop}	Dependent on municipality type			

[a] Derived from literature, backed up by experts and contractor.
[b] Difficult to optain, based on own judgement, backed up by expert.
[c] Every day, eight hours a day.
[d] Difficult to access but good rules of thumb exist.
[e] Derived from a network optimization model described by Bing et al. (2012b).
[f] Well known figure.
[g] Difficult to access, counted within own neighbourhood, backed up by experts.
[h] Derived from experts and contractor.

($freq_{col}$) 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 ($truck_{load}$).

$$C_{veh\_var} = \frac{C_{veh\_fuel} + C_{veh\_main}}{Q_{year}} \tag{1}$$

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

$$C_{veh\_dri} = CS_{dri\_fuel} \times D_{veh\_dri} \times P_{fuel} \tag{1b}$$

Total fuel cost while idling $C_{veh\_idl} = CS_{idl\_fuel} \times n_{stops} \times P_{fuel}$ (1c)

Table 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	4.6%
32	Leeuwarden	13.61	6.0%
1	Rotterdam	15.00	6.6%
68	Wijster	9.00	3.9%

Total fuel cost while hauling C_{veh_haul}

$$= CS_{haul\_fuel} \times D_{veh\_haul} \times P_{fuel} \tag{1d}$$

The total travel distance while collecting

$$D_{veh\_dri} = (n_{stops} - 1) \times D_{dri\_stop} \tag{1e}$$

The number of stops while collecting

$$n_{stops} = \begin{cases} (n_{hh} \times freq_{col})/hh_{con}, & curbside\ collection \\ Q_{year}/truck_{load}, & else \end{cases} \tag{1f}$$

2.2.1.2. 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.

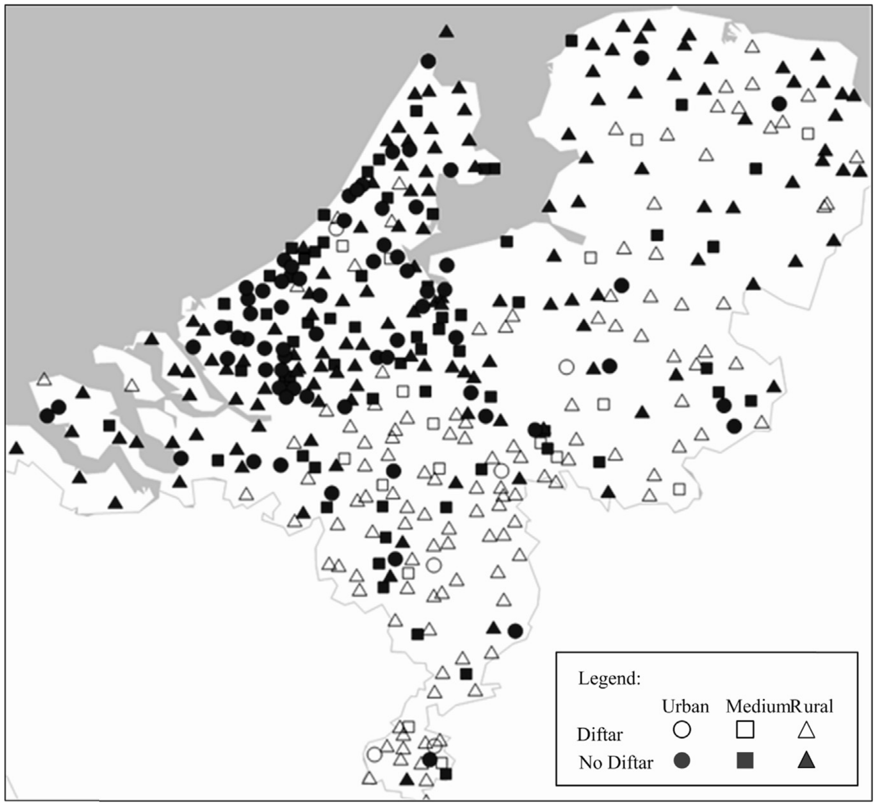

Fig. 1. Geographical locations of all municipality types.

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 ($Time_{veh\_col}$), 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.

$$C_{veh\_fix} = \frac{n_{veh} \times [C_{veh\_cap} + C_{veh\_insu} + C_{veh\_tax}]}{Q_{year}} \tag{2}$$

Vehicle capital cost

$$C_{veh\_cap} = \frac{C_{veh\_inv} - C_{veh\_sal}}{Dep + 0.5(C_{veh\_inv} + C_{veh\_sal})} \times \%_{\text{int}} \tag{2a}$$

The number of vehicles $$n_{veh} = \frac{1}{Eff\%} \times \frac{Time_{\_veh}}{Time_{\_tyr}} \tag{2b}$$

Time needed to collect waste $$Time_{\_veh} = Time_{veh\_col} + Time_{veh\_idl} + Time_{veh\_haul} \tag{2c}$$

Total collection time between stops $$Time_{veh\_col} = \frac{D_{veh\_dri}}{V_{veh\_dri}} \tag{2d}$$

Total idling time $$Time_{veh\_dri} = n_{stops} \times Time_{\_stop} \tag{2e}$$

Total hauling time $$Time_{veh\_haul} = \frac{D_{veh\_haul}}{V_{veh\_haul}} \tag{2f}$$

The total hauling distance $$D_{veh\_haul} = 2 \times n_{loads} \times D_{dri\_haul} \tag{2g}$$

The number of drops at the unloading location

$$n_{loads} = \frac{Q_{year}}{truck_{load}} \tag{2h}$$

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.

$$C_{labour} = (C_{driver} + C_{loader}) \times freq_{col} \times n_{veh} \tag{3}$$

Driver's labour cost $$C_{driver} = W_{driver} \times n_{driver} \times \frac{Time_{\_tyr}}{hr_{driver}} \tag{3a}$$

Loader labour cost $$C_{loader} = W_{loader} \times n_{loader} \times \frac{Time_{\_tyr}}{hr_{loader}} \tag{3b}$$

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 ($C_{cont,drop\text{-}off}$) (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 L 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 L 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

$$C_{cont,drop-off} = n_{cont} \times (C_{cont\_maint} + C_{cont\_inv}) \tag{4}$$

The investment cost of drop-off containers

$$C_{cont\_inv} = \frac{Cont_{inv}}{Dep + Cont_{inv}} \times \%_{inv} \tag{4a}$$

The number of drop-off containers $$n_{cont} = \frac{Q_{year}/freq_{col}}{Cont_{cap}} \tag{4b}$$

The cost of plastic bags for curbside collection

$$C_{bag,curbside} = n_{hh} \times freq_{col} \times C_{bag} \tag{5}$$

The cost of post-separation containers $$C_{cont,post} = n_{hh} \times \frac{C_{240\_inv}}{Dep} \tag{6}$$

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).[3] 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.

[3] Note that in our case the cost of CO_2 is not already internalized in the price of fuels, as might be the case in other countries.

Table 4
Average distance between stops (km).

Urbanization level	Curbside	Drop-off
Urban	0.155	3.0
Medium	0.180	3.0
Rural	0.195	3.0

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

$$C_{GHG} = Ct_{CO_2} \times F_{tot} \times GHG_{factor} \tag{7}$$

Total fuel use $$F_{tot} = CS_{dri\_fuel} \times D_{veh\_dri} + CS_{idl\_fuel} \times Time_{veh\_idl} + CS_{haul\_fuel} \times D_{veh\_haul} \tag{7a}$$

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 (levels 1 and 2), medium (level 3) and rural (levels 4 and 5).

3. Results

We conducted the cost calculation for all the municipalities in the Netherlands. On average, the total collection costs per tonne 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 Fig. 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

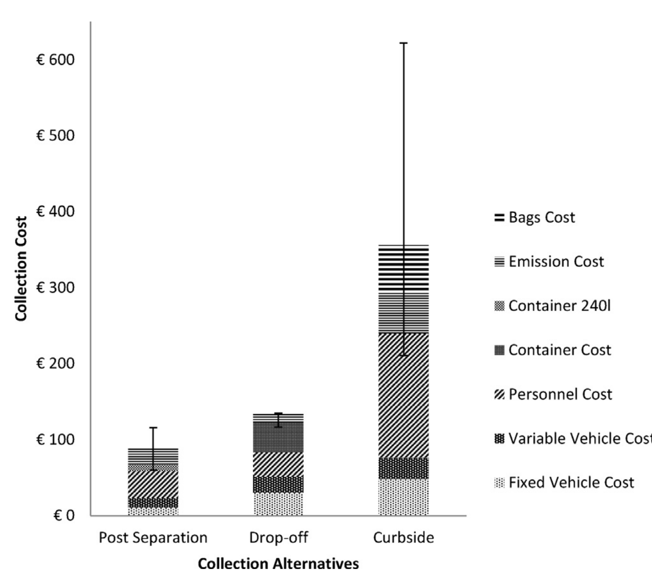

Fig. 2. Collection cost of post separation and source separation municipalities, the latter split into drop-off and curbside collection, including min and max municipalities. (€/tonne).

Table 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.

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 15% of the total cost for curbside collection municipalities and 8% for drop-off collection municipalities, which is 53 €/tonne for curbside and 11 €/tonne for drop-off. 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 (Fig. 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.

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.

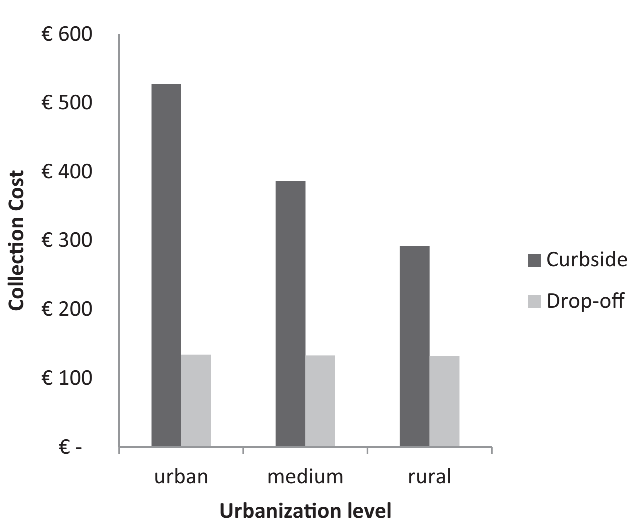

Fig. 3. Average total collection cost per municipality type of curbside and drop-off collection (€/tonne).

Tax charges influence the total collection cost which can be seen in Fig. 4. DIFTAR is 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.

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.

4.1. 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 analyzed with our model the impact of a different utility rate of the trucks and

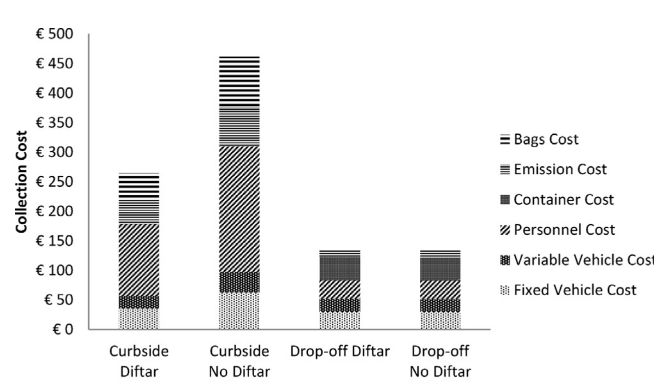

Fig. 4. Average total collection cost per municipality of curbside and drop-off collection with different tax charges (€/tonne).

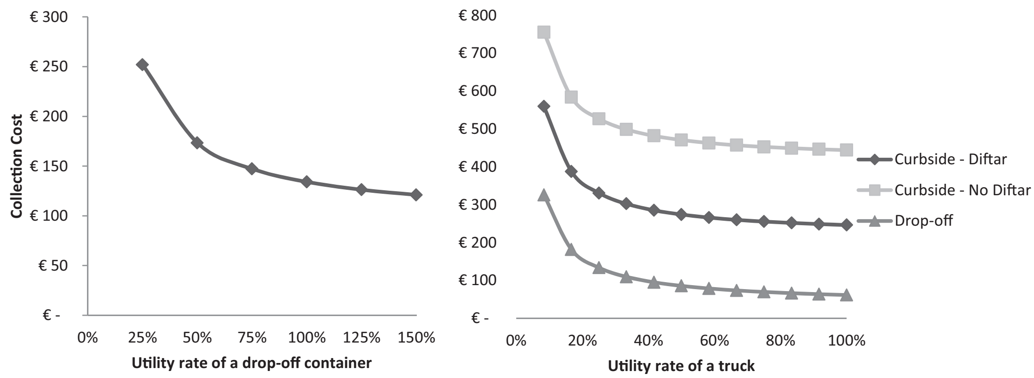

Fig. 5. Average total collection cost per municipality of curbside and drop-off collection with different utility rates of a container and collection truck (€/tonne).

containers on the total cost, without changing investment costs. The results are shown in Fig. 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.

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 Fig. 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

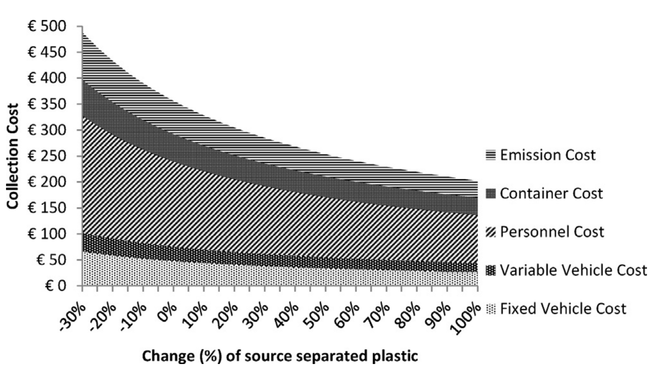

Fig. 6. Average total collection cost by a change in the amount of source separated plastic by curbside collection (€/tonne).

plastics. Doubling the current amount of source separated plastics, the total cost can drop by about 100 €/tonne. This result implies that a higher response rate can improve the efficiency of collection trucks.

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 9% in source-separation and 12% in post-separation. While, doubling the carbon cost would lead to a larger increase of total cost by 13% in source-separation and 24% in post-separation. This difference shows that carbon price, as a policy instrument, plays a critical role in the collection cost, although, from a reverse logistics network scale, carbon price has very limited impact on the total cost (Bing et al., 2012b).

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 9% to 12%, depending on the collection scheme used. The impact of doubling the currently used carbon pricing on the total collection scheme costs is larger than doubling the fuel price for trucks. This indicates that carbon price could be used as a powerful economic tool in the transition to sustainable waste management systems.

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) (of Michael) 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.

References

Agentschap NL. Waste charges 2011 “Afvalstoffenheffing 2011”. Utrecht; 2011. p. 45.

Beigl P, Salhofer S. Comparison of ecological effects and costs of communal waste management systems. Resources, Conservation and Recycling 2004;41: 83–102.

Bel G, Fageda X. Empirical analysis of solid management waste costs: some evidence from Galicia, Spain. Resources, Conservation and Recycling 2010;54:187–93.

Bing X, Bloemhof-Ruwaard JM, van der Vorst JGAJ. Sustainable reverse logistics network design for household plastic waste. Flexible Services and Manufacturing Journal 2012a., http://dx.doi.org/10.1007/s10696-012-9149-0.

Bing X, Groot JJ, Bloemhof-Ruwaard JM, van der Vorst JGAJ. Multimodal network design for sustainable household plastic recycling. International Journal of Physical Distribution and Logistics Management 2012b;43(6.).

Bohm RA, Folz DH, Kinnaman TC, Podolsky MJ. The costs of municipal waste and recycling programs. Resources, Conservation and Recycling 2010;54:864–71.

Cruz NF, da Simões P, Marques RC. Economic cost recovery in the recycling of packaging waste: the case of Portugal. Journal of Cleaner Production 2012;37:8–18.

Defra guidelines to Defra/DECC’s GHG conversion factors for company reporting: methodology paper for emisssion factors. Technical report. UK: Department for Environment, Food and Rural Affairs; 2012.

E. U. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Commission E, editor. Official Journal of the European Union 2012;312:3–30.

Hage O, Soderholm P. An econometric analysis of regional differences in household waste collection: the case of plastic packaging waste in Sweden. Waste Management 2008;28:1720–31.

Kplus V. Valuatie-onderzoek bron- en nascheiding kunststof verpakkingsafval (Evaluation research on source- and post-separated plastic packaging waste, in Dutch). Technical report. The Netherlands: Vereniging van Nederlandse Gemeenten (The Association of Dutch Municipalities, in Dutch); 2011.

Larsen AW, Merrild H, Moller J, Christensen TH. Waste collection systems for recyclables: an environmental and economic assessment for the municipality of Aarhus (Denmark). Waste Management 2010;30:744–54.

PlasticEurope. Plastics – the Facts 2012: An analysis of European plastics production demand and waste data for 2011. Plastic Europe, EuPC, EuPR and EPRO; 2012.

Rogge N, De Jaeger S. Measuring and explaining the cost efficiency of municipal solid waste collection and processing services. Omega 2013;41:653–64.

Sahlin J, Ekvall T, Bisaillon M, Sundberg J. Introduction of a waste incineration tax: effects on the Swedish waste flows. Resources, Conservation and Recycling 2007;51:827–46.

Statistics Netherlands [online database]; 2012, Available from: http://statline.cbs.nl/ [accessed 16.09.12].

Thoden van Velzen EU, Bos-Brouwers HEJ, Groot JJ, Bing X, Jansen M, Luijsterburg BJ. Scenarios study on post-consumer plastic packaging waste recycling. Wageningen UR Food & Biobased Research 2013.

VNG. Raamovereenkomst tussen I&M, het verpakkende bedrijfsleven en de VNG over de aanpak van de dossiers verpakkingen en zwerfafval voor de jaren 2013 t/m 2022 (Framework agreement between the Dutch ministry of infrastructure and environment, the packaging industry and the Association of Dutch Municipalities on the approach of the domain of packaging and litter for the years 2013 t/m 2022, in Dutch), [online]; 2012, available from: http://www.vng.nl/onderwerpenindex/milieu-en-mobiliteit/afval/nieuws/ledenraadpleging-overeenkomst-verpakkingen [accessed 10.12.12].