Contributions of municipalities to the recycling of post-consumer packages

Scientific basis for a municipal recycling model

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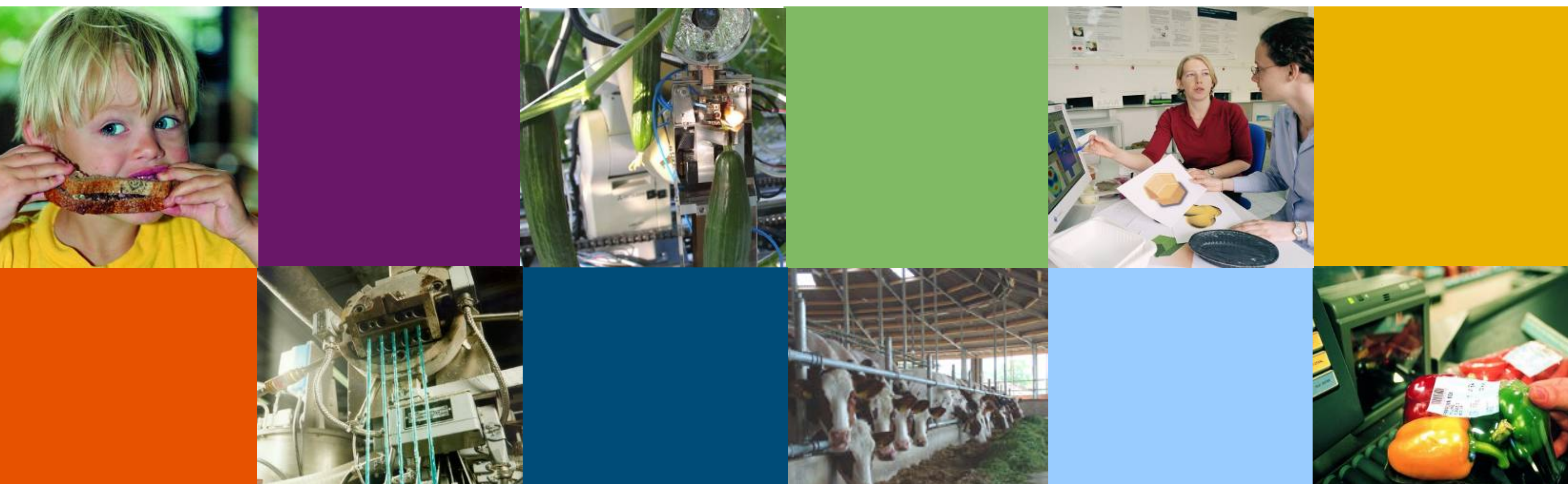
Report 1687



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Abstract

This report describes the technical background of a model that indicatively calculates the amounts of secondary materials produced on behalf of a municipality. This model describes the three steps in the recycling chain: 1) collection and recovery, 2) sorting and 3) recycling in net amounts of material. Based on trade relationships between incumbents in the recycling chains, the model predicts the applications of the secondary materials.
This model is intended to guide municipalities towards a more circular economy. Since municipalities are responsible for the management of local waste management systems, they have direct access to information relating to the amounts and frequently also the composition of municipal solid refuse waste (MSW) and separately collected (packaging) materials within their borders. With this information the model calculates the net amounts of secondary materials that are produced from the separately collected materials and where these materials have most probably been applied. This helps municipalities in fourfold:

- to estimate their current contribution to the circular economy,
- to analyse the development in time (by comparing historic data with current data),
- to plan for future policies and
- to use in communication towards the citizens; making the contribution of these citizens in separating packaging materials more tangible by showing what was produced from it.

Municipalities will have to insert the following data in the model: the collection systems that they operate, the amounts of waste and materials that are collected annually within the municipality and optionally the composition of the municipal solid waste. With this input data the model calculates the amounts of secondary materials produced on behalf of that municipality and indicates in which applications these are likely to be used.
The applied calculation method of the model is based on the amount of material being collected and/or mechanically recovered and net material yields for the three steps in the recycling chain (collecting & recovering, sorting and recycling). This involves corrections for gross weights of collected and / or recovered materials into the net weights and a subsequent multiplication with the net material yields for sorting and recycling. The net material yields were derived of the recovered masses that the incumbents have reported and material concentrations in input and output flows.
The calculated amounts of secondary products are based on reported data, own measurements and derived separating efficiencies. In a few limited cases assumptions had to be made. These secondary materials can be applied in various products. This is described with a market division. The market division of the secondary products is stable in time for glass, metal and beverage cartons, and for plastics, paper and board rather dynamic. Hence for glass, metal and beverage cartons, the expected applications are reasonable reliable, whereas for plastics and paper and board the expected applications are rather a first estimation.

Samenvatting

Dit rapport geeft de technische achtergrond bij een rekenmodel dat indicatief berekent hoeveel secundaire grondstoffen er zijn gemaakt namens een gemeente. Dit model beschrijft de drie stappen van de hergebruiksketen: 1) inzamelen en nascheiden, 2) sorteren en 3) recyclen in netto hoeveelheden materiaal. Op basis van de handelsrelaties in de hergebruiksketens voorspelt het model waar deze grondstoffen zullen worden toegepast.

Dit model is bedoeld om gemeenten te helpen richting een meer circulaire economie. Aangezien gemeenten verantwoordelijk zijn voor het gemeentelijk afvalbeheer, hebben ze direct toegang tot informatie aangaande de hoeveelheden en vaak ook de samenstelling van het huishoudelijk gemengde restafval en de gescheiden ingezamelde (verpakkings)materialen binnen de grenzen van hun gemeente. Met deze informatie berekent het model de netto hoeveelheden secundaire grondstoffen die worden geproduceerd en waar deze materialen vermoedelijk worden toegepast. Dit ondersteunt de gemeenten op vier wijzen:

- om hun huidige bijdrage tot de circulaire economie in te schatten,
- om de ontwikkelingen hiervan in de tijd te volgen, door historische data met huidige data te vergelijken,
- als ondersteuning voor beleid,
- om het te gebruiken in voorlichting naar burgers toe, en zo de bijdrage van de burgers aan de circulaire economie tastbaar te maken door te tonen wat er mee gemaakt is.

De gemeenten voeren in dit model de hoeveelheid afval- en materiaalstromen in die ze jaarlijks inzamelen en optioneel wat de samenstelling van het gemengde huishoudelijk restafval is. Dan berekent het model de hoeveelheden secundaire grondstoffen die er namens die gemeente zijn geproduceerd en geeft het model aan waar die waarschijnlijk zijn toegepast.

De berekeningswijze die het model volgt is gebaseerd op de netto materiaalstromen en de materiaalopbrengsten van deze netto materiaalstromen voor de drie stappen in de recyclingketen (inzamelen / nascheiden, sorteren en recyclen). Hiertoe worden eerst de ingezamelde en nagescheiden materiaalstromen teruggerekend naar netto-materiaal-hoeveelheden en vervolgens vermenigvuldigd met de netto materiaalopbrengsten. De laatste zijn afgeleid vanuit de door de betrokkenen gemelde massa-opbrengsten en de materiaalconcentraties in de ingaande en uitgaande stromen.

De berekende hoeveelheden secundaire grondstoffen zijn gebaseerd op gerapporteerde gegevens, eigen metingen en afgeleide efficiënties. Slechts in een paar gevallen moesten er veronderstellingen worden gemaakt. De secundaire grondstoffen kunnen breed worden toegepast, welke met een marktverdeling wordt beschreven. Deze marktverdeling is of heel stabiel (glas, metaal, drankenkartons) of sterk dynamisch (kunststof, papier & karton), zodat de ingeschatte toepassingen hiervan of nog redelijk betrouwbaar zijn of niet meer zijn dan een eerste indicatieve inschatting.

Content

1 Introduction

Motivation

Municipalities play a crucial role in the circular economy. They are responsible for the selection, application and implementation of either the separate collection of (packaging) materials or the mechanical recovery of the same materials from the municipal solid refuse waste (MSW). Without this step of collection and recovery the circular economy would not be possible. Decisions made by municipalities regarding the collection and recovery have profound consequences for the subsequent sorting and recycling facilities. The quantity and quality of the materials collected or recovered determine the amounts of secondary materials produced and the end-of-life fates of these secondary materials. To assist the municipalities in the decision making process regarding waste management and circular economy, a model was created that predicts the amounts of secondary materials produced on behalf of that municipality and the end-of-life fates of these materials. The model also renders the net recycling yields for five post-consumer packaging materials. These net recycling yields can be regarded as objective quantitative measures for the levels of circularity that municipality have attained. Additionally, it also expresses the potential for improvement for the municipality with respect to the recycling of the post-consumer packaging materials.

Municipalities are thus not only responsible for the selection of collection and recovery systems; they are also responsible for the selection of the post-collection business partners such as sorting and/or traders. These decisions define the further steps in the recycling chain.

The business relevance of the model is that it enables municipalities to make informed decisions to raise their contribution to the circular economy of recycling post-consumer packages. It renders the municipalities a quantitative insight in their current performance and gives them directions for further improvement.

The scientific relevance of this report and model is that it describes the Dutch post-consumer packaging material recycling chains in detailed technical terms for the first time. Most scientific contributions focus on either the general flaws of material recycling systems (Bartl 2014; Velis and Brunner 2013), or on detailed environmental analysis of these chains with nationally averaged figures (Ansems et al. 2015; Bergsma et al. 2011). Both approaches do not technically analyse the recycling chains in detail on the level of the decision making party (the municipality) and hence do also not give relevant bespoke directions to individual municipalities on how to improve their contribution to the circular economy.

Objectives

The primary aim of this report is to describe the relationship between the collection results of individual Dutch municipalities and their recycling performance in scientific terms, such as net recycling yields and the net amounts of secondary materials produced. This report is the scientific

basis under a modelling tool for municipalities, intended to give municipalities insight in what happens with the recyclable materials that are either separately collected within their borders or mechanically recovered from their MSW. This report explains the algorithms in the modelling tool and their relation to the current recycling practises.
The model itself (an Excel based calculation tool and a Dutch language manual) will be made publically available via internet. This model is primarily intended for municipal civil servants that seek support for local packaging waste management and circular economy policies. This model assists them in calculating the performance of their municipality with regard to packaging material recycling, and contributes to the decision making process on collection methods and material recovery contracts.
The secondary aim of this report is to scientifically describe the recycling chains for post-consumer packaging materials, in terms of overall efficiencies, improvement points and weaknesses.

Scope
This model will relate to recyclable packaging materials that are collected within municipalities from households, so-called post-consumer packaging materials. It will deal with the four main packaging material categories; plastic, paper & board, glass and metal. Beverage cartons will be treated in this report as a separate fifth type of packaging material. Although beverage cartons are legally considered a packaging type from the paper & board material group, its recycling pathway is different than for normal paper & board and hence is treated separately. Wood, however, will be disregarded as packaging material, since it is hardly used in consumer packaging and hence also hardly discarded by consumers.
This model deals with recycling schemes that are influenced by decisions on the municipal level, so they include separate collection schemes, recovery schemes, but not deposit refund systems or any other conceivable consumer-to-business remuneration scheme.
The recycling model will describe the process to convert the collected materials into secondary raw materials for these five types of packaging materials. Usually these recycling chains are composed of several conversion steps. In the most basic form a recycling chain is comprised of three steps: collecting, sorting and material recycling. A general description of the structure of the recycling chain for each material is part of this study.
This scope-limitation (post-consumer packaging materials) is well-chosen from a legal and scientific perspective. It is, however, difficult to relate to the municipal reality in which packages and non-packaging objects are treated similarly and hence a focus on only packaging materials can create differences with the perceived reality. Therefore, the model will calculate the results from both perspectives.
The model is a municipal model and not a national model. The total amounts of packaging materials consumed and discarded are known to show regional variations and hence municipal input data is required to achieve meaningful results on the municipal level.

For the second objective (technical descriptions of the recycling chains), the recycling chains are evaluated on a more aggregated, national level. Here the focus is on a qualitative analysis of the recycling chains in terms of the issues that have to be solved to achieve a more circular economy. The technical performances of the recycling chains are also assessed on a national level (see paragraph 4.1) to generate a benchmark for the performance of the municipalities. The results of the calculated national average net recycling chain yields will differ from officially reported recycling yields, due to four differences:

1. The net chain yields are based on net weights and not on gross weights,
2. The net chain yields consider three steps of the recycling chain and not only the first two steps (also see paragraph 5.2),
3. The net chain yields relate to post-consumer packaging materials only (and hence they do not include post-industrial packaging materials) and
4. The net potentials are not derived from industrial reports, but from an analysis of both the separately collected materials and the MSW.

This study is not intended to question the currently accepted method of calculating recycling yields, it is intended as a scientific attempt to analyse and understand the recycling chains. Nevertheless, we believe that a thorough scientific description is the best guidance towards improved circularity and hence a discussion on the method of calculating recycling yields is inevitable in case a high level of circularity is pursued.

Finally, this report is a technical study, and does neither include an environmental study, life cycle analysis nor economic analysis.

Client and financier
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2 Framework of the model

In this chapter the framework of the model to describe the relationship between the collection results of individual Dutch municipalities and their recycling performance is explained. Details about the framework of the model, such as the schematic overview, definitions and calculations, are included. The datasets that are used in the model are described in Chapter 3 Datasets in the model.

2.1 The model

The model itself is an Excel-sheet in which datasets and conversion equations translate the data on the collected packaging waste on behalf of a municipality into information about the municipal potential (amount of packages present at the households) and recycling performance. In figure 1 a schematic overview of this model framework is shown. The calculations and conversion equations in the model represent the packaging waste recycling chain, from potential at the consumers' houses to objects from recycled materials. The municipal data that is needed as input in the model consist of:

1) general information about the municipality, such as the name, the amount of inhabitants and optionally the amount of connections[1],
2) the amount of collected municipal solid waste (MSW),
3) the composition of the MSW (optionally but strongly recommended to obtain reliable results),
4) the amount of separately collected materials, per material type (for the five types of packaging materials).
5) optionally, the municipalities can enter information on the composition of the separate collected packaging materials, namely: the concentration of residual waste, the concentration of non-packaging materials and the level of attached moisture and dirt. Since many municipalities have not analysed these collected products, most calculations will be performed with national averaged default values.

In case (3) the composition of the MSW is not known, then as default value the national average composition is used. Although it is preferred to use local MSW-composition data, a first estimation can also be made with national averaged MSW composition data.

[1] *Connections is the waste management term used for the amount of households that are connected to the municipal waste management infrastructure.*

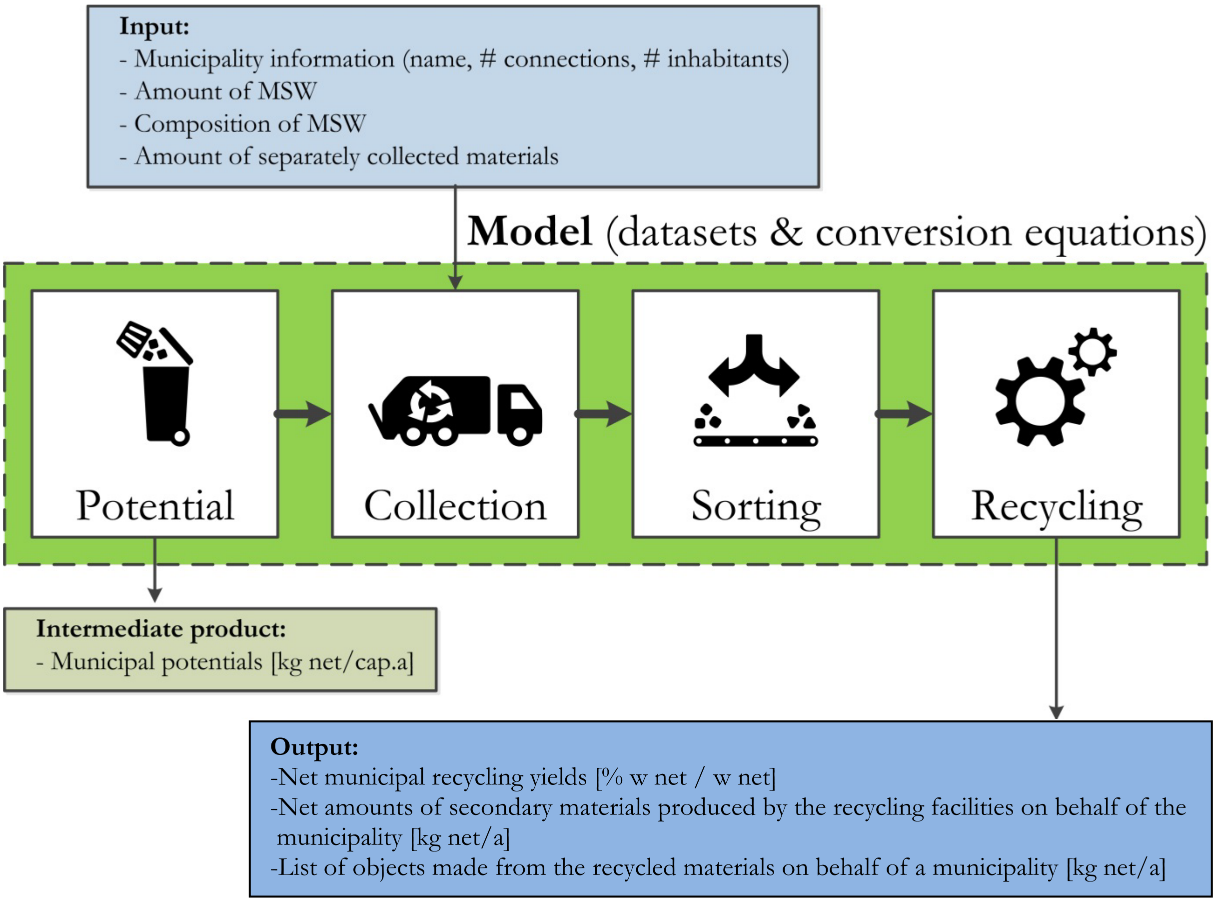

Figure 1: Schematic representation of the model which estimates the amounts of recycled objects made on behalf of municipalities.

Based on the input data, and the datasets in the model, calculations are performed for the five types of post-consumer packaging materials to estimate:

1) the net municipal potentials,
2) the net chain recycling yields,
3) the amounts of secondary materials produced by the recycling facilities on behalf of the municipality,
4) the type of objects that are likely to be manufactured from these secondary materials.

The municipal potentials are intermediate parameters. The net chain recycling yields can be considered as circularity indicators and hence as performance indicators for the municipalities. The list of products made from the recycled materials gives an indication of the municipality's contribution to the circular economy.

2.2 Major model assumptions

Municipalities strongly influence the effectiveness of packaging recycling systems in two ways. First of all, by their choice of a separate collection and / or mechanical recovery system, they strongly influence the gross quantity and the quality of materials that are collected and / or recovered. Secondly, with their selection of a sorting facility and / or trading partner, the sorting yields and often also the applications of the recycled materials are determined (since many sorting facilities have stable trading relationships with recycling facilities).

The influence of the gross collected and / or recovered amount is central in this model. The influence of the quality of the collected and / or recovered material is taken into account with nationally averaged values on the composition and optionally with municipality specific data, in case these are available.

The influence of the choice for a sorting facility on the effectiveness of the recycling chain cannot be considered in this public model, since facility specific performance data are considered company secrets and are not available in the public domain. Hence, we will use nationally averaged data for the performance of sorting facilities and recycling facilities.

2.3 Definitions

The five recycling chains are described with the parameters and terms defined below. These parameters are structured in line with the model and common steps of a recycling chain; potential, collection, sorting and material recycling.

Potential

- <u>Potential (P)</u>. Is the amount of packaging material that is potentially present at the households of a municipality. This parameter is expressed in the unit net kilogram weight per household per annum [kg net/hh.a]. The potential is derived of the net mass of packaging materials in the separate collection system and the net mass of packaging materials in the MSW (Municipal Solid Waste), see Equation 1 for an example. The net weight implies the weight of the dry and clean objects, thus without any attached moisture and dirt and contained product residues. Since most recorded weights are gross weights (thus with attached moisture and dirt and product residues), correction factors are required, see levels of attached moisture and dirt (LAMD).

Equation 1: Example of the calculation of the net material potential, in this instance for glass.

$$P_{Ede}^{Glass} = M_{Separate\ collected}^{Net\ Glass} + M_{MSW}^{Net\ Glass}$$

Parameter	Meaning	Unit
P_{Ede}^{Glass}	Net material potential for Glass packaging in the municipality Ede[2]	kg net/hh.a
$M_{Separate\ collected}^{Net\ Glass}$	Net amount of separately collected glass packaging in the municipality Ede	kg net/hh.a
$M_{MSW}^{Net\ Glass}$	Net amount of glass packaging present in the MSW of municipality Ede	kg net/hh.a

Collection

- MSW. Municipal solid refuse waste (in Dutch: *gemengd huishoudelijk restafval*).
- Response. Is the amount of separately collected packaging materials in a municipality. Responses are normally registered as gross weights, hence including residual materials and attached levels of moisture and dirt. This is the gross response. In order to model recycling chains, the net response has to be calculated from gross response, the total amount of residual materials present in the separately collected packaging material and the level of attached moisture and dirt. An example of this calculation is given in Equation 2. Since, the concentration of residual waste in the separately collected material and the packaging ratio (PR) are used in the model, this equation is slightly rewritten in the second line.
- Contaminants. Impurities present in the separate collected material stream which are not desired. These are studied by sorting analysis and often published as overall contaminant levels in %. Two different type of contaminants can be discerned for packaging waste:
    - Packaging components from different materials. (Dutch: *producteigen vervuiling*)
    - Unrelated materials and residual waste. (Dutch: *productvreemde vervuiling*)

  In this report the packaging components are treated as integral parts of the packages and not as contaminants, but their presence will be accounted for with the recycling yields. Residual waste and unrelated materials are treated as contaminants in this report.

[2] *The municipality of Ede was chosen in the example equations for its short name.*

Equation 2: Example of the calculation of net responses of a certain packaging material (in this instance glass) for a municipality (in this case Ede).

$$M_{Ede}^{Net\ Glass} = \left[M_{Ede}^{Gross\ Glass} - M_{Ede}^{Res.mat.in\ glass} - M_{Ede}^{Non-pack.mat.}\right].\left[100\% - LAMD\right]$$
$$= M_{Ede}^{Gross\ Glass}\left[100\% - c_{Ede}^{res.mat\ in\ glass}\right].PR.\left[100\% - LAMD\right]$$

Parameter	Meaning	Unit
$M_{Ede}^{Net\ Glass}$	Net glass packaging response of the municipality of Ede[3]	kg net/hh.a
$M_{Ede}^{Gross\ Glass}$	Gross glass packaging response of the municipality of Ede	kg gross/hh.a
$M_{Ede}^{Res.mat.in\ glass}$	Gross amount of residual materials present in the separately collected glass material of the municipality Ede	kg gross/hh.a
$M_{Ede}^{Non-pack.mat.}$	Gross amount of non-packages present in the separately collected glass of the municipality Ede	kg gross/hh.a
$LAMD$	Level of attached moisture and dirt	%
$c_{Ede}^{res.mat\ in\ glass}$	Concentration of residual waste in the separately collected packaging glass of municipality Ede	%
PR	Packaging ratio	%

- Levels of attached moisture and dirt (LAMD). For all packages in all different collection streams, the levels of attached moisture and dirt have to be measured to allow the conversion of gross amounts to net amounts and vice versa. These levels are determined by measuring the gross weight of a sample of packages, washing and drying them and measuring the net weight. The calculation is shown in Equation 3. These levels vary with packaging type, collection method and storage time. Furthermore, this level usually drops along the recycling chain. Since paper packages cannot be washed without disintegrating them, for paper packages usually only the moisture content is determined.

Equation 3: Calculation of the levels of attached moisture and dirt (LAMD).

$$LAMD = \frac{Gross\ weight - Net\ weight}{Gross\ weight}\ [\%]$$

- Material recovery. Several materials, such as metals, plastics and beverage cartons are recovered from the MSW in material recovery facilities (in Dutch: *nascheiden*).
- Net collection yield ($\eta^{collection}$). In case a municipality has a separate collection system in place, the net collection yield is net response for a certain material in a certain

[3] *The municipality of Ede was chosen in the example equations for its short name.*

municipality per year divided by the net potential for a certain material in a certain municipality. An example of this calculation is given in Equation 4.

Equation 4: Calculation of the net collection yield, of a certain material (in this instance glass) for a certain municipality.

$$\eta_{Glass\ in\ Ede}^{net\ collection} = \frac{M_{Separate\ collected\ in\ Ede}^{Net\ Glass}}{P_{Ede}^{Glass}}$$

- Net recovery yield ($\eta^{recovery}$). In case the municipality has a recovery system for a certain packaging material, the net recovery yield equals the net amount of material recovered on behalf of the municipality divided by the net material potential of that municipality. An example of this calculation is shown in Equation 5.

Equation 5: Calculation of the net recovery yield, of a certain material (in this instance metal) for a certain municipality.

$$\eta_{Metal\ from\ Ede}^{net\ recovery} = \frac{M_{Recovered\ from\ MSW\ on\ behalf\ of\ Ede}^{Net\ Metal}}{P_{Ede}^{Metal}}$$

- Net combined collection yield ($\eta^{combined\ collection}$). In case a municipality operates multiple separate collection systems and a recovery system for a certain packaging material, the combined collection yield equals the sum of net collected and or recovered amounts of packaging materials divided by the net potential for that material in that municipality. An example of this calculation is shown in Equation 6.

Equation 6: Calculation of the net combined collection yield, for a certain material (in this instance plastic) for a certain municipality.

$$\eta_{plastic\ from\ Ede}^{comb.collection} = \frac{M_{Sep.Coll.\ in\ Ede}^{Net\ plastic} + M_{Recovered\ from\ MSW\ of\ Ede}^{Net\ plastic}}{P_{Ede}^{Plastic}}$$

- Packaging ratio (PR). Is the amount of packages inside a separately collected material. This ratio is calculated from the gross weight ratio between packages and non-packaging objects , as shown in Equation 7. This ratio does not relate to residual waste present in the separate collection stream.

Equation 7: Calculation of the packaging ratio.

$$PR = \frac{M_{packages}}{M_{packages} + M_{non-packaging\ objects}}$$

Sorting

- Sorting facility / light-weight packaging processing plant. Industrial plants which convert collected and recovered materials into sorted products which are traded to recycling facilities.
- Sorting product / fraction. Products made by sorting facilities which are traded with recycling facilities. Sorting products have to comply with quality specifications to be acceptable for recycling facilities and to formally register as ‘recycling’.
- Sorting residue(s). Waste products formed during the sorting processes which are incinerated.
- Recovery of mass (R_m). The weight of a sorting product in relation to weight of the input material, expressed in percentages, as shown in Equation 8. In the industrial practise, recoveries of mass are based on gross masses. Furthermore, in several instances the registered recoveries of mass are not based on the weight of the input material, but instead on the total weight of the products. Since in many sorting processes moisture is lost during the process, recovery of mass based on input weights is often smaller than the recovery of mass based on total product weight. In this report the units of the numerator and the denominator are mentioned (w net/w net or w gross/ w gross).

Equation 8: Calculation of the recovery of mass.

$$R_m = \frac{M_{sorting\ product}}{M_{Input}}\ [\%]$$

- Sorting division. Distribution of sorting products made from the collected materials, expressed in percentages and often visualised in pie-charts. This parameter is a recovery of mass, but specifically used to describe the markets to which the sorted products are sold to.
- Sorting loss. Is the recovered mass of the sorting residues.
- Sum of recovered masses for sorting products. In Dutch named “*Sorteerrendement*”. This equals 100% minus the sorting loss, or the sum of the recovered masses of all sorting products with the exception of the sorting residues.
- Sorting yield. Is the yield of a certain recyclable product in a sorting product. It is basically the amount of a desired, recyclable material that has been sorted out in a certain sorting product in relation to the amount of that valuable material in the input. It is derived from the mass of the sorting product multiplied by the concentration of the desired material inside this sorting product divided by the total amount of this desired material present in the input material. Below is an example for plastic recycling, the sorting yield of PE packages in PE sorting product.

Equation 9: Calculation of the sorting yield of a certain material (in this instance PE) at sorting facility A.

$$\eta_{Sort.fac.A}^{sorting\ PE} = \frac{c_{PE\ objects}^{PE} \cdot M_{PE}}{c_{PE\ objects}^{Input} \cdot M_{Input}}$$

Parameter	Meaning	Unit
$\eta_{Sort.fac.A}^{sorting\ PE}$	Sorting yield of PE packages in the PE sorting product at sorting facility A	[%]
$c_{PE\ objects}^{PE}$	Concentration of PE objects in the PE sorting product	[%]
M_{PE}	Gross weight of the PE sorting product	[kg gross]
$c_{PE\ objects}^{Input}$	Concentration of PE objects in the input / feedstock	[%]
M_{Input}	Gross weight of the input material	[kg gross]

Both concentration terms ($c_{PE\ objects}^{PE}$ and $c_{PE\ objects}^{Input}$) refer to the plastic objects that are intended to be present in the sorted product, so for the PE sorting product this is basically the sum of all the rigid PE objects. These concentrations are derived from object-wise manual sorting, in which packages are sorted according to their main polymer and hence effects of components from different polymers and materials are not reflected in these concentrations.

- Sorting value ratio (SVR). Ratio of valuable sorting products over all sorting products, with the exception of the residues, see Equation 10. This ratio is only used for sorting plastics and co-collected mixtures such as PMD. It is calculated from the gross weights of the sorting products (PET, PE, PP, Film, MP (mixed plastics) and optionally BC (beverage cartons)). This ratio is not useful for calculating recycling yields, it is however used to assess sorting facilities and hence often reported.

Equation 10: Calculation of the sorting value ratio (SVR)

$$SVR = \frac{[M_{PET} + M_{PE} + M_{PP} + M_{Film} + M_{BC}]}{[M_{PET} + M_{PE} + M_{PP} + M_{Film} + M_{BC} + M_{MP}]}$$

Material recycling

- Recycling facility. An industrial plant that converts sorted material fractions into higher value intermediate products (*e.g.* washed milled goods, casted ingots, fresh pulp). In some chains (plastics, metals) there are several intermediate products and several recycling steps have to be described and analysed.
- Recycling yields. These yields are similarly expressed in terms of recovered masses (R_m) and material recycling yields (η) as with the sorting facilities. As the sorting product is the

feedstock of the recycling process and this material contains attached moisture and dirt, whereas the recycling product consists of dry and clean products, the net matter content (nmc) of the feedstock needs to be known to be able to calculate recovered masses and recycling yields. Recycling processes often result in multiple products and waste products. The most frequent recorded recovered masses and yields relate to the main product. Application of the yield-equation on the recycling of plastics and metals requires a clear definition of the objects & materials that are intended to be present in the recycled product, before the concentrations can be calculated.

Equation 11: Example of the calculation of the recovered mass (R_m) of a certain material (in this instance PE). For PE three products are formed during mechanical recycling: a floating plastic product (this is the main product) and a sinking by product and sludge as waste.

$$R_m{}^{recycling\ PE} = \frac{M_{Floating\ product}^{PE\ recycling}}{M_{Sorted\ PE} . nmc}$$

Equation 12: Example of the calculation of the material recycling yield (η) of a certain material (in this instance PE)

$$\eta_{Sort.fac.B.}^{recycling\ PE} = \frac{c_{PE\ recyclate}^{Intended\ plastics} . M_{Floating\ product}^{PE\ recycling}}{c_{Sorted\ PE}^{Contributing\ plastics} . M_{sorted\ PE} . nmc} \approx \frac{R_m{}^{recycling\ PE}}{c_{Sorted\ PE}^{Contributing\ plastics}}$$

Parameter	Meaning	Unit
$R_m{}^{recycling\ PE}$	Recovered mass for the recycling of PE	[%]
$\eta_{Sort.fac.B.}^{recycling\ PE}$	Recycling yield of PE at recycling facility B	[%]
$c_{PE\ recyclate}^{Intended\ plastics}$	Concentration of intended plastic in the PE recyclate	[%]
$M_{Floating\ product}^{PE\ recycling}$	Net weight of the main PE recycling product, the floating product	[kg net]
$c_{Sorted\ PE}^{Contributing\ plastics}$	Concentration of contributing plastic objects present in the feedstock, (here sorted PE)	[%]
$M_{Sorted\ PE}$	Gross weight of the input material (sorted PE)	[kg gross]
nmc	Net material content = 100%-LAMD of the input	[%]

The concentration of intended plastic objects in the main recycling product will approach 100%, implying that the most important concentration term is the concentration of plastic objects that contribute to the main recycling product in the feedstock (the sorting product). This concentration can be estimated from compositional data (derived from object-wise sorting), but remains an approximation, since it does not consider the complex material and polymer composition of single packages with multiple packaging components.

For the recycling of polyolefines (PE, PP, Film) this concentration relates to all the polyolefinic plastic objects, for PET this concentration relates to the total concentration of PET objects in the sorted product and for MP all plastic objects are relevant with exception of PVC.

- Product distribution. The estimated market division to which the intermediate recycling products (washed milled goods, cullets, ingots, pulp) are sold to.

2.4 Calculations

2.4.1 Net packaging material potential of municipalities

The material potential is the amount of material that is potentially present at the households of a municipality. This parameter is often expressed in the unit of net kilograms weight per household and annum [kg net/hh.a]. It is derived from the amount of packaging material present in the MSW and the amount of material present in the separately collected packaging material. Both quantities are converted from gross weights to net weights by subtracting the weights of other materials and correcting for the level of attached moisture and dirt. This is explained in Equation 13.

Equation 13: Calculation of net material potential (in this instance for glass) for a certain municipality.

$$NP_{Ede}^{Glass} = \frac{\left[M_{Ede}^{MSW} . c_{MSW\ of\ Ede}^{Glass} . (100\% - LAMD_{MSW}^{Glass}) + M_{Ede}^{Glass} . c_{Glass\ of\ Ede}^{Glass} . \left(100\% - LAMD_{Glass}^{Glass}\right)\right]}{AH_{Ede}}$$

Parameter	Description	Unit
NP_{Ede}^{Glass}	Net potential of packaging glass present in the municipality of Ede	kg net/hh.a
M_{Ede}^{MSW}	The gross weight of MSW collected in the municipality of Ede per year	kg gross/a
$c_{MSW\ of\ Ede}^{Glass}$	Concentration of packaging glass in the MSW of the municipality of Ede	%
$LAMD_{MSW}^{Glass}$	Level of attached moisture and dirt on glass found in MSW	%
M_{Ede}^{Glass}	The gross weight of packaging glass collected in the municipality of Ede	kg gross/a
$c_{Glass\ of\ Ede}^{Glass}$	Concentration of packaging glass in the separately collected glass of the municipality of Ede	%
$LAMD_{Glass}^{Glass}$	Level of attached moisture and dirt for packaging glass in separately collected glass	%
AH_{Ede}	Amount of households in the municipality of Ede	#

The concentration terms are defined in the same manner as the net responses in equation 2, implying only the desired packaging material is accounted for, and residual waste and non-packaging materials are excluded. The subtraction of residual waste is relevant for all materials. The subtraction of non-packaging materials is hardly relevant for paper, metal and beverage carton recyclers but more significant for the glass and the plastic industries. Non-packaging glass has usually a different chemical composition than packaging glass, hence higher melting temperatures and therefore larger chances of production incidents. The chemical composition of non-packaging plastics can also differ from packaging plastics.

Net packaging material potentials are not constant and known to vary between municipalities (Thoden van Velzen and Brouwer; Jansen 2016; Thoden van Velzen, Brouwer, et al. 2013). This probably reflects cultural differences in the consumption behaviour between those different municipalities.

2.4.2 Recycling chain yields

The recycling chain yield can be calculated in two ways, either with the recovered masses for each step (Equation 14), or with the net material yields for each step (Equation 15). In either way, the calculated amount of secondary materials produced should be equal (see Equation 17), whether the gross potential is multiplied with the recovered mass of the chain, or the net material potential is multiplied with the net material chain yield. Since business information on recycling is often expressed in recovered masses and scientific data is often available in net material yields, depending on the information position calculations can either be done with recovered masses or with net material chain yields.
Although it is also possible to convert recovered masses into net material yields, this requires detailed information on the concentration of the targeted material in the feedstock and the products, including moisture levels. Since the variation in the concentrations can be substantial, conversions can generate large propagated errors and hence these should be minimised where possible.
In this study, for each recycling chain it is decided to calculate the amount of secondary products either via the recovered masses or the net material yields, depending on the quality of the information available for each chain.

In order to calculate reliable chain yields, it is very important that the same units are used in the numerator and the denominator; in this report net weights will be used. This implies that for the gross recovered masses the loss of moisture during process steps has to be accounted for.

Equation 14: Calculation of recycling chain yield, with recovered masses.

$$R_M^{gross\ chain} = R_M^{gross\ collection} . R_M^{gross\ sorting} . R_M^{gross\ recycling}$$

Parameter	Description	Unit
$R_M^{gross\ chain}$	Gross recovered mass of recycling chain for a certain packaging material on behalf of a specific municipality	%
$R_M^{gross\ collection}$	Gross recovered mass for collection of a certain packaging material in a specific municipality	%
$R_M^{gross\ sorting}$	Gross recovered mass for sorting packaging materials at the sorting facility that is contracted by the municipality	%
$R_M^{gross\ recycling}$	Gross recovered mass for the recycling of packaging materials at the recycling facility	%

The municipality has direct influence on the chosen collection method and hence the recovered mass of collection and with the municipal choice for a sorting facility also on the recovered mass of sorting. And since many sorting facilities have long-lasting business relationships with recycling facilities, the choice for a sorting facility often also implies choices for recycling facilities.

Equation 15: Calculation of recycling chain yield, with material yields.

$$\eta_{\text{Ede}} = \eta_{Ede}^{collection} . \eta_{Ede}^{sorting} . \eta_{Ede}^{recycling}$$

Parameter	Description	Unit
η_{Ede}	Net recycling chain yield for a certain packaging material on behalf of the municipality of Ede	%
$\eta_{Ede}^{collection}$ *	Net collection yield for a certain packaging material in the municipality of Ede	%
$\eta_{Ede}^{sorting}$	Net sorting yield for a certain packaging material on behalf of the municipality of Ede	%
$\eta_{Ede}^{recycling}$	Net recycling yield for a certain packaging material on behalf of the municipality of Ede	%

* In case the municipality operates a recovery system or a combined collection system, then the net recovered mass of collection should be substituted for the net recovered mass of mechanical recovery or the net combined recovered mass of collection and recovery.

This general equation for the recovered mass of a recycling chain is valid for simple recycling chains with only one sorting product and one recycling product. However, most recycling chains are diverging chains, where multiple sorting and recycling products are formed. The equation for the recovered mass changes accordingly to accommodate for this complexity. Equation 16 shows the recovered mass for plastic from a municipality with a separate collection system.

Equation 16: Recovered mass calculation with multiple products, for a municipality with a separate collection system.

$$R_M^{chain} = R_M^{collection}.\left[R_M^{sorting\ PET}.R_M^{recycling\ PET} + R_M^{sorting\ PE}.R_M^{recycling\ PE} + R_M^{sorting\ PP}.R_M^{recycling\ PP} + R_M^{sorting\ Film}.R_M^{recycling\ Film} + R_M^{sorting\ MP}.R_M^{recycling\ MP}\right]$$

2.4.3 *Amounts of secondary materials produced*

The net total amounts of secondary materials produced equals the product of the net recovered mass of the recycling chain and the net potential or the product of the net chain yield and the net potential.

Equation 17: Calculation of the amounts of secondary materials produced.

$$M_{Ede}^{glass} = P_{Ede}^{Glass\ gross}.R_M^{chain}$$

or

$$M_{Ede}^{glass} = P_{Ede}^{Glass\ net}.\eta^{net\ chain}$$

Parameter	**Meaning**	**Unit**
M_{Ede}^{glass}	Net amount of recycled glass produced on behalf of municipality Ede	kg net/hh.a
$P_{Ede}^{Glass\ gross}$	Gross glass packaging potential for the municipality of Ede	kg gross/hh.a
R_M^{chain}	Gross recovered mass of the recycling chain yield	%
$P_{Ede}^{Glass\ net}$	Net glass packaging potential for the municipality of Ede	kg net/hh.a
$\eta^{net\ chain}$	Net glass recycling chain yield	%

2.4.4 *Sources of uncertainty and the quality of the results*

The modelling of the secondary products made from the packaging recycling chains renders estimated, indicative results and not precise results with known standard deviations. There are many sources of uncertainty within the model and these cannot all be quantified, for example (see also Table 1):

- The municipal data that is input in the model:
    - Compositional data of MSW are typically performed once every few years for a few neighbourhoods within the municipality and are often averaged. But the composition of MSW varies with the sampling method, season and the

neighbourhood (Dahlén and Lagerkvist 2008; Edjabou et al. 2015). Rijkswaterstaat reports averaged compositional data for Dutch MSW and confidence intervals that vary from 1-2% for the larger fractions to 0.1-0.6% for the smaller fractions (Rijkswaterstaat 2014).
    - The gross amounts of MSW and separately collected material streams are often reported in the unit of ton. Although the uncertainty in these gross amounts is small, due to the evaporation of moisture from these streams the uncertainty in the net amounts is still substantial. Additionally, due to the reporting in gross tons with a precision level of 1 tonne, the errors in the smaller streams of separate collected materials such as mono-collections of beverage cartons and metal packages can be substantial.
- Conversion parameters applied in the model:
    - Previous measurements of LAMD-parameters have shown that these parameters have broad distributions and hence the use of these parameters creates a relatively large error.
    - Packaging ratios also have distributions, but an average value is used in the calculation.
- Product distributions:
    - Sorting facilities and recycling facilities are diverging production units, making various products from single feedstocks. Both the distribution of the products made and the clients to which the products are sold vary in time. The plastic sorting distribution is known to be relatively stable in time[4], showing variations of maximally 1% on a monthly basis. The market relationships tend to be more dynamic for the plastic chain and since the recycling companies to which the sorting products are sold determine for a large extent the applications in which the recycled products are used, the latter will vary strongly with the market dynamics. Therefore, the list of plastic products in which recycled plastics are applied should only be used as an example and the reality can differ.

This implies that amounts of secondary materials produced can still be calculated and an estimation of the uncertainty for these numbers can be given. For those recycling chains with much market dynamics (plastics, paper & board) the precise applications of the secondary materials is not more than an impression of likely possibilities. For those recycling chains with relatively stable market relationships (glass, beverage cartons, metals) it is possible to also define fairly precise the applications in which the recycled materials is being re-used.

[4] *Based on confidential production data of individual sorting facilities that is aggregated on weekly and monthly basis.*

Table 1: The major sources of uncertainty for calculating the recycling chain yields.

Material	**Major sources of uncertainty**
Paper & board	Packaging ratio, Market division
Beverage cartons	Levels of attached moisture and dirt, in case of PMD collection the sorting yield
Plastics	Levels of attached moisture and dirt, Market divisions, in case of PMD collection the sorting yield
Metals	Market divisions In case of PMD-collected metals the losses during sorting and recycling
Glass	Sorting division

3 Datasets in the model

As explained in the previous chapter the model consist of datasets and conversion equations. In this chapter the datasets that are used in the model are explained.

3.1 Method of data collection

Detailed knowledge of two recycling chains was already present from previous projects. For both plastic packages and beverage cartons detailed technical parameters had already been determined previously (Thoden van Velzen, Brouwer, et al. 2013; Thoden van Velzen, Bos-Brouwers, et al. 2013) and just required checks, updates and scans of the scientific literature via Scopus.
The paper & board recycling industry publishes substantial amounts of nationally aggregated technical details on its own website (PRN 2012). For a description of the glass and metal recycling chain, interviews with stakeholders were held.
In general, for each material recycling chain documents of their material organisation and / or recycling organisation were sought and in case these documents were present, special attention was paid to the description of the industry structure, yields, compositions, purity levels etc. Furthermore, relevant national documents of Stichting Afvalfonds, Nedvang, Rijkswaterstaat and Vereniging Afvalbedrijven were collected. Additionally, a statistical overview with collection data was downloaded from the CBS-Statline site.
For two packaging material recycling chains (glass and metals) and one collection system (PMD) relatively little public data was available. Scientific publications sought via Scopus and Google also did not yield much insights in the structure and efficiencies of these recycling chains. Therefore, interviews were held with incumbents to fill these data gaps.

3.2 Model data

In this chapter all the input data that was used for the municipal recycling model is presented. Both the available data from public literature is systematically given and the estimations made to fill the data gaps are given including their justification.

3.2.1 Potential

The total amounts of packaging materials placed on the Dutch market are reported by Stichting Afvalfonds and Nedvang annually in their monitoring reports, see Table 2. These numbers are the net total amounts of packaging materials that are used and discarded by civilians and companies. The division between household use of packaging materials and company use of packaging materials is not known. Stichting Afvalfonds, Nedvang and the environmental inspection agency ILT take much effort to raise the reliability of these numbers, as is apparent from their reports and the discussion in these reports (ILT 2012). Nevertheless, the official amounts of packages annually placed on the Dutch market are derived from many different numbers. Some of these underlying numbers are estimations, as is explained in the monitoring report and inspection report (Afvalfonds Verpakkingen 2015). We cannot use this data in our municipal model directly, but it is used to verify calculated municipal potentials.

Table 2: National potential of packaging materials in the Netherlands according to Stichting Afvalfonds (Stichting Afvalfonds 2015).

Packaging material	National potential in 2013, [kton net/a]	National potential in 2014, [kton net/a]
Paper and board packages	1200	1167
Plastic packages	468	474
Glass packages	540	526
Metal packages	204	221

In this data, beverage cartons are considered as a part of the paper & board packages. The national consumption of beverage cartons is estimated to be 70 kton net annually (Thoden van Velzen, Brouwer, et al. 2013).

There is no reliable public data on the packaging material potential of individual municipalities. Three previous projects have indicated that there are substantial differences in packaging potentials between regions and municipalities and that therefore the national packaging potentials can deviate from municipal potentials, probably due to differences in consumption behaviour (Thoden van Velzen, Brouwer, et al. 2013; Thoden van Velzen and Brouwer; Jansen 2016). Therefore, in the model the potential (P) will be calculated based on the input data of collection of the municipalities (Equation 13).

3.2.2 Collection

The amounts of MSW and separately collected waste streams per municipality are available on-line via Centraal Bureau voor de Statistiek (CBS)[5] . The last available reported data (checked 17 November 2015) is from 2013 and is nearly complete for all Dutch municipalities with only a few exceptions. The reported data is in the unit kg gross/capitant.annum. The precision level is unfortunately in whole integers, meaning that the precision of the data is limited, especially for relatively small material streams such as beverage cartons and metals. In Table 3 the reported data is shown in terms of statistical parameters. Since this data only relates to separate collected waste fractions, it does not reveal amounts of metals, plastics and beverage cartons that are recovered from MSW.

[5] *CBS-Statline, http://statline.cbs.nl/Statweb/*

Table 3: Statistical representation of the collection results of MSW and separately collected packaging materials per municipality in terms of kg gross/cap.a (retrieved from CBS/Statline for 2013)

	MSW	P&B	Glass	Metal	BC *	Plastic
Average	193	64	23	2	1	10
St. dev.	62	16	9	2	2	5
Median	202	64	22	1	1	8
Minimum	22	21	10	0	0	0
Maximum	599	179	130	8	6	30
Number	408	405	408	37	66	357

*: BC stands for Beverage Cartons; a complete list of abbreviations is added on page 76.

The total amount of MSW generated in the Netherlands is reported by both CBS and the annual report of Vereniging Afvalbedrijven, this equalled 3526 and 3451 kton gross/a in 2013 and 2014, respectively, see Table 4[6]. The total amounts of separately collected materials are reported by CBS and Nedvang. The latter amounts of total collected material are related to municipal collection systems with the intention to only collect from households. The conversion to specific collection figures was done by CBS with the total inhabitants of the Netherlands, and not to the total inhabitants that have access to such a separate collection systems. This yields distortion of the data for separate collection systems, as these are not present in all municipalities. Additionally, the numbers of total collected amounts of materials do reflect all the material, not just packaging material.

Table 4: Total collected amounts of MSW and separately collected post-consumer materials within the Netherlands in 2013 and 2014[6].

	MSW	P&B	Glass	Metal	BC	Plastic
Total 2013, [kton gross]	3526	924	344	2	4	116
Total 2013, [kg gr/cap.a]	209.16	54.81	20.41	0.12	0.24	6.88
Total 2014, [kton gross]	3451	929	340	2	4	129
Total 2014, [kg gr/cap.a]	204.18	54.96	20.12	0.12	0.24	7.63

Furthermore, no distinction in collection system is made for these figures. This is especially relevant for glass drop-off collection, whether it is an all-colour collection system or a separate (white, green, brown and other) colour collection scheme. There is no public data on the

[6] *CBS statline, http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=7467*

amounts that are collected as separate colours and as mixed colours. However, Nedvang supplied us with a print-out from the Wastetool registration system, see Table 5. This indicates that roughly 34% of the glass collection is all-colours and 66% is colour-separated.

Table 5: Collection results for separately collected packaging glass according to Nedvang[7], [kg gross/a].

	2014	2015*
Glass all colours	113,136,743	114,407,235
Glass brown	19,000,944	19,873,824
Glass green	71,529,793	68,648,061
Glass clear	132,497,585	135,758,401
Total	**336,165,065**	**338,687,521**

*: preliminary data

3.2.2.1 Composition of Dutch MSW

The average composition of the Dutch MSW is regularly published by Rijkswaterstaat (RWS) as averaged numbers from sorting results of many different municipalities (Rijkswaterstaat 2013, 2015). The last public report on the composition of Dutch MSW gives the averaged composition for 2013 as triannual (2012-2014) averaged numbers for 2013 (Rijkswaterstaat 2013). This average composition of MSW in relation to packaging materials is listed in Table 6. The category of non-recyclable paper and board materials present in the Dutch MSW is mostly composed of non-packaging objects, when beverage cartons are excluded as separate category.

Table 6: Triannual average composition of Dutch MSW in 2013 in relation to packaging materials, according to Rijkswaterstaat (Rijkswaterstaat 2015).

Component	Average composition	Packaging	Non-packaging
Paper&Board wo BC	12.5%	4.5%	8.0%
-Beverage cartons[A]	3%	3%	0%
-Non-recyclable wo BC	4.5%	0.7%	3.8%
Plastics	14%	8.8%	5.2%
Glass	5.2%	4.9%	0.3%
Ferrous metals	3.3%	2.3%	1.0%
Nonferrous metals	1.1%	0.78%	0.32%

A): compositional data of the paper & board fraction was used to single out beverage cartons and present them as a separate category.

The levels of attached moisture and dirt for packaging materials found in Dutch MSW have only been reported for beverage cartons (Thoden van Velzen, Brouwer, et al. 2013). Additional

[7] *Personal communication with Dick Zwaveling of Nedvang on May 26th 2016 via an email message.*

measurements have been performed on MSW from Friesland in September 2015 to complete the levels of attached moisture and dirt for all the packaging materials. The crude measurement data is listed in Annex A. An overview of the data is given in Table 7.

Table 7: Levels of attached moisture and dirt for packages found in Dutch MSW.

Packaging materials	Level of attached moisture and dirt, [%]	Source
Paper&Board wo BC	40% (*)	AM
-Beverage cartons	41%	(Thoden van Velzen, Brouwer, et al. 2013)
Plastics	40%	AM
Glass	8%	AM
Metals	25%	AM

(*): for P&B only the moisture content was measured. AM: Additional measurement, see Annex A.

3.2.2.2 Composition of separately collected packaging materials

Separately collected (packaging) materials contain besides packages also non-packaging objects, foreign materials that were not intended to be collected and attached moisture and dirt. Although some of the foreign materials added to the mono-collection systems are still recycled (for instance paper & board added to a mono-collection of beverage cartons) the majority will not be recycled and will just increase the amount of sorting residues and lower the recycling yield. Therefore, this category of foreign materials is named 'residual waste'. For some mono-collected materials such as paper & board there are rich sources of public data on contamination (Hoogland 2015), whereas for others there is no public information. These parameters are used in Equation 2 to convert gross collected amounts in net collected amounts.

The content of foreign materials and/or residual waste in separate collected packaging materials are listed in Table 8. For all materials average values have been reported, except for metal packages, for which these values were estimated. In the same table also the levels of attached moisture and dirt are given for the five packaging materials. For both plastic packages and beverage cartons these values have been determined in the past extensively. From the available data it appears that these values have broad distributions and hence calculations based on such figures introduce relatively large uncertainties in the final results.

The packaging ratios for the five mono-collected packaging materials are shown in Table 9. These are based on the gross weights of packages and non-packaging objects only (hence irrespective of the amounts of foreign materials).

Table 8: Residual waste content and LAMD for the five separately collected packaging materials.

Mono collected packaging materials	Residual waste content, [%] *(NL:productvreemde verontreinigingen)*	Source
Paper & board wo BC	4.2%	(Hoogland 2014)
- Beverage cartons	15%	(Thoden van Velzen, Brouwer, et al. 2013)
Plastics	10%	(Thoden van Velzen and Brouwer 2014)
Glass	0.54%	(Bureau Milieu & Werk BV 2014)
Metals	5%	Guessed estimation

Mono collected packaging materials	LAMD, [%]	Source
Paper & board wo BC	10%	Estimation based on PRN acceptance criterion
- Beverage cartons	29%	(Thoden van Velzen, Brouwer, et al. 2013)
Plastics	15%	(Thoden van Velzen 2013)
Glass	2%	Guessed estimation
Metals	10%	Guessed estimation

Table 9: Packaging ratios for the five mono-collected packaging materials.

Mono collected packaging materials	Packages	Non-packaging objects	Source
Paper & board wo BC	23-45%	55-77%	(PRN 2012) / [8]
- Beverage cartons	100%	0%	(Thoden van Velzen, Brouwer, et al. 2013)
Plastics	89%	11% (*)	(Thoden van Velzen and Brouwer 2014)
Glass	99.9%	0.1%	(Bureau Milieu & Werk BV 2014)
Metals	80%	20%	Guessed estimation

*: The Eureco report of 2016 reports 9.8 ± 1.5% of non-packaging plastics in sorted plastic products, not in separately collected plastic packaging waste (Eureco 2016).

The packaging ratio for paper & board has last been reported to be 23% by PRN in 2012. Several stakeholders have suggested that this ratio will rise due to the rise of the online market and hence the increased use of board-based parcels and the simultaneous decline in the amount of newspaper subscriptions. Recently, Nedvang has published a number of 45% for this ratio on its website[8]. According to the director of PRN, this ratio can, however, still best be estimated to be 23%.[9] This is a substantial difference, which is likely to involve methodical differences. For the model an average value of 35% was taken as average between both perspectives.
For beverage cartons the ratio is estimated to be 100%, since during the pilot beverage cartons in 2013 not a single non-packaging object was found in samples of separately collected beverage cartons.
The packaging ratio for plastics was calculated from the same dataset which was used to report the average composition of Dutch post-consumer plastic packaging waste (Thoden van Velzen and Brouwer 2014).
The packaging ratio for separately collected metal packages is unknown and therefore the ratios of metal packages in MSW were taken and numbers were rounded.

3.2.2.3 PMD-collection

From 2015 on, a growing number of Dutch municipalities have implemented the separate co-collection system for plastic packages, metal packages and beverage cartons, named PMD. Although more and more municipalities are adapting this collection system and hence PMD appears to become the most important collection system for the three packaging materials, hardly any public technical data is available on the performance of this collection system and the subsequent sorting and recycling steps.
Belgium has a related PMD separate co-collection system in place for many years and has documented this (FostPlus 2014; De Jaeger and Rogge 2014). The Dutch PMD co-collection system is different with respect to the portfolio of plastic packages that are accepted in both systems, though. In Belgium only plastic bottles and rigid packages are accepted within PMD collection bags. Whereas in the Netherlands all plastic packages are accepted and hence it contains much more flexible plastic packages. The presence of flexible packages are well-known to reduce sorting efficiencies (Jansen et al. 2015). In this respect, the Dutch PMD collection rather resembles the German LVP-collection system (Leicht Verpackungsmüll). Nevertheless, in Germany only about half of the sorted plastic packages has to be recycled mechanically into secondary materials, whereas in the Netherlands as much as possible has to be recycled mechanically into secondary materials. This puts a larger constraint on the sorting process for the Dutch PMD system as compared to the German LVP system to avoid the formation of mixed plastics and residual fractions. Increased sorting losses could result from agglomerate formation, which obstruct sorting processes as agglomerated materials are less easy to separate. These

[8] *Nedvang, http://www.nedvang.nl/nedvang-en-monitoring*
[9] *Personal communication with Wienus van Oostrum of PRN on December 8th 2015 via email message.*

agglomerates can be formed by consumers stuffing smaller packages in one larger package and discarding these agglomerates and by mechanical pressing within the collection vehicles which can result in the spearing of plastics and beverage cartons by the sharp edges of metal packages to form agglomerates. It is likely that well-engineered sorting facilities can deal with this challenge for a large extent and form sorted products without increasing the sorting losses too much. But for a technical analysis this needs to be assessed and that has not been done, yet. Hence, due to a lack of technical data the recycling chain for PMD material can only be described with estimations and not with measured parameters. Therefore, in this report the PMD recycling chain will be described with data from related mono-collections and co-collections. One sorting analysis on PMD material from a Dutch city revealed that this material is composed of about 65-70% plastic packages, 10-12% beverage cartons, 10-12% metal packages and about 10% residual waste, see Figure 2. The composition of the plastic packages was similar[10] to the mono-collected plastic packages (Thoden van Velzen and Brouwer 2014). Since this was the only compositional analysis present, it should be used indicatively.

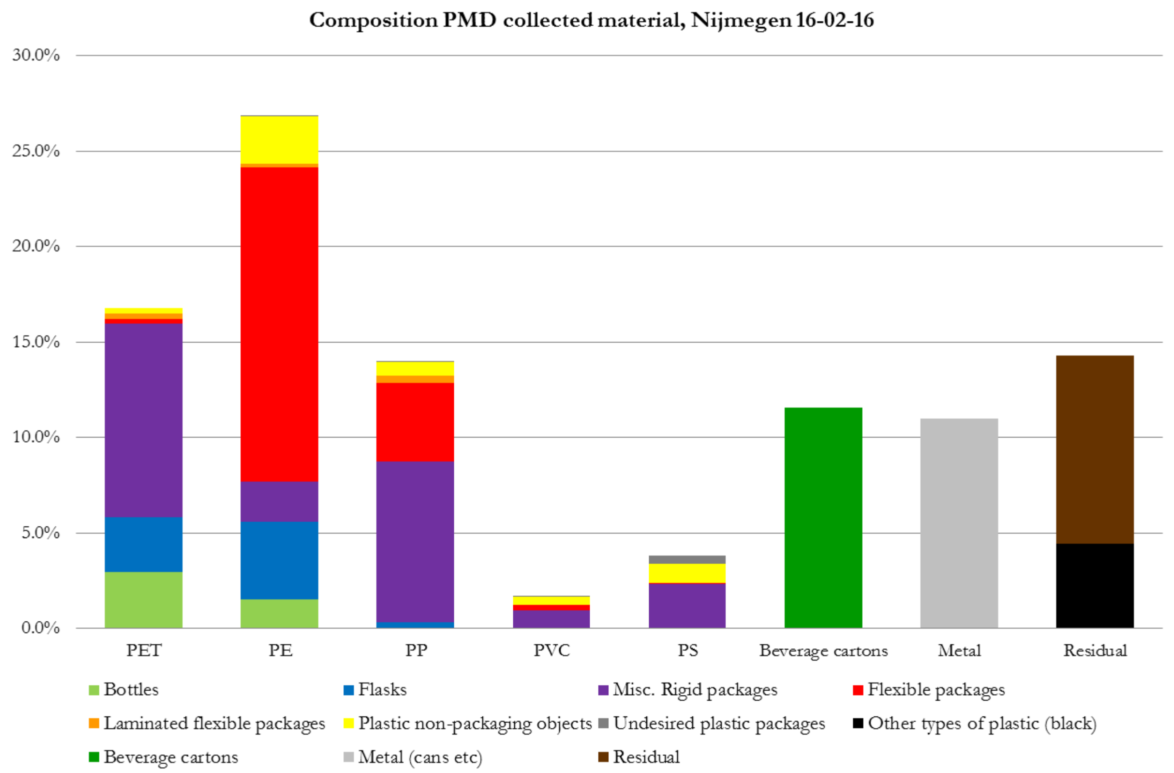

Figure 2: Composition of co-collected PMD material from the city of Nijmegen in February 2016.

[10] *Only the concentration of carriage bags was slightly reduced (from about 3 to 1%), which can most likely be attributed to the new prohibition policy for free carriage bags.*

3.2.2.4 Recovery of packaging materials from MSW

In 2015 three Dutch waste recovery facilities recovered post-consumer plastic packaging waste from MSW. The recovery facility of Omrin produces a film fraction and a rigid plastic fraction. The latter is sorted at Augustin in Meppen (D). The recovery facility Attero Noord operates similarly but sends the produced plastic fractions to Attero Wijster for sorting and trading. The Attero Wijster facility is a combination of a recovery facility and a sorting facility. For the recovery systems, the amounts of sorted fractions produced are recorded and registered in kg gross/a. All three recovery facilities work for different service areas of municipalities, with different amounts of inhabitants and connections.

Table 10: Main technical parameters that describe the amount of sorted fractions produced on behalf of a group of municipalities.

	Attero Noord	Attero Wijster	Omrin
Inhabitants in service areas	479700	2682800	785900
Households in service area	242700	1415600	342900
Produced sorted fractions, [kton gross/a]	7.0[A]	11.1[A]	12.8[B]
Amount of infeed MSW, [kton gross/a]	104.3	472.9	165.8
Estimated percentage of plastic / plastic packaging in the infeed MSW, [%]	18.8% / 12.1%	13.6% / 8.7%	20% / 12.8%

A: Amount registered for 2014, B: extrapolation of the total amount for 2015 based on production data up to June 2015.

The precise amount of plastic packages inside the MSW that is fed into the recovery facilities is unknown and is likely to vary between the facilities, since the facility Attero Wijster recovers plastic from MSW of municipalities that already have a separate collection system in place. According to representatives of Omrin[11], the concentration of plastics in the MSW is likely to be 20%, equal to the national average that was reported by RWS for 2012 (Rijkswaterstaat 2013). Hence in accordance with these numbers, the concentration of plastic packages in the infeed MSW is estimated to be 12.8%. For the Attero Noord facility, there are only four municipalities that have a separate collection system for plastic packages in place. Corrected for the amounts of separately collected plastic packages and the different levels of attached moisture and dirt for separate collected plastics and plastics in MSW, the percentage of plastics in the infeed MSW is calculated to lower on average from 20% to 18.8%. For the facility of Attero Wijster the situation is more complex, since most municipalities operate a separate collection system. When the same correction is applied, it is estimated that the concentration of plastics is lowered to 13.6% in the infeed MSW.

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[11] *Personal communication with Aucke Bergsma of Omrin on July 13th 2015.*

All the three recovery facilities that recover plastic packages, also simultaneously recover beverage cartons from MSW. Unfortunately, no similar production data of sorted fractions of beverage cartons were present for these three recovery facilities. According to Ms. Eggermont[12] of Hedra the expected production volumes in 2015 for Omrin and both Attero's are roughly 2 ktons and 4 ktons, respectively, of recovered and sorted beverage carton products (complying with DKR 510).[12] Since the numbers are only rough estimates, the previously established recovery and sorting yields in the pilot study beverage carton recycling were further used for the three facilities. The previously determined recovery yield was 80% and the previously determined sorting yield was also 80% (Thoden van Velzen, Brouwer, et al. 2013; Thoden van Velzen et al. 2014).

Two of the three material recovery facilities that process MSW also directly recover metals from the MSW, but the precise amounts are not known. However, all MSW is incinerated in the Netherlands and the metals are recovered from the bottom ashes. Hence, the description of the metal recovery process is slightly simplified with respect to the reality. The real recovery rates are expected to be slightly higher than calculated with this model, though. Both ferrous and nonferrous metals are sorted from the bottom ashes of municipal solid waste incinerators (MSWI's) with dedicated magnets, Eddy Current separators and the newly developed ADR-technology of Inashco. Some MSWI's have their own bottom ash treatment facility, others rely on contract companies like Heros[13] and NRC[14] to recover the metals. The recovery yields for ferrous metals and aluminium from the bottom ashes of Dutch MSWI had been determined to be 82.5% and 48.2%, respectively, in 2006. However, in the last decade new recovery techniques like the advanced dry recovery technique of Inashco have been developed and largely implemented, improving the recovery yields of ferrous metals and aluminium to 96.1% and 64.1%, respectively during a test in 2014 (Gijlswijk and Ansems 2014).
According to Mr. de Bode of Heros, metal packaging objects can easily be recognised in the recovery product "Ferrous middle scrap 40-80 mm" with a ferrous metal purity of more than 95%. However, in case of aluminium packaging, the metal melts in the MSWI and solidifies in the form of droplets.[15] These aluminium droplets are mostly recovered from the bottom ash in the fine nonferrous fraction 12-40 mm that is composed of roughly 40-50% aluminium, 15-25% other nonferrous metals (Pb, Zn, Cu, etc.) and mineral ashes.[16] Hence, in this recovered nonferrous metal product, packages cannot be recognised.[15] Furthermore, these recovered molten droplets of NF-metals should be considered as alloys, since the elementary impurities are molten through the droplets.

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[12] *Personal communication with Ms. Eggermont of Hedra, e-mail-message of November 24th 2015.*
[13] *Heros, http://www.heros.nl/*
[14] *NRC, http://www.nrc-nl.com/*
[15] *Telephonic discussion with Mr. Bode of Heros on October 30th 2015.*
[16] *Interview with Mr. van Hoften of Forest Metal in Rotterdam November 30th 2015.*

3.2.3 Sorting

The structure of the recycling industry and data available on sorting processes differ largely for the 5 packaging materials. For the plastics, glass and metals the collected materials will always pass through a sorting facility, for paper & board this is dependent on contracts and the market situation. Beverage cartons originating from a mono-collection are almost always directly sold to recycling companies and not sorted.

3.2.3.1 Sorting of collected paper & board

The Dutch paper and board industry association VNP reported that in 2014 the national consumption of paper & board products was 2986 ktons, the total collected amounts of paper & board from households and companies amounted 2375 ktons. About 93% of this collected material (namely 2209 ktons) was used as feedstock (recycled fibres)(VNP 2014b). This implies that the combined losses (sorting losses and weight losses due to drying) are 166 kton or 7%.

3.2.3.2 Sorting of Dutch separately collected post-consumer plastic packaging waste

The sorting divisions that were common for Dutch post-consumer plastic packaging waste up to January 1st 2015 are listed in Table 11. From this date on, not one organisation, but six different sorting facilities competed with each other for municipal sorting contracts and consequently sorting divisions have become business-sensitive data and have hitherto not been published.

Table 11: Sorting division of post-consumer plastic packaging waste up to 2014 and estimated for 2015, recovered masses % (w gross/ w gross) (Thoden van Velzen 2014).

Product	**2014**	**2015**
PET, DKR 328-1	6-8%	7%
PE, DKR 329	6-9%	8%
PP, DKR 324	6-8%	10%
Film, DKR 310	14-17%	21%
Mix, DKR 350	38-41%	39%
Metals	0-1%	-
Sorting residues	23-26%	15%

Nevertheless, several anonymous incumbents in the sorting industry have confirmed that from January 2015 on the amount of sorting residues is reduced and the amounts of film and mixed plastics are relatively raised in comparison to the sorting division of 2014 (see Table 11). In a recent trade journal Nedvang disclosed the new sorting distribution for 2015 (based on product output only) being about 46% mix, 25% film, 12% PP, 9% PE and 8% PET; additionally, sorting residuals would amount about 10-20% of the feedstock (Buijze 2016). This data can be recalculated in a new sorting distribution for 2015, see Table 11.

Sorting yields can be calculated from the recovered masses in Table 11 with concentration data on the concentration of desired plastics in the input and the sorting products, see Table 12. The concentration of targeted plastic objects in the input material (the separately collected plastic packaging waste) was derived from the datasheet of the composition of separately collected plastic packaging waste (Thoden van Velzen and Brouwer 2014). The concentration of the targeted plastic objects in the sorted products were derived by averaging the compositional data of samples of sorted products from 2011-2014 from 8 different sorting facilities. The crude concentration data is collected in Annex B.

Table 12: Calculated sorting yields % (w gross/ w gross) for separately collected plastic packaging waste in the Netherlands.

Sorting product	Target plastic objects	$c_{target\ plastics}^{Input}$, [%]	$c_{target\ plastics}^{Sorted\ product}$, [%]	$\eta^{sorted\ product}$, [%]
PET, 328-1	PET bottles & flasks	9±4%	88±7%	68±9%
PE, 329	All rigid PE objects	11±3%	91±4%	62±4%
PP, 324	All rigid PP objects	13±3%	88±6%	73±4%
Film, 310	All flexible plastic objects (non PVC)	31±6%	91±6%	60±2%
Mix, 350	Non-bottle PET, PS, black…	24±6%	40±22%	65±10%
Rest	PVC, silicon kit tubes	12±9%		

3.2.3.3 Sorting of Dutch recovered plastic packaging waste

The recovery and sorting of plastic packaging waste are registered simultaneously, see paragraph 3.2.2.4. Therefore, the combined recovered masses and plastic yield is calculated for both steps, see Table 13.

Table 13: Calculated combined recovered masses % (w gross/w gross) and sorting yields % (w gross/w gross) for mechanical recovered plastic packaging waste in the Netherlands.

Sorting product	Target plastic objects	R_M, [%]	$c_{target\ plastics}^{Input}$, [%]	$c_{target\ plastics}^{Sorted\ product}$, [%]	$\eta^{sorted\ product}$, [%]
PET, 328-1	PET bottles & flasks	0.48%	0.9±0.3%	94±5%	48±4%
PE, 329	All rigid PE objects	0.91%	1.6±0.7%	94±5%	55±10%
PP, 324	All rigid PP objects	0.85%	2.2±0.6%	90±5%	35±3%
Film, 310	All flexible plastic objects (non PVC)	3.59%	6.0±0.1%	76±5%	46±1%
Mix, 350	Non-bottle PET, PS, black…	1.89%	5.5±2.1%	38±10%	13±1%
Rest	PVC, silicon kit tubes		0.6±0.2%		

The concentration of targeted plastic objects in the input material was derived from 3 detailed sorting analysis of the composition of MSW, see Annex C. The concentration of the targeted plastic objects in the sorted products were derived by averaging the compositional data of samples of sorted products from 2011-2014 from 6 different sorting analysis. The crude concentration data is collected in Annex C.

3.2.3.4 Sorting of Dutch packaging glass waste

There is hardly any public data on the sorting of (Dutch) post-consumer packaging glass. However, interviews with two incumbents (Mr. Van Swartenbrouck of GRL[17] and Mr. Maas of Van Tuijl glasrecycling BV[18]) clarified most. First of all, the activity of sorting packaging glass from separately collected glass bottles and jars into a saleable and valuable product of glass cullets is named 'glass recycling' in the trade. Collected packaging glass of municipalities is combined to obtain sufficient large amounts of feedstocks with similar compositions. For instance, glass packaging from mixed colour collections is sorted separately from glass packaging from single colour collection systems. The feedstocks of mixed colours glass and brown glass are known to contain more contaminants (ceramics, stones, china, metal, plastics) than the transparent and

[17] *E-mail correspondence of September 25th 2015.*
[18] *Interview with Mr. Maas of Van Tuijl Glasrecycling BV on June 16th 2016.*

green glass feedstocks, especially with respect to stoneware jugs. The sum of contaminants in Dutch packaging glass is on average according to Nedvang 1.5%, but according to the Mr. Maas more close to 2.5%. This number is known to vary in Europe with the colour, collection method and municipality between 0 and 6%.[17]

As a first step the infeed material is either first composted on heaps in halls (biological drying) or directly heated and dry mechanically treated in which the glass packages are broken into cullets and product residues are rubbed off from the cullets surfaces. During both the composting and the thermal mechanical treatment the glass material dries (moisture content drops), but this is not registered. Glass that is first composted is also subsequently dry mechanically treated to break it and rub off dried product residues from the cullets surfaces. The broken and partially cleaned cullets are subjected to several sorting machines in which metals, ceramics, corks, plastics etc. are removed. The metals are removed with both magnets and Eddy current separators. Subsequently the cullets are sieved into several size categories and they are automatically sorted with a cascade of optical sorting machines (to remove non-transparent objects and different colours glass) and X-ray fluorescence sorting machines (to remove impurities such as ceramics and other types of glass). Finally, glass cullets of three or four main colours are produced (transparent, green, brown and optionally dead-leaf).

Some glass sorting companies only produce packaging glass cullets and a few by-products (metals, plastics, ceramics and stones, etc.). The metals by-products are traded to metal scrap dealers, the stones and ceramics are traded with road work construction companies and the plastic fraction is too strong polluted with glass residues and has to be incinerated.

Other glass sorting companies also produce glass by-products, like a fine fraction (0-2 mm) and glass by-products that are enriched in undesired non-packaging glass types (glass with elementary pollution of Pb, Zr, B, etc.) for the production of foam glass, thermal insulation, etc.

Some glass sorting facilities mix the desired packaging glass cullets with recycled flat glass cullets (demolition and automotive) to obtain glass cullet products in which elementary pollution is sufficiently contained and managed to be recycled as packaging glass.

The sorting losses for packaging glass are not published. The annual report of the association of flat glass recyclers reports 7% (Stichting Vlakglas Recycling Nederland 2014), yet packaging glass is not flat glass. Additionally, moisture is lost from the feedstock during either the thermal treatment or the biological drying. These losses are not recorded recorded, implying that the recorded recovered masses are based on the sum of the products and not the input weight. Sorting losses for packaging glass vary with the purity of the feedstock and the level of impurities in the feedstock of separately collected glass from different European countries is known to vary between 0-5 %.

Mr. van Swartenbrouck expects the sorting losses to vary between 5 and 15%, depending on the age of the facility and the purity of the feedstock. Mr. Maas of Van Tuijl estimates the sorting loss for packaging glass to be roughly 6% in the Dutch facilities with transparent and green glass

and 10% for brown and mixed-colour glass.[18] This 10% sorting loss for mixed glass sorting is also reported in a Scottish report (Hartley and Ogden 2012).
The recovered mass of packaging glass cullets (in dry weights) equals 100% minus the sorting loss. The sorting loss is divided in by-products and waste products. The exact division depends on choices of the sorting facilities' management and the detail composition of the feedstock. There is no public literature of the Dutch situation regarding this division. But we do know that one sorting facility does produce a glass by-product and another one doesn't. Therefore, we have chosen an average division; 10% metals, 20% ceramics and stones, 20% glass-polluted plastics, wood, corks for incineration and 50% glass by-products (foam glass, insulation material, polishing powder, etc.).

These estimations were used to calculate recovered masses, see Table 14. The calculation shown is for the total amount of colour-selective collected glass, assuming a 2% moisture content of the feedstock, a 60:30:10% colour ratio, 6% sorting loss for clear and green glass and 10% sorting loss for brown glass. Therefore, the net packaging glass sorting yield amounts to 94% for clear and green glass and 90% for the brown glass.

Table 14: Estimated recovered masses of packaging glass for mono-colour collected glass, assuming a 2% moisture content of the feedstock and a 60:30:10% colour ratio, a 6% sorting loss for clear and green and a 10% sorting loss for brown glass.

	Recovered mass, R_M, [% (w gross/w gross)]					Yield
	Packaging glass	Glass by-products	Mineral by-product	Metal by-product	Waste	$\eta^{pack\ glass}$, [%]
Clear	55.3%	1.8%	0.7%	0.4%	0.7%	94%
Green	27.6%	0.9%	0.4%	0.2%	0.4%	94%
Brown	8.8%	0.5%	0.2%	0.1%	0.2%	90%

The recovered mass and glass packaging yields for separate collected multi-coloured packaging glass was calculated with the same assumptions as above and additionally that the colour ratio is 60% transparent, 30% green and 10% brown (derived from Table 3). The estimated results are listed in Table 15. The high yield (171%) for brown packaging glass from mixed colour collected glass is caused by the substantial losses of clear and green glass cullets that are added to the brown glass product.

Table 15: Estimated recovered mass and yield of packaging glass for multi-colour collected glass.

	Recovered mass, R_M, [% (w gross / w gross)]					Yield
	Packaging glass	Glass by-products	Mineral by-product	Metal by-product	Waste	$\eta^{pack\ glass}$, [%]
Clear	47.6%	2.9%	1.2%	0.6%	1.2%	81%
Green	23.8%	1.5%	0.6%	0.3%	0.6%	81%
Brown	16.8%	0.5%	0.2%	0.1%	0.2%	171%

3.2.3.5 Sorting of Dutch recovered metals

The recovered ferrous metals are traded to steel works, either via intermediate traders or directly. A few years ago most of these metals were sold to Asiatic clients, but currently most of the ferrous metals are traded within Europe, especially to local Dutch and Belgium steel works.[15]
The recovered nonferrous metal mixture is sorted by sorting facilities as Dolphin and Liquisort-Baetsen. Dolphin uses dedicated sink-float-technology and Eddy current technology to separate the nonferrous metals and sorts the bulk of the recovered NF-metals. Liquisort-Baetsen is a sorting facility dedicated for the finer NF fractions with higher contents of valuable metals. This company uses the magnetic density separation technology to separate the metals.
Dolphin produces sorted aluminium in three size classes, with the following sorting distribution: 0-15 mm (25%), 15-25 mm (60%) and > 25 mm (15%). The middle size fraction has additionally been mechanically treated to remove attached residues. These aluminium products have variable elementary composition, but in general they are composed of 95% Aluminium, 1-3% Silicon and several other elements (Iron, Zinc, Copper, Lead, etc.). The sorting losses with respect to Aluminium are not known, but this wet separation process removes Aluminium-oxide-rich dust from the surface of the droplets. This dust accumulates in the sludge from the sink-float-separation vessel.[16] These sorting losses are crudely estimated to be 5%.
Based on the aluminium-concentrations and the product-division, an overall recovered mass of 45% (w gross / w gross) for the sorting of aluminium can be calculated, which can be split up to 11.3% for the fine (0-15 mm) product, 27.0% for the middle (15-25 mm) product and 6.75% for the coarse (>25 mm) aluminium product. The overall aluminium yield equals 95% (w gross / w gross).

3.2.3.6 Sorting of PMD

There is no public technical data on the sorting process of PMD material collected in the Netherlands. Representatives of the sorting facility that sorts PMD and of municipalities that collect PMD material have been asked for technical details of the sorting process, yet these requests weren't granted. Therefore, as a first order approximation, the sorting yields are assumed to be more or less equal to those registered for the single material streams. This assumption is in agreement with the results on sorting PD (co-collected plastics and beverage cartons) (Thoden van Velzen et al. 2014). This implies that the recovered masses of sorting are used for plastic and beverage cartons from co-collected PD-material after correction for the relative amount of these materials in the feedstock. The recovered masses for sorting metal products from the PMD mixture were crudely estimated from their share in the feedstock (hence approximating the sorting yield to 100%) and adding 45% weight of other materials, to account for the 40-50% process losses during the subsequent recycling of these metals (see paragraph 3.2.4.6). From this additional material, 10% is estimated to be moisture and hence 35% is expected to be plastics, beverage cartons and residual waste. These sorting losses of plastics and beverage cartons to the metal sorting product is estimated based on the mass ratio of these materials as they are present in the collected feedstock. These masses of plastics and beverage cartons that are lost to the metal sorting product are estimated and subtracted from the masses of these materials predicted by calculation mentioned above with the single material approximation. This calculation remains to be an estimation, since public technical studies about the sorting of Dutch PMD material are not available.

3.2.4 Recycling

3.2.4.1 Paper & Board

A general description of the recycling efficiency of the Dutch paper & board industry can be deduced from documents of the Dutch paper & board industry association (VPN) and of the paper & board recycling companies association (PRN). This is a first order approximation, since large quantities of paper & board are simultaneously imported and exported and these effects cannot be taken into account in this model.

Separately collected paper & board and sorted fractions of paper or board are used for the production of new paper and board products in the Netherlands. The Dutch paper & board industry reported the annual use of the following feed stocks: recycled fibres 2209 ktons, virgin fibres 544 ktons and 366 ktons of fillers, implying that 71% of the feedstock are recycled fibres (VNP 2014c).
Simultaneously the paper & board industry produces waste streams, of which most types, except for the chemical waste, can be attributed to the recycled fibre feed stock. The total amount of waste of the Dutch paper industry that could be attributed to the recycled feedstock was 262 ktons in 2012[19], see Table 16.

[19] *CBS statline, http://statline.cbs.nl/*

Table 16: Wastes produced by the Dutch paper & board industry in 2012.[19]

Waste type	Amount, [ktons]
Paper waste	202
Plastic waste	22
Iron waste	20
Mixed metal waste	3
Wood waste	14
Textile waste	1
Sub-total	262
Chemical waste	59

This implies that the overall production loss is 8.4% and that the recovered mass during paper and board production is 91.6%(w gross/w gross). These numbers reflect the overall recycling efficiency and relate to all feedstocks. However, it is likely that most of these losses can only be attributed to the recycled fibre feedstock and in that case the production loss amounts to 11.9% and the recovered mass of recycled fibre during production amounts to 88.1% (w gross / w gross), with an estimated fibre yield of 92% (w gross/w gross). The recycled fibres are used to produce eight type of P&B products (VNP 2014a), for which the relative input division of recycled fibres were estimated. The product of the production and this relative input of recycled fibres gave a division of recycled fibre use, see Table 17.

Table 17: Estimated division of recycled fibre use by the Dutch paper & board industries, based on their production data and the estimated content of recycled fibres in 2014.

P&B products	Production in 2014, [tons]	Estimated input of recycled fibre	Estimated division of recycled fibre input over all P&B products
Newspaper	253000	100%	11.3%
Uncoated writing paper	232000	20%	2.1%
Coated writing paper	406000	20%	3.6%
Container board	934000	100%	41.8%
Wrapping paper	79000	100%	3.5%
Solid board	628000	100%	28.1%
Folding carton	125000	85%	4.8%
Hygienic products	116000	90%	4.7%
Total	**2,773,000**		

3.2.4.2 Beverage cartons

The recycling yields of separately collected beverage cartons can be calculated from the average material compositions, the determined fibre yield and the determined by-product yield in the pilot beverage cartons (Thoden van Velzen, Brouwer, et al. 2013). Since the average net fibre content of separately collected beverage cartons equalled 50.9% (w net / w gross) and the net fibre yield amounted 80% (w net/w net), multiplying both factors with the gross collected amount by the municipality yields the net amount of recycled fibres. Likewise the amount of recycled by-products can be calculated by multiplying the gross collected amount with the average net concentration of by-products (17.6% (w net / w gross)) and the net by-product yield of 95% (w net/ w net), see Table 18.

For recovered and sorted beverage carton products the same parameters have also been determined in the pilot study beverage carton recycling (Thoden van Velzen, Brouwer, et al. 2013).The fibre composition of this material and the recycling yields are listed in Table 18. For PMD-collected and sorted beverage cartons these numbers have not been measured previously, but for the related co-collection system of plastics and beverage cartons they have been measured. Therefore the latter numbers are indicatively used for analysis of the recycling yields for the beverage cartons from PMD-collection systems.

Table 18: Net material composition of mono-collected and / or sorted beverage carton products and their subsequent recycling yields (Thoden van Velzen, Brouwer, et al. 2013).

	BC product from separate collection	Sorted BC product from recovery	Sorted BC product from co-collection with plastics	Sorted BC product from co-collection with plastics and metals
Net fibre content, [%]	50.9%	46.6%	58.7%	~58.7%
Net fibre recycling yield, [%]	80%	98%	87%	~87%
Net by-products content, [%]	17.6%	18.2%	21.3%	~21.3%
Net recycling yield of by-products, [%]	95%	92%	92%	~92%

The separately collected beverage cartons in the Netherlands are being recycled by Papierfabrik Niederauer Mühle in Kreuzau (PNM). Also sorting provider Van Scherpenzeel trades the sorted beverage carton products with PNM. PNM produces various types of board and solid board cores. PNM sends a large part of the by-products to a Chinese company in Luhai which converts this mixture in mixed aluminium-plastic granulate.[12]
From 2016 on, the paper mill van Houtum in Swalmen will process the beverage cartons that are sorted from PMD-collected material by sorting facility Suez Rotterdam. Van Houtum will make sanitary products from the beverage cartons such as toilet paper and paper wipes. The fate of the by-products from this recycling facility is not decided yet.[20]
The recovered and sorted beverage cartons are recycled by Delkeskamp in Nortrup. Delkeskamp will produce mostly corrugated board from the beverage cartons. The by-products are traded as SRF (Secondary Recovered Fuel).

3.2.4.3 Plastics

The sorted plastic fractions are traded with recycling companies which transform the baled plastic packages into either washed milled goods, granulates or products. The recycling yields are company secrets and are not published. These yields have, however, been studied in previous projects with a standardised laboratory recycling process, of which the results have been shared via presentations (Thoden van Velzen 2015) and also recently been submitted for publication (Thoden van Velzen et al. 2016). The standardised laboratory recycling set-up is composed of a mill, washing mill, a swim-sink-separation vessel, centrifuges and ovens. The input weight of the feedstock and the dry matter content is accurately determined. Also the dry product weights of the floating product, the sinking product and the sludge waste is determined. From the balance between the net input weight and the product weights the amount of dissolved substances is estimated. These recycling tests were repeated at least three times with sorted fractions from different sorting facilities. The recovered masses and the derived yields are tabulated below for the five sorted plastic products of both origins. In order to calculate the yields, concentrations of contributing plastics objects in the sorted feedstocks are required (see Equation 12). These were derived from the sorting analysis of sorted fractions, see Annex B and C. Since the composition of the mixed plastic feedstock varied greatly with respect to the amount of PET trays, also the ratio between the floating and sinking product varied largely for this feedstock. The results are listed in Table 19.
The market distributions for each sorted product from both collection systems were estimated based on discussions with recycling industries. As the market dynamics in the plastic recycling is substantial, these should only be used as rough indications. They are listed in Annex D.

[20] *Van Houtum, http://www.vanhoutum.nl/nieuws-pers/nieuwsberichten/7897/wc-papier-van-drankenkartons.html*

Table 19: Recovered mass and recycling yields for sorted plastic fractions in (% w net/w net) as determined with a standard laboratory set-up.

Sorted product	$R_m^{floating\ product}$, [%]	$R_m^{sinking\ product}$, [%]	$R_m^{sludge\ waste}$, [%]	$R_m^{dissolved\ matter}$, [%]	$c_{Sorted\ input}^{Contributing\ plastics}$	$\eta^{recycling}$, [%]
Sorting products originating from the Dutch separate collection system						
PET	11 ± 1%	83 ± 2%	3 ± 2%	3 ± 2%	94 ± 4%	88 ± 4%
PE	94 ± 2%	3 ± 1%	0.8 ± 0.3%	2 ± 2%	97 ± 2%	98 ± 3%
PP	90 ± 1%	7 ± 1%	0.7 ± 0.6%	3 ± 1%	94 ± 4%	95 ± 4%
Film	90 ± 6%	4 ± 4%	0.8 ± 0.6%	6 ± 3%	92 ± 4%	98 ± 8%
Mix	64 ± 12%	32 ± 11%	0.7 ± 0.8%	5 ± 1%	91 ± 6%	105 ± 7%
Sorting products originating from the Dutch plastic recovery system						
PET	10 ± 2%	84 ± 2%	3 ± 2%	3 ± 2%	99 ± 6%	85 ± 7%
PE	93 ± 1%	2 ± 1%	2 ± 2%	3 ± 1%	96 ± 4%	97 ± 4%
PP	83 ± 2%	3 ± 2%	6 ± 2%	8 ± 2%	94 ± 3%	88 ± 3%
Film	83 ± 15%	4 ± 2%	3 ± 4%	10 ± 9%	93 ± 3%	90 ± 3%
Mix	65 ± 4%	28 ± 1%	3.1 ± 0.1%	4 ± 3%	91 ± 4%	100 ± 5%

3.2.4.4 Glass

The sorted glass cullets are traded with glass factories, which use these cullets directly in their production. As discussed previously in paragraph 3.2.3.4, the majority will be used for the production of new packaging and a minority for glass wool and glass foam products.

3.2.4.5 Metals

The ferrous metals are directly used in the production processes of steel mills. Ferrous scrap is added in the convertor. After the conversion process is complete and a liquid iron mixture has been obtained, various elements are added to create special alloys. With the choice of the added elements the application window of the steel is also determined. Tata steel uses ferrous scrap in all their products, but the amount of scrap available is small in comparison to the complete feedstock use (0.03 Mton versus 1.5 Mton). So recycled ferrous metals are used in construction steel, automotive steel and packaging steel, but the percentage of recycled input is low.[21]

[21] *Telephonic discussion with Mr. A. von Keitz of Tata Steel on June 22nd 2016.*

The sorted aluminium products are traded with secondary foundries that melt the metal, cast ingots of it and simultaneously remove the dross. The latter is the technical term for a mixture of salts and mineral impurities that float on top of the molten metal. The recovered masses for the aluminium products are approximately 65-70% for the sorting product 0-15 mm, 88-92% for the sorting product 15-25 mm and 78-82% for the coarse sorting product >25 mm.[16] This yields a weight-averaged recovered mass of 82.9% (w net/w gross). In case we estimate a 5% loss of aluminium in this process and assume that the aluminium concentration of the ingots is 95% then the weight-averaged aluminium yield is 89% (w net/w gross).
Most of these ingots of secondary aluminium contain a relative high concentration of silicon (1-5%) and are traded with the automotive industry, since this quality is well suited for casting engine parts.[16, 22] This is the predominant use for recovered, sorted and recycled aluminium from MSWI's bottom ashes. A second application is "desox". This aluminium is cast in the form of small pyramids and is added to molten steel in the steel mill to remove oxygen. This is, however, a destructive application of the aluminium, since it will oxidise and the aluminium oxide salts are removed from the steel as dross. Therefore this use cannot be considered as a form of recycling, but rather a form of useful application. The market division between both applications is estimated to be 90:10%.[16] Since Aluminium castings are also used in the machine market, this 90% was further split up in 75% automotive, 10% machines and 5% miscellaneous.

3.2.4.6 Recycling of the three materials in PMD

From PMD materials the following materials are sorted: five different types of plastics, beverage cartons, ferrous metals and non-ferrous metals. As a first order approximation the recycling of the plastics and beverage cartons is treated similar as the mono-collected materials, as previous research indicated that the mutual impacts are limited (Thoden van Velzen et al. 2014).
For the two metal products (sorted ferrous metals and sorted non-ferrous metals) it was, however, less clear which processes are used to recycle these fractions. An interview with directors Mr. Stuiver and Mr. Klaasen of MDH[23] clarified this processing chain. MDH has processed the recovered mixed metals from two Northern Dutch recovery facilities that process MSW for many years. Since the sorted metal fraction from PMD collection has become available on the market, MDH has processed this sorting product from 2 sorting facilities. Currently, a competitor also processes metals from PMD collection. The processing steps involved are milling, sieving, separation of ferrous metals with magnets and separation of non-ferrous metals with Eddy current separators. The major concern of both directors with the sorted metals from the comingled PMD collection system is the large weight loss of 40-50%. They register the gross input weight and the gross weights of the two metal products. The weight of the sieving fine fraction is not separately registered. The gross weight loss between the input and the output

[22] *Email conversation with Mr. van de Winckel, Inashco on September 7th 2016.*
[23] *Interview with Mr. Stuiver and Klaasen of Metaalhandel de Horne (MDH) on October 17th 2016 in Heerenveen.*

metal products is 40-50%; this equals the sum of moisture loss and sieving fines. Since the sorted metal product from PMD is a relative moist material, a substantial amount of moisture evaporation can be expected. Additionally, a visual inspection of the sieving fines revealed that it is mostly composed of organics, paper and plastics. The product "ferrous metals" is sufficiently pure to be directly traded to steel companies. The product "nonferrous metals" is mostly aluminium, but also contains some lead, zinc, copper, etc. Therefore, this product is traded with non-ferrous metal sorting facilities, which produce primarily secondary aluminium from it, which is subsequently traded to secondary aluminium foundries.

This process loss is relatively large. According to Mr. Stuiver and Mr. Klaasen, the process loss for the metal mixture that is directly recovered from MSW is 23-24% (average for multiple years), which is in relative good agreement with the LAMD for metal packages of 25% in MSW, see Table 7. A visual inspection of PMD material revealed the presence of 'agglomerates' and this is a likely explanation for these relatively large process losses. Agglomerates are clumps of different packages that stick strongly together. Two of the most common causes for agglomerate formation are consumer behaviour and mechanical compression during transport in collection vehicles. Some civilians use one relatively large package, such as a large beverage carton or a soup can as receptacle for other smaller packages, which are pressed in the larger package. This offers convenience to the civilians, since they only have to walk once from the kitchen to PMD waste bag or container. Additionally, in some municipalities modalities of the collection scheme (such as low collection frequencies) can cause civilians to compress their separately collected packaging materials inside mini-containers or bags. The second reason for the formation of agglomerates lies in the collection vehicles that mechanically compress the PMD material. A few packages such as metal cans and PET trays can distort under pressure and retain this distorted shape back after the pressure is released. In the distorted state other packages can be clamped to form rigid agglomerates.

In case the moisture loss is estimated to be 10%, than 30-40% of the process loss can be attributed to plastic packages, beverage cartons and residual waste, implying that the sorting yields for these materials should be adjusted accordingly.

3.3 Summary of recovered masses and yields per process step

The collected data per process step of the Dutch packaging recycling chains has been interpreted in terms of either gross recovered masses or net material yields per process step in the previous paragraphs for the three main steps: collection, sorting and recycling. The collection responses are strongly dependent on municipal collection methods and cannot be generalised. The recovered masses and the material yields of the two other process steps can, however, be generalised and are summarised in Table 20. The net recycling chain yields can now be calculated with equations 14 and / or 15.

Table 20: Overview of the recovered masses and net material yields for the sorting and recycling steps of the Dutch packaging material recycling chains for separately collected packaging materials.[24]

	Sorting		Recycling	
	R_M,[%]	η^{net},[%]	R_M,[%]	η^{net},[%]
Paper & Board wo BC	~93%		~88.1%	~92%
Beverage Cartons		~80%		80-87%
Glass mono-colour	**91.7%**	**~93.6%**	100%	100%
-Clear	-55.3%	~94%		
-Green	-27.6%	~94%		
-Brown	-8.8%	~90%		
Glass mixed	**88.2%**	**~90%**		
-Clear	-47.6%	~81%		
-Green	-23.8%	~81%		
-Brown	-16.8%	~171%		
Metal				
-Ferrous	~100%	~100%		100%
-Nonferrous	~45%	~95%		88%
Plastics				
-PET	~7%	~68%	~83%	88%
-PE	~8%	~62%	~94%	98%
-PP	~10%	~73%	~90%	95%
-Film	~21%	~60%	~90%	98%
-MP	~39%	~59%	~96%	105%

[24] *Due to a lack of verifiable data on PMD material, calculations for PMD material can only be estimated with this data.*

4 Results per municipality

The model was tested with two Dutch municipalities for which sufficient data was publically available. The results are given in paragraphs 4.2 and 4.3. These results are compared to the national reference, which is calculated in paragraph 4.1 with national figures of 2014. This gives the municipalities insight in their comparative performance.

4.1 National reference of 2014

The model had to be adjusted to allow for the calculation of a national reference in three aspects. First of all, the correct national division between plastic separate collection and mechanical recovery capacity was added to the model. Secondly, with regard to glass collection, the correct national division between municipalities that operate a multicolour collection system and a colour separated collection system was added to the model. Thirdly, the amount of recovered and sorted beverage cartons had to be estimated for 2014. The used input data is listed in Table 21.

Table 21: Overview of the input data used for the National reference calculation for 2014.

Input parameters	Value	Source
Amount of inhabitants	16,092,000	CBS
Amount of connections	7,639,826	Gemeentelijst
Amount MSW collected	3,451,000 ton gross	CBS
Amount of Paper & board collected	929,000 ton gross	CBS
Amount of Glass packaging collected	340,000 ton gross	CBS
Share of mono-colour glass collection	66.3%	Nedvang
Amount of Plastic packages collected	129,000 ton gross	CBS
Amount of Beverage cartons collected	4,000 ton gross	CBS
Amount of Metal packaging collected	2,000 ton gross	CBS
Amount of PMD collected	-	
Plastic recovery capacity used	100%	
Amount of BC's recovered and sorted	3,000 ton gross	Own estimation (+)
Is the composition of the MSW known?	Yes	
Percentage of P&B (wo BC) in MSW	16.86%	RWS 2015 (*)
Percentage of plastics in MSW	13.89%	RWS 2015 (*)
Percentage of glass in MSW	5.16%	RWS 2015 (*)
Percentage of metals in MSW	4.36%	RWS 2015 (*)
Percentage of beverage cartons in MSW	2.98%	RWS 2015 (*)

*: The average values of the RWS report were taken and indexed to 100%.

+: In 2015 a production of 6 kton was reported, but for 2014 no official data was available, hence we estimated the half.

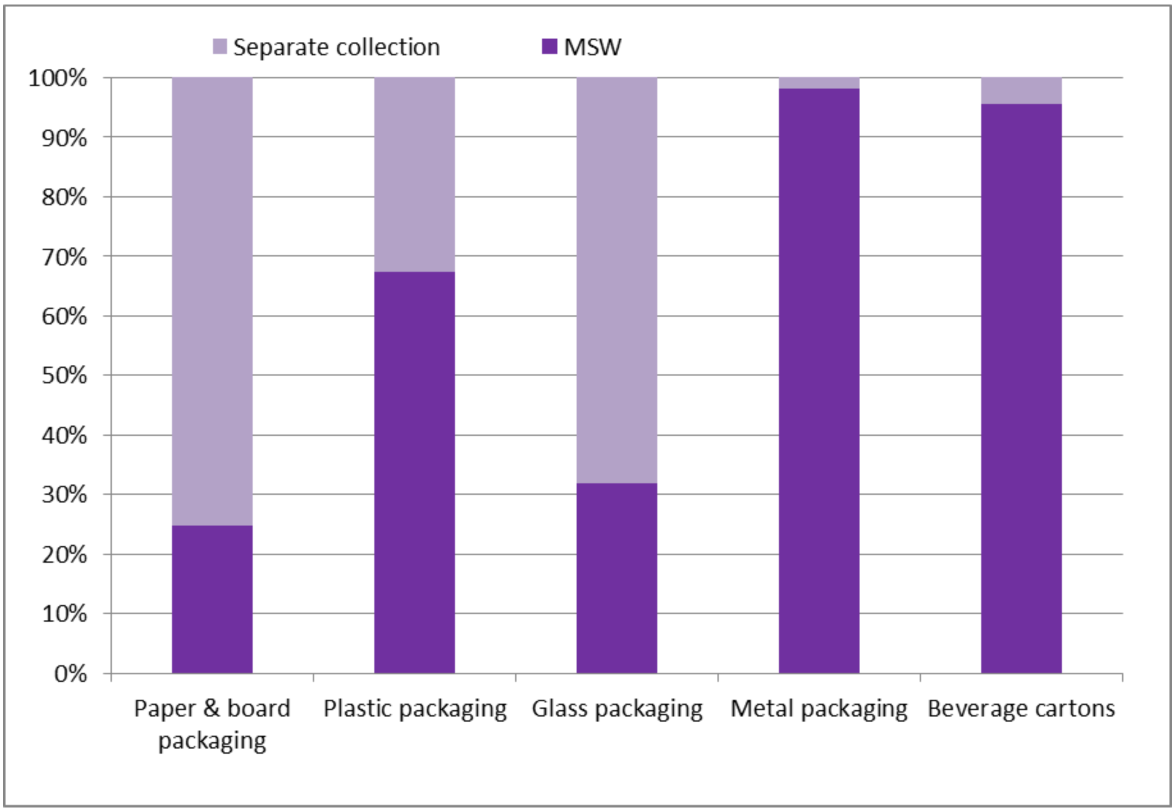


Figure 3: The net collection efficiencies for the five packaging materials that are separately collected and those that are collected with the MSW for the Netherlands in 2014 (post-consumer packaging materials only).

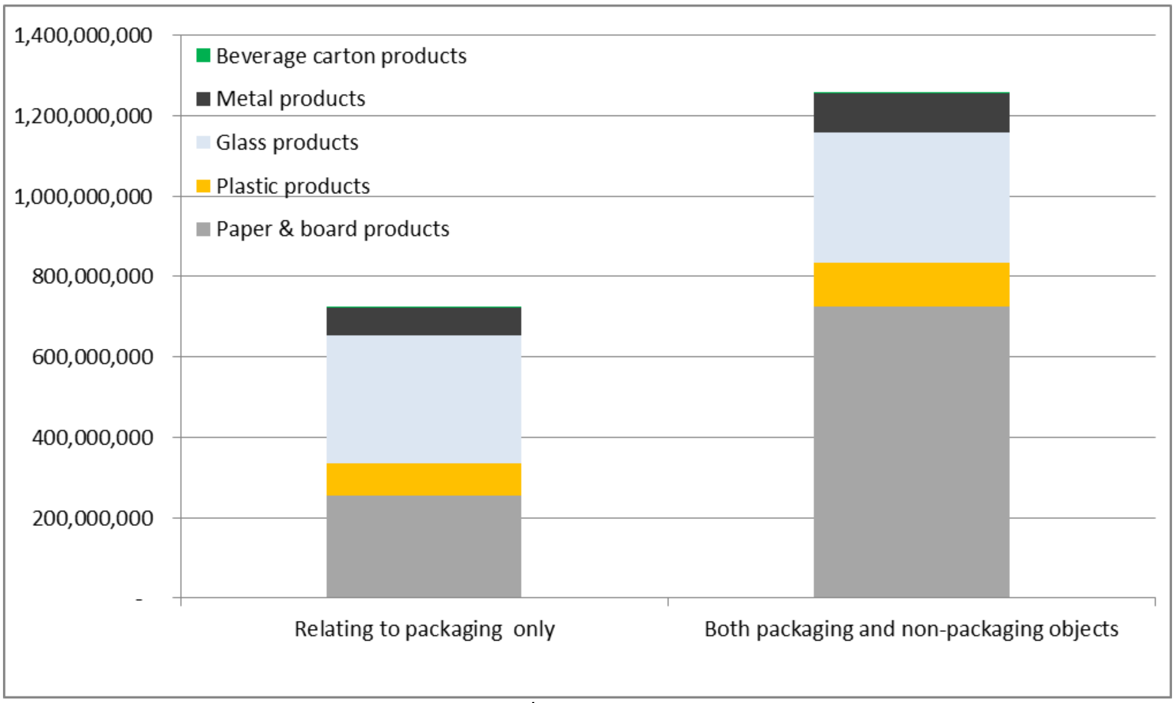
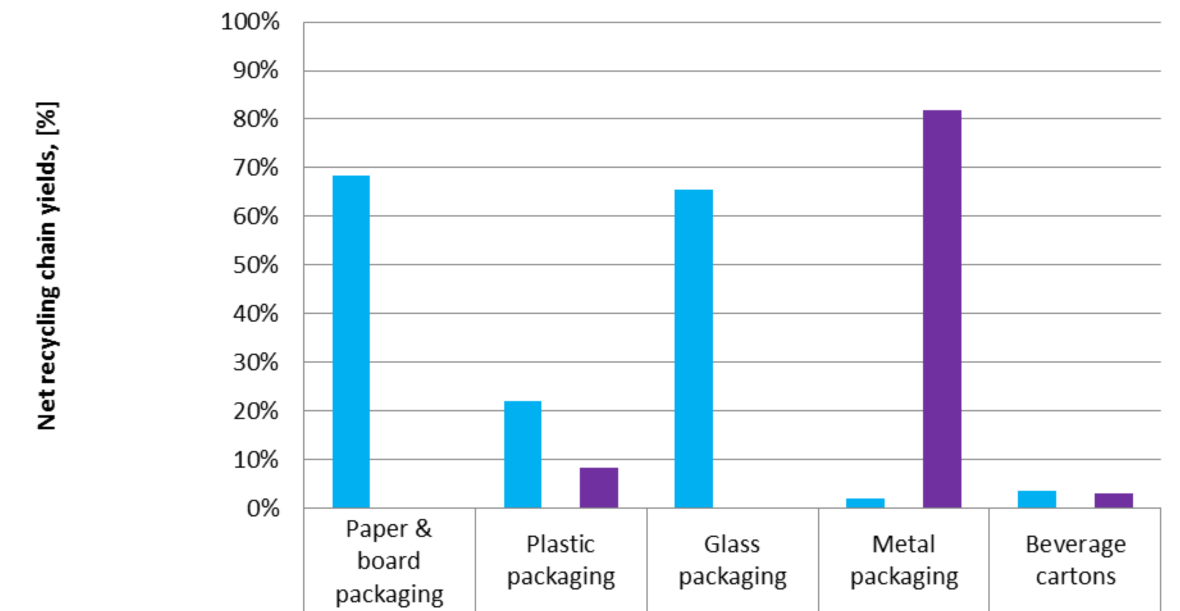


Figure 4: Net amounts of recycled products [kg net/a] for the 5 packaging materials and with two perspectives: packaging materials only and all materials for the Netherlands in 2014.

The net collection efficiencies for Dutch post-consumer packaging materials in 2014 as national reference point are shown in Figure 3. For paper & board post-consumer packaging materials the national net collection efficiency was roughly 75% in 2014. For post-consumer glass packaging it was 68%. For post-consumer plastic packaging this amounted to about 33%.
The amounts of recycled post-consumer material products for the Netherlands in 2014 are shown in Figure 4 and Table 22, with both a packaging perspective and an all material perspective. In case only packaging materials are considered, roughly 725 kton net of recycled materials were produced, of which the glass cullets (318 kton net) and paper fibres (255 kton net) count for the largest part, followed by plastic milled goods (80 kton net), metal scrap (68 kton net) and paper fibres from beverage cartons (2.9 kton net). In case both packaging and non-packaging materials are considered, the produced paper fibres dominate (725 kton net).



	Paper & board packaging	Plastic packaging	Glass packaging	Metal packaging	Beverage cartons
Separate collection	69%	22%	66%	2%	4%
PMD-co-collection	0%	0%	0%	0%	0%
Mechanical recovery	0%	8%	0%	82%	3%

Figure 5: Net recycling chain yields for the Dutch post-consumer packaging materials in 2014.

The Dutch net recycling chain yields for post-consumer packaging materials for 2014 are shown in Figure 5. The net recycling yields for post-consumer paper & board packaging and glass packaging amount to 69% and 66%, respectively. The net recycling yield for post-consumer metal packaging amounts to 84% in total of which the majority (82%) is almost exclusively obtained via mechanical recovery. The net recycling yields for plastic post-consumer packaging equalled 30% in 2014, of which 22% was attained by separate collection and 8% by mechanical recovery. The net recycling chain yield for beverage cartons amounts to 7%. These net recycling chain yields are lower than the officially reported numbers (Afvalfonds Verpakkingen 2015) for four different reasons:

1. The net chain yields are based on net weights and not on gross weights,
2. The net chain yields consider three steps of the recycling chain and not only the first two steps (also see paragraph 5.2),
3. The net chain yields relate to post-consumer packaging materials only (and hence they do not include post-industrial packaging materials) and
4. The net potentials are not derived from industrial reports, but from an analysis of both the separately collected materials and the MSW.

Given these differences in calculation method, it is not unexpected that the net recycling chain yields are lower than the official reported recycling yields. These net recycling chain yields for post-consumer packaging materials will be used as benchmark for the recycling performance of the municipalities.

Table 22: The total net amount of secondary materials produced in the Netherlands in 2014 expressed in total net amounts and in total net specific amounts in a packaging-only and an all-material perspective.

Secondary material	Net annual amounts, [kg net/a]	
	Relating to packaging only	Relating to packaging and non-packaging object recycling
Recycled fibres P&B	255,359,256	724,572,805
Recycled fibres BC	2,997,100	2,997,100
Glass cullets	318,464,983	324,884,555
Ferrous metals	58,017,674	82,618,620
Nonferrous metals	10,419,758	14,837,996
Plastic milled goods	80,675,279	109,142,014
Total	**725,934,050**	**1,259,053,090**

Secondary material	Net annual specific amounts, [kg net/cap.a]	
	Relating to packaging only	Relating to packaging and non-packaging object recycling
Recycled fibres P&B	15.1	42.9
Recycled fibres BC	0.2	0.2
Glass cullets	18.8	19.2
Ferrous metals	3.4	4.9
Nonferrous metals	0.6	0.9
Plastic milled goods	4.8	6.5
Total	**43.0**	**74.6**

4.2 Municipality Boxtel

The municipality of Boxtel was chosen as an example to execute the model, since almost all the required data is publically available. The input data for the model and the source is listed in Table 23. The composition of the MSW of Boxtel for 2011 was reported for low-rise and high rise buildings, we took the composition of the MSW of the low rise buildings for this exemplary calculation. The amounts of MSW and separately collected materials were registered for 2013 in the CBS datasheet. In Boxtel the following relevant waste and material streams are collected from households: MSW, paper & board, packaging glass and packaging plastics.

Table 23: Overview of the input data used for the exemplary calculation for the municipality of Boxtel.

Input parameters	Value	Source
Name	Boxtel	
Amount of inhabitants	30356	CBS 2013
Amount of connections	12925	FBR list
Amount MSW collected	6358 ton/a	CBS 2013
Amount of Paper & board collected	1912 ton/a	CBS 2013
Amount of Glass packaging collected	637 ton/a	CBS 2013
Amount of Plastic packages collected	304 ton/a	CBS 2013
Amount of Beverage cartons collected	0	CBS 2013
Amount of Metal packaging collected	0	CBS 2013
Amount of PMD collected	0	
Is the composition of the MSW known?	Yes	Eureco*
Percentage of P&B in MSW	18.3%	Eureco
Percentage of plastics in MSW	13.0%	Eureco
Percentage of glass in MSW	5.3%	Eureco
Percentage of metals in MSW	5.2%	Eureco
Percentage of beverage cartons in MSW	4.0%	Eureco
Are plastics & beverage cartons recovered from the MSW	No	
Is the packaging glass separately collected in 3 colours?	Yes	

* (Eureco 2011)

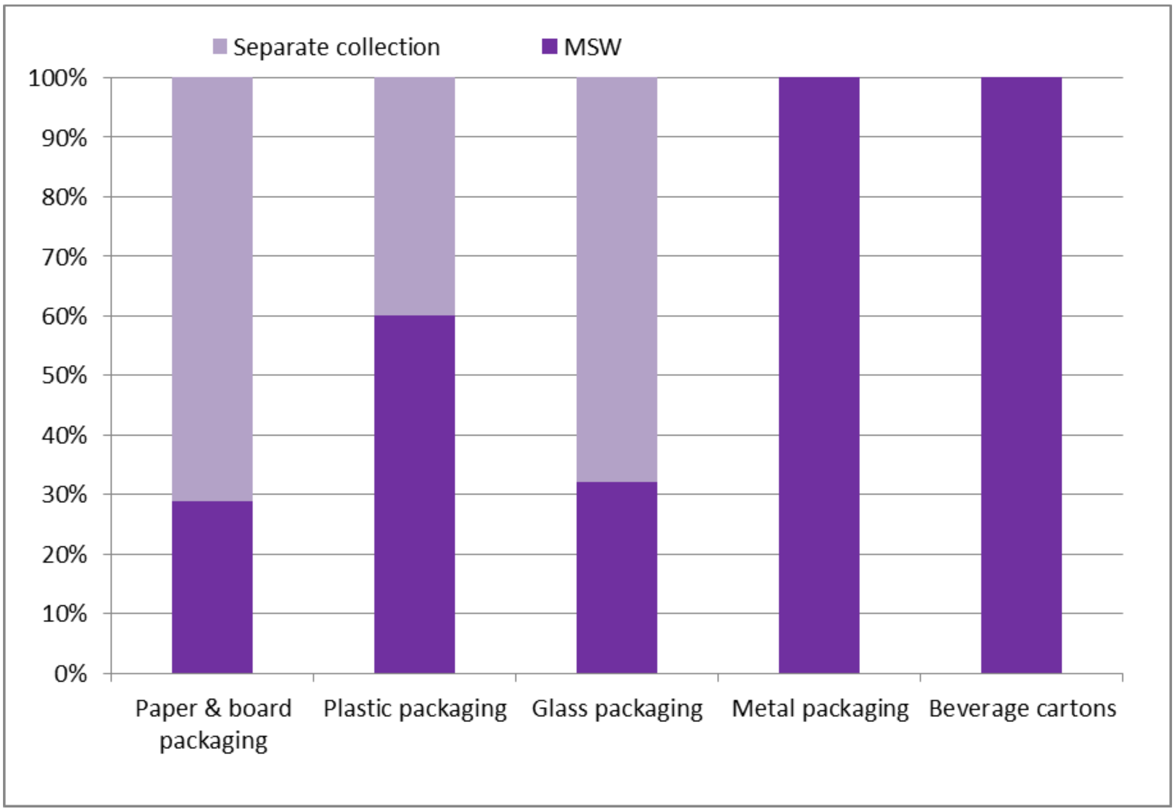


Figure 6: The net collection efficiencies for the five packaging materials that are separately collected and those that are collected with the MSW for the municipality of Boxtel in 2013 (packaging materials only).

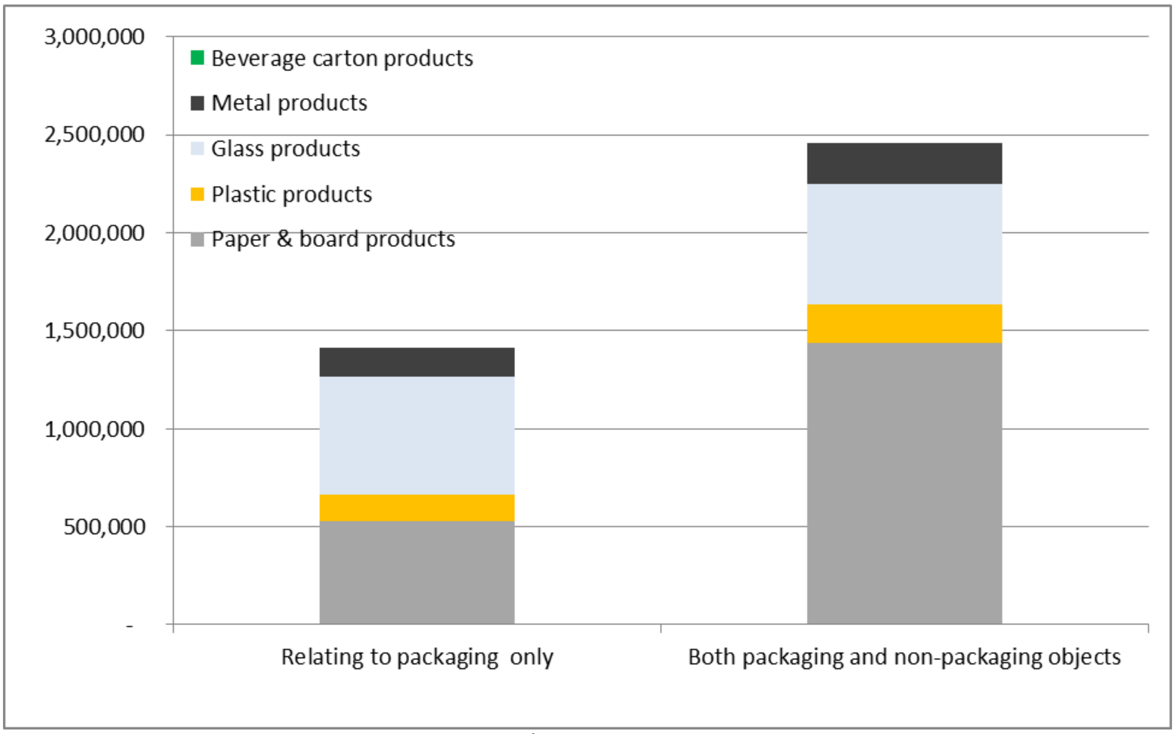
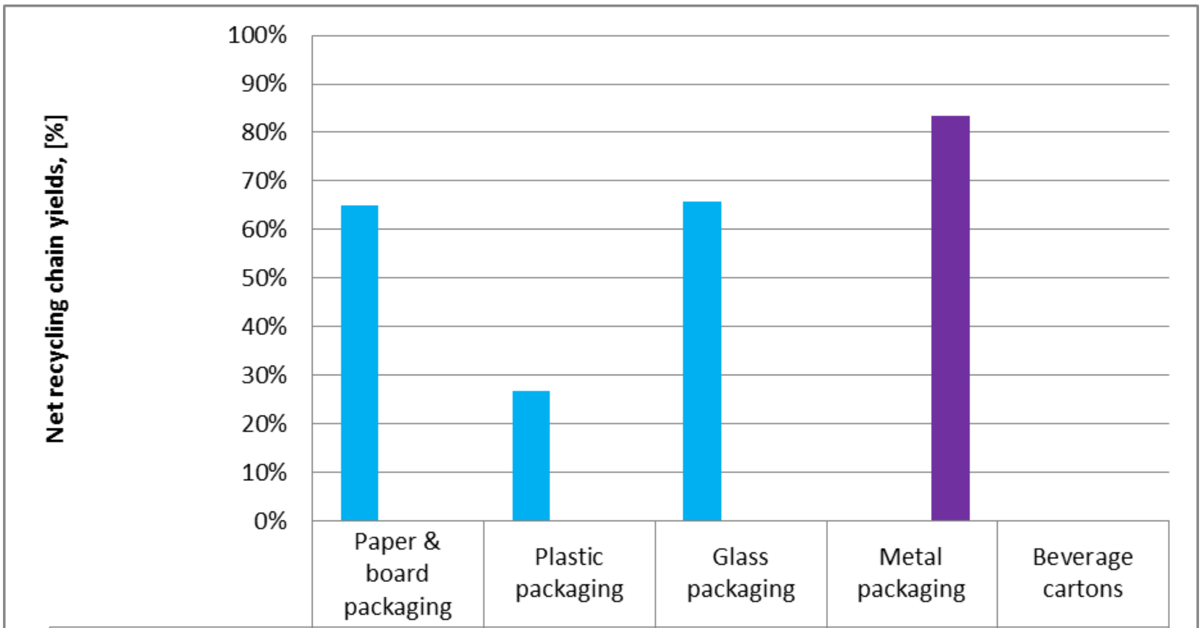


Figure 7: Net amounts of recycled products [kg net/a] for the 5 packaging materials and in 2 perspectives; relating to packaging materials only and to all materials for Boxtel in 2013.

The model calculates the net collection efficiencies for the five packaging materials, the amount of recycled materials produced on behalf of that municipality and the net recycling chain yields, these are shown in Figure 6, Figure 7 and Figure 8, respectively.



	Paper & board packaging	Plastic packaging	Glass packaging	Metal packaging	Beverage cartons
Separate collection	65%	27%	66%	0%	0%
PMD-co-collection	0%	0%	0%	0%	0%
Mechanical recovery	0%	0%	0%	83%	0%

Figure 8: Net recycling chain yields for the exemplary municipality of Boxtel in 2013 (based on packaging materials only).

The largest contribution that the municipality Boxtel made in 2013 to 'packaging material recycling' was the separate collection of paper & board materials, see Figure 7. Since this material group contains mostly non-packaging objects, the recycling of non-packaging objects like newspapers and magazines was the most important. In case only packaging materials are regarded, glass was the most important material class.
In case the net collection efficiencies are considered (figure 3) then it is clear Boxtel in 2013 performed better than the national benchmark for 2014 with respect to plastic packaging recycling, similar for metal and glass packaging and worse than the national average for paper & board packaging and beverage cartons recycling. Hence for the latter two packaging materials there is room for improvement. Since net recycling chain yields can be considered as a good indicators for circularity, it also shows that metal and glass were the most circular packaging materials in the municipality of Boxtel in 2013. When compared with national reference data for 2014, it is clear that the especially the separate collection of paper & board can be improved in Boxtel.

Table 24: Indicatively calculated amount of recycled products made on behalf of the municipality of Boxtel in 2013.

Material class	Application	Amount of recycled products made from packaging materials, [kg net/a]	Amount of recycled products made from all materials, [kg net/cap.a]
P&B	Newspaper	59566	163274
	Uncoated writing paper	10924	29944
	Coated writing paper	19118	52402
	Container board	219901	602757
	Wrapping paper	18600	50983
	Solid board	147857	405280
	Folding carton	25016	68568
	Hygienic paper	24580	67375
Glass	Packaging glass clear	349826	356925
	Packaging glass green	174913	178463
	Packaging glass brown	55823	56956
	Glass by-products (foam glass)	19848	20251
Fe-metals	Construction steel	62552	89359
	Automotive steel	12510	17872
	Packaging steel	18765	26808
	Durable consumption goods	12510	17872
	Excavating machines	12510	17872
	Shipbuilding steel	6255	8936
NF-metals	Transport Aluminium	16424	23463
	Machine building Al	2190	3128
	Misc. applications for Al	1095	1564
	Desox	2190	3128
Plastics	PET trays	8418	11822
	PET fibres	1203	1689
	PET strapping	2405	3378
	Cable liner	3113	4372
	Drainage pipes	20317	28534
	Roll tubes	3113	4372
	Road plates	18761	26348
	Waste containers	1401	1967
	Non-food bottles	156	219
	Flower trays	9314	13081
	Crates	3726	5232
	Tree crates	2794	3924
	Appliances	931	1308

	Pallets	12195	17127
	Garden furniture	3912	5494
	Play sets	9078	12750
	Traffic dividers	5166	7256
	Embankment	5166	7256
	Plastic lumber	17092	24005
	Mortar tubs	10332	14511

The list of recycled products made from the separately collected and mechanically recovered packaging materials for the municipality of Boxtel is shown in Table 24. The overview of the total annual net amounts of secondary products is listed in Table 25.

Table 25: The total net amount of secondary materials produced on behalf of Boxtel in 2013 expressed in total net amounts and in total net specific amounts in a packaging-only and an all-material perspective..

Secondary material	Net annual amounts, [kg net/a]	
	Relating to packaging only	Relating to packaging and non-packaging object recycling
Recycled fibres P&B	525,562	1,440,583
Glass cullets	600,411	612,595
Ferrous metals	125,103	178,719
Nonferrous metals	21,899	31,285
Plastic milled goods	138,593	194,645
Total	**1,411,568**	**2,457,826**

Secondary material	Net annual specific amounts, [kg net/cap.a]	
	Relating to packaging only	Relating to packaging and non-packaging object recycling
Recycled fibres P&B	17.3	47.5
Recycled fibres BC	0	0
Glass cullets	19.8	20.2
Ferrous metals	4.1	5.9
Nonferrous metals	0.7	1.0
Plastic milled goods	4.6	6.4
Total	**46.5**	**81.0**

The separate collection and recovery systems for packaging materials yielded 1.4 mln kg of recycled products for the municipality of Boxtel in 2013 (46.5 kg net/cap.a), which is slightly higher than the national average for 2014 of 43 kg net/cap.a. In case all the materials (packaging and non-packaging combined) are considered, the total sum amounted to 2.4 mln kg of recycled products for the municipality of Boxtel in 2013 (81.0 kg net/cap.a), which is again slightly better than the national average of 74.6 kg net/cap.a..

4.3 Municipality Franekeradeel

The municipality of Franekeradeel was chosen as a typical example of a municipality which operates a combined separate collection and mechanical recovery system. Besides the amounts of waste that has been collected in 2013 in this municipality (CBS), little information is available. Franekeradeel has a separate collection system for paper & board and glass. Plastics, beverage cartons and metals are mechanically recovered at the facility of Omrin.

Table 26: Overview of the input data used for the municipality of Franekeradeel.

Input parameters	Value	Source
Name	Franekeradeel	
Amount of inhabitants	20746	CBS 2013
Amount of connections	8861	FBR list
Amount MSW collected	4075 ton/a	CBS 2013
Amount of Paper & board collected	1188 ton/a	CBS 2013
Amount of Glass packaging collected	328 ton/a	CBS 2013
Amount of Plastic packages collected	0	CBS 2013
Amount of Beverage cartons collected	0	CBS 2013
Amount of Metal packaging collected	0	CBS 2013
Amount of PMD collected	0	CBS 2013
Is the composition of the MSW known?	No	
Are plastics & beverage cartons recovered from the MSW	Yes at Omrin	
Is the packaging glass separately collected in 3 colours?	Yes	

The model calculates the net collection efficiencies for the five packaging materials, the amount of recycled materials produced on behalf of Franekeradeel and the net recycling chain yields, these are shown in Figure 9, Figure 10 and Figure 11, respectively. Since this municipality commissioned the recovery of plastics, beverage cartons and metals from its MSW, the collection yields for these materials are zero. The net collection efficiencies for paper & board and glass are mediocre and can be improved. Nevertheless, the largest contribution the municipality Franekeradeel made to material recycling was with the separate collection of paper & board, see Figure 10.

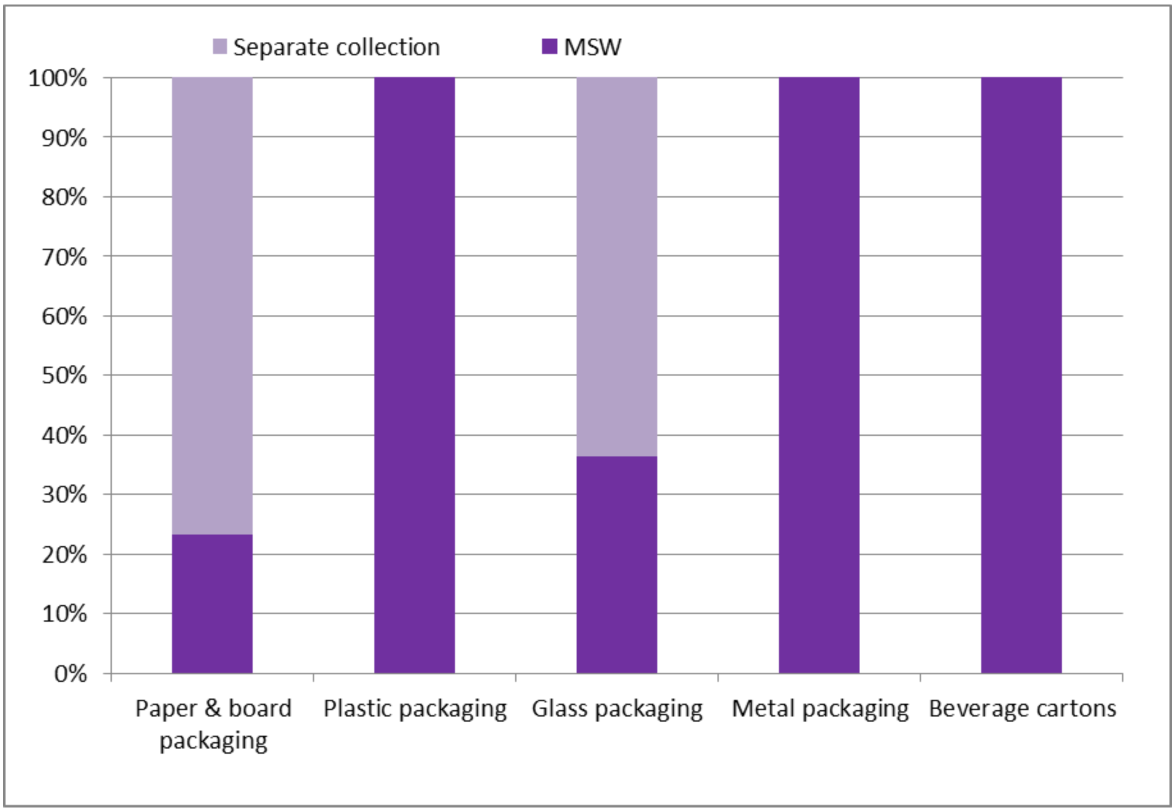


Figure 9: The net collection efficiencies for the five packaging materials that are separately collected and those that are collected with the MSW for the municipality of Franekerdeel in 2013 (packaging materials only).

The net recycling chain yields in Figure 11 reveal that this municipality is highly efficient for the three packaging materials which are recovered (plastics, beverage cartons and metals), mediocrely efficient for paper & board and less efficient than the national average for packaging glass. These latter two materials are separately collected. This creates an overall impression of reasonably efficiency in recycling packaging materials, with as improvement point the separate collection for glass and paper & board.
These results for Franekeradeel should only be used indicatively, since the composition of the MSW was not known and default values were used. Furthermore, Omrin also recovers metals directly from the MSW and not only from the bottom ashes. So the recycling yields for the metals might be slightly higher. Nevertheless, the overall conclusions remain the same.

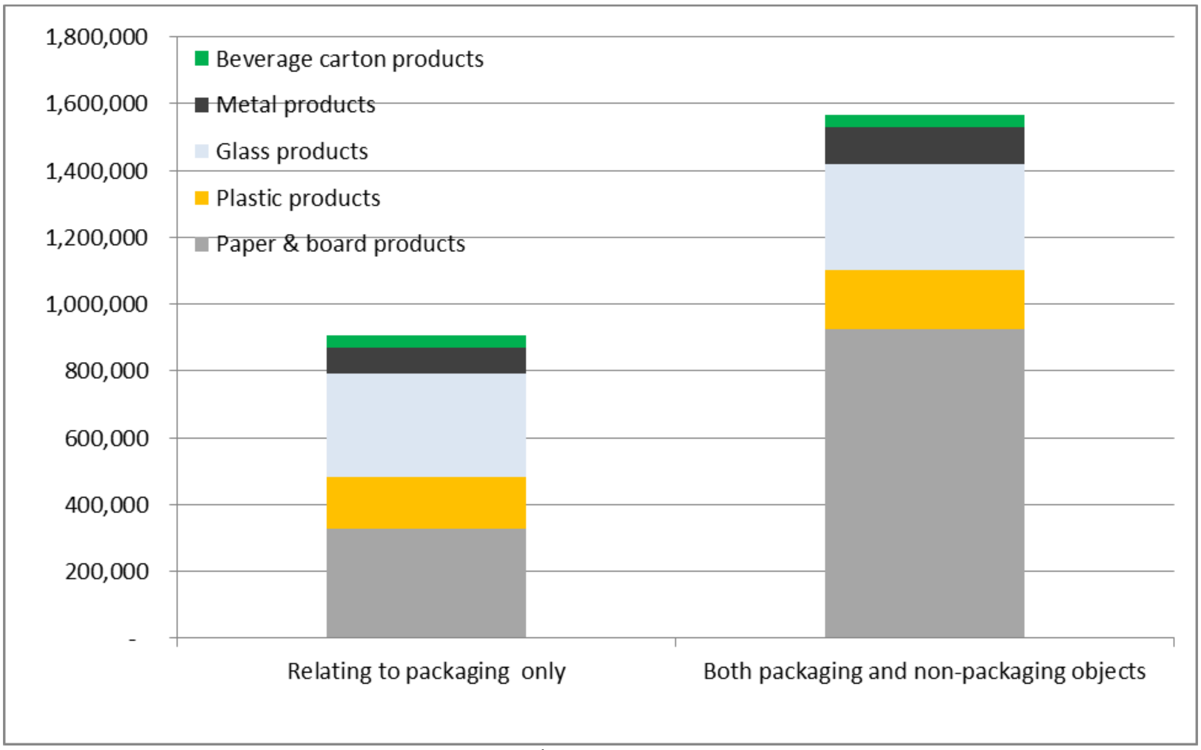
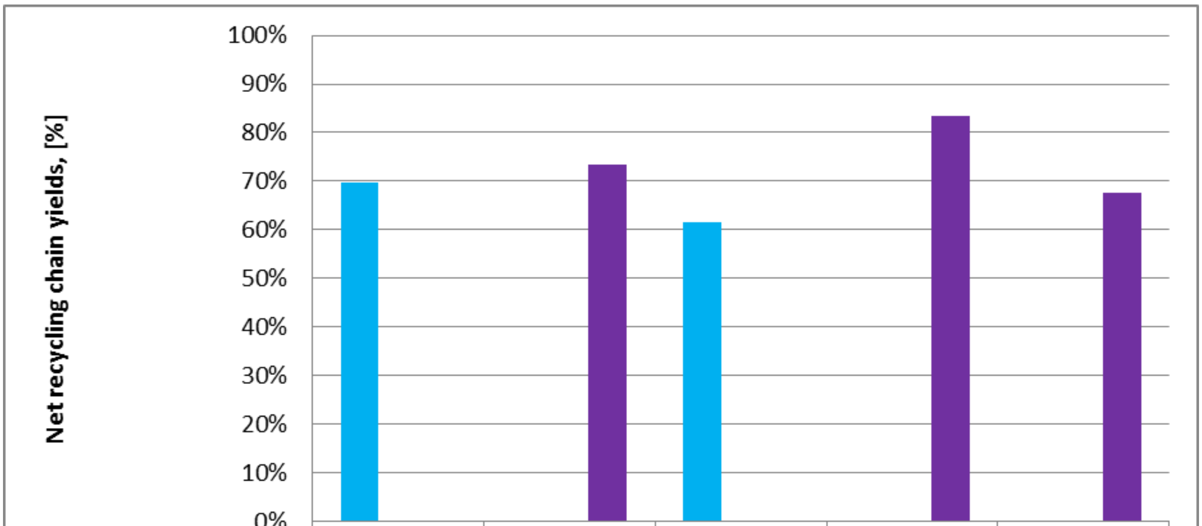


Figure 10: Net amounts of recycled products [kg net/a] for the 5 packaging materials from Franekeradeel in 2013 in 2 perspectives : only packaging and all the materials.



	Paper & board packaging	Plastic packaging	Glass packaging	Metal packaging	Beverage cartons
Separate collection	70%	0%	62%	0%	0%
PMD-co-collection	0%	0%	0%	0%	0%
Mechanical recovery	0%	73%	0%	83%	68%

Figure 11: Net recycling chain yields for the municipality of Franekeradeel in 2013 (based on packaging materials only).

Table 27: Indicatively calculated amount of recycled products made on behalf of the municipality of Franekeradeel in 2013.

Material class	Application	Amount of recycled products made from packaging materials, [kg net/a]	Amount of recycled products made from all materials, [kg net/cap.a]
P&B	Newspaper	36999	105025
	Uncoated writing paper	6786	19262
	Coated writing paper	11875	33708
	Container board	136588	387721
	Wrapping paper	11553	32794
	Solid board	91839	260695
	Folding carton	15538	44106
	Hygienic paper	15267	43338
Glass	Packaging glass clear	179919	184040
	Packaging glass green	89960	92020
	Packaging glass brown	28711	29368
	Glass by-products (foam glass)	10208	10442
Fe-metals	Construction steel	33580	47972
	Automotive steel	6716	9594
	Packaging steel	10074	14391
	Durable consumption goods	6716	9594
	Excavating machines	6716	9594
	Shipbuilding steel	3358	4797
NF-metals	Transport Aluminium	8889	12698
	Machine building Al	1185	1693
	Misc. applications for Al	593	847
	Desox	1185	1693
Plastics	PET trays	6073	6824
	PET fibres	1012	1137
	PET strapping	3037	3412
	Cable liner	6398	7189
	Drainage pipes	43904	49330
	Roll tubes	4266	4793
	Road plates	15002	16856
	Waste containers	4266	4793
	Non-food bottles	0	0
	Flower trays	10647	11963
	Crates	3549	3988
	Tree crates	3549	3988

	Appliances	0	0
	Pallets	6190	6955
	Garden furniture	7501	8428
	Play sets	18097	20334
	Traffic dividers	3095	3478
	Embankment	3095	3478
	Plastic lumber	16680	18742
	Mortar tubs	0	0
Beverage carton	Fibres for container board	35441	35441

The list of recycled products made from the separately collected and mechanically recovered packaging materials for the municipality of Franekeradeel is shown in Table 27. The total annual net amounts of secondary materials are listed in Table 28.

Table 28: The total net amount of secondary materials produced on behalf of Franekeradeel in 2013 expressed in total net amounts and in total net specific amounts in a packaging-only and an all-material perspective..

Secondary material	Net annual amounts, [kg net/a]	
	Relating to packaging only	Relating to packaging and non-packaging object recycling
Recycled fibres P&B	326,444	926,650
Recycled fibres BC	35,441	35,441
Glass cullets	308,798	315,870
Ferrous metals	67,160	95,943
Nonferrous metals	11,852	16,931
Plastic milled goods	156,361	175,686
Total	**906,056**	**1,566,522**

Secondary material	Net annual specific amounts, [kg net/cap.a]	
	Relating to packaging only	Relating to packaging and non-packaging object recycling
Recycled fibres P&B	15.9	45.3
Recycled fibres BC	1.7	1.7
Glass cullets	15.1	15.4
Ferrous metals	3.3	4.7
Nonferrous metals	0.6	0.8
Plastic milled goods	7.6	8.6
Total	**44.3**	**76.5**

The separate collection and recovery systems for packaging materials yielded 0.9 mln kg of recycled products for the municipality of Franekeradeel in 2013 (44.3 kg net/cap.a), which is slightly higher than the national average for 2014 of 43 kg net/cap.a. In case all the materials (packaging and non-packaging combined) are considered than the total sum amounted to 1.6 mln kg of recycled products for the municipality of Franekeradeel in 2013 (76.5 kg net/cap.a), which is again slightly better than the national average of 74.6 kg net/cap.a.

4.4 Concise reflection

Although both municipalities perform on average slightly better than the national average in terms of net recycling chain yields (or level of circularity), they both can still make significant improvements in their recycling schemes. These improvements should be aimed at increasing the collection responses without simultaneously raising the levels of contaminants in the separate collected materials. Conventional solutions might be found in communication campaigns focussed on raising the motivation of civilians to participate and simplifying the separate collection system or enlarging the participation options. Additionally, the relatively new collection schemes as reversed collection, PMD-collection and remuneration schemes might contribute, but these strategies have not been evaluated extensively yet. Although it is known in general that they successfully raise the gross responses.
The two studied municipalities are not prototypical for all Dutch municipalities. For instance, it is known that the gross responses of most urban centres in the western part of the Netherlands are much lower than of the two studied municipalities [6]. Hence the challenge for these municipalities to raise the level of circularity is much more substantial than for the two studied municipalities.

5 Discussion on the model

5.1 Municipal choices in a circular economy

Municipalities strongly influence the packaging recycling system in terms of *gross quantity* and *quality*. Both terms can be combined in the parameter *net quantity,* which largely determines the amounts of secondary materials produced. By comparing the net quantity with *the net potential*, the *net recycling yield* is obtained. This net recycling yield expresses the level of circularity the municipality has attained. It is an objective, quantitative parameter that clarifies both the municipality`s current results as well as potential for improvement. Additionally, the quality aspect *composition* largely determines the application for which these secondary materials are suitable and hence the nature of the circularity (closed loop, open loop, etc.).

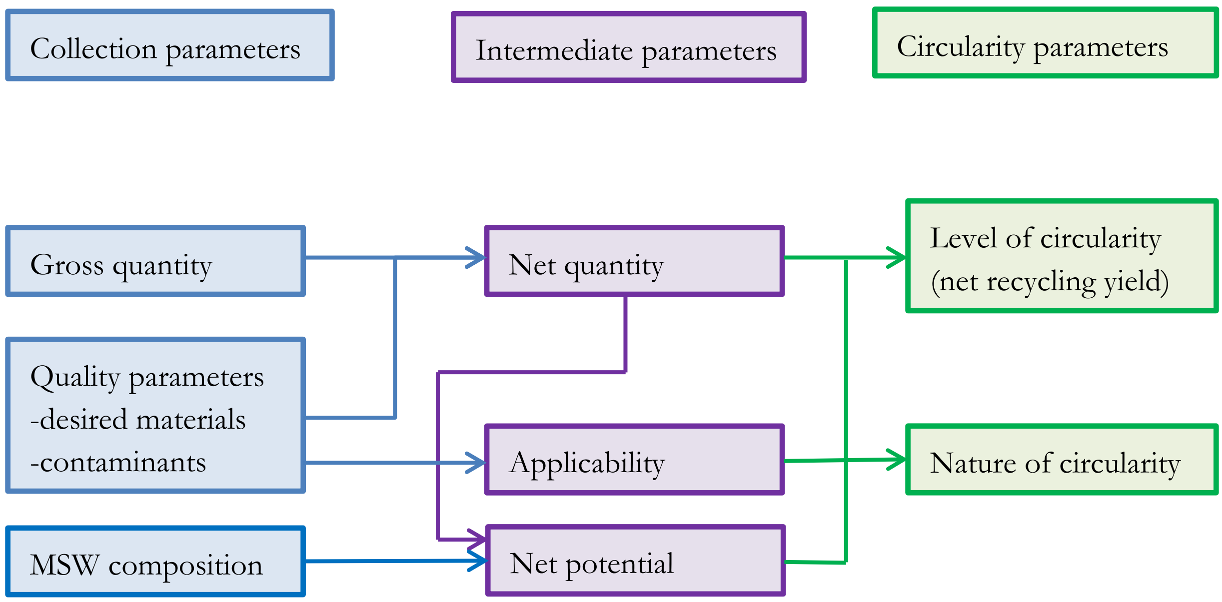


Figure 12: Municipalities that actively want to promote the circular economy not only need to manage the gross quantities of the collected or recovered materials but also the quality of these materials and need to know the composition of their MSW.

The primary influence of municipalities on the recycling systems is the choice for the separate collection system and / or mechanical recovery system. Their secondary influence is the selection of a sorting facility or trading partner. With the choice of a sorting facility the sorting yields are determined. Since some sorting facilities even have stable trading relationships with recycling facilities this choice can also determine the recycling yields and the applications for the secondary materials.

In case municipalities choose to operate a separate collection system for packaging materials, the details of the collection method and the contextual factors will determine the gross response and the quality of the material. The paper & board recycling industry studies the quality of the collected paper & board annually intensively and reports on the contaminants present in the collected material in relation to collection methods and contextual factors (Hoogland 2014). In this respect the paper & board recycling industry could be considered as example for other material organisations. Clearly they have understood the importance of municipal collection policies on the quantity and quality of recycled paper & board. As a consequence of their continuous effort to document contamination levels in collected paper & board from 2001 to now, the contamination level is known to vary between 0 and 6%. Although this is still significant for the paper recycling industry, this variation level in contaminants is relatively small in comparison to those of plastics and beverage cartons.

Nedvang published a thorough statistical study of packaging glass collection within municipalities in 2015 (Nedvang 2015). They can predict the gross packaging glass response for 63% with twelve contextual parameters. Unfortunately, no similar systematic study was performed with respect to the residual waste in collected packaging glass.

For separately collected plastic packaging the amount of residual waste in separately collected material was reported to vary between 0 and 30%, with 10±8% as weighted average (Thoden van Velzen and Brouwer 2014). On top of that there is about 10±5% plastic non-packaging objects present in the material (Thoden van Velzen and Brouwer 2014) and these plastic packages can contain significant amounts of product residues (Thoden van Velzen 2013; Thoden van Velzen et al. 2014).

For separately collected beverage cartons the amount of residual waste varies between 1 and 30% (with a few outliers of 70 and 90%) in the pilot beverage cartons (Thoden van Velzen et al. 2014). Moreover, this material contains high level of product residues of about 30% (Thoden van Velzen et al. 2014).

This implies that for both separate collection systems of plastic packages and beverage cartons there are serious challenges to contain the amounts of residual waste, non-packaging materials and contained product residues, hence the quality of the collected material and the net quantity of the collected material. The data suggests a non-normal distribution (skewed to the right), meaning that there are a few municipalities that contribute more than average to the contamination and that there are many municipalities with relatively normal contamination-levels. One typical example of a group of municipalities are the municipalities from West-Groningen that operate the 'Milieuzak'-system. These municipalities have received awards for the high gross amounts of separately collected plastic packages and beverage cartons, which approach or even exceed the net potentials derived from the national consumption data (Thoden van Velzen, Brouwer, et al. 2013). However, sorting analysis in 2010 and 2013 of this Milieuzak-material revealed that it contains about 30% and 25% of residual waste, respectively. Additionally, process technological analysis of the sorting process of the Milieuzak-material in 2013 at their sorting facility revealed that the sorting yield was about 82%, the recovered mass of mixed plastics was strongly elevated to 55% and hence the SVR only reached 29% instead of the required 45% (Thoden van Velzen et al. 2014; Thoden van Velzen 2015). Which implies that the net chain efficiency is reduced and relatively much invaluable mixed plastic products are produced from this Milieuzak-material. This reality contrasts with the overall objectives of a circular economy and shows that a municipal policy based on only gross quantities does not suffice to achieve all circular economy objectives. This example therefore reconfirms the analysis of Velis and Brunner that municipalities will have to manage both the quantity and the quality of the collected and/or recovered materials in order to progress towards a more circular economy (Velis and Brunner 2013). This model is intended to assist the municipalities in making this progress. In case municipalities perform compositional analysis of their MSW and their separately collected materials and run this model, they will get a clear impression of their achievements in packaging material recycling.

5.2 Gross recycling yield versus net recycling yield

Recycling yields are expressed in various ways. Recycling yields within municipalities are often expressed as the gross collected amounts divided by gross potentials (gross response). This is fine in terms of describing the primary role of municipalities. However, the amounts of secondary materials produced on behalf of that municipality can only be calculated with the net amounts of materials. Additionally, calculations based on gross amounts do not consider the losses that occur at the sorting and the recycling facilities. Therefore, the net recycling yield is a better parameter for circularity than gross responses, etc.

On the national and European level recycling yields are often expressed as the gross amount of collected material multiplied by the sorting yield and divided by the net material potential. This is the legally approved method of calculation. This definition might appear cumbersome but there are practical and logical reasons for it. First of all, the net amounts of packaging placed on the market are registered by packaging companies and monitoring agents (Stichting Afvalfonds in the Netherlands). At the stage that these freshly produced packages enter the market, only their net weight is obviously known and not their gross weight (net packaging weight with product residues and potentially other types of attached moisture and dirt). Additionally, the collection operators and sorting facilities only register gross weights. Furthermore, the recycling step is neglected in these national recycling yields, since the recycling yields are not known in the public domain. Recycling companies are regular businesses often in open competition with each other and regard yields as company secrets.

The scientific perspective on recycling yields is that all steps in the chain should be considered and net weights should be used to calculate net yields for each process step. This is impractical for the incumbents, since the levels of attached moisture and dirt vary and are often not known. Nevertheless, it is a scientific attempt to describe and understand the flow of materials through the recycling chain in a reliable manner. The downside of this scientific approach is that it introduces an additional source of error, namely the uncertainty in the levels of attached moisture and dirt, see paragraph 2.3.4.

5.3 Packaging material recycling systems as circular economy concepts

The circular economy is a relatively new political concept for future societies to reuse their wastes as feedstocks. This would reduce the need for mining fossil feedstocks, harvesting renewable feedstocks and would simultaneously reduce the need to manage huge volumes of waste, but instead use these wastes as alternative feedstocks. Several scientists have argued that glass and metal are fully circular and phrase this as 'permanent materials' (Conte et al. 2014). However, scientists as Bartl and Velis have debated that the current recycling systems are in general still far from circular, since the recycled materials are often too impure for direct reuse and much material is lost due to low collection rates and societal dissipation (Bartl 2014; Bartl and Velis 2015; Velis 2015a, 2015b).

This technical analysis of the Dutch packaging material recycling chains offers an option to evaluate the level of circularity of the packaging material recycling systems and to identify the shortcomings and improvement points. This is analysis is done for each material group separately.

<u>Paper and Board</u>

The Dutch paper & board packaging recycling chain is characterised by the input of a renewable feed stock (wood fibre), a cascadar recycling system[25] with official national collection responses of about 80% (Afvalfonds Verpakkingen 2015) (or in our scientific terms a net collection response of about 75%, see paragraph 4.1) and relative high sorting and recycling yields. For example, fresh spruce fibre is for instance used for beverage cartons, recycled and reused in corrugated board boxes, recycled and reused in solid board, recycled and reused in sanitary products and then incinerated. On average, paper is recycled 3.5 times in this cascadar recycling system. (Pivnenko et al. 2016). Finally, the degraded and shortened fibres are incinerated with paper sludge or with waste water sludge. This recycling system is mature. It is a combined collection and recycling system in which newspapers, magazines and other non-packaging objects dominate.

This recycling system is relatively successful in removing undesired foreign objects such as plastics, minerals, metals etc. However, this recycling system is less successful in removing molecular impurities, such as ink-chemicals, glue residues. Hence these chemicals tend to accumulate in recycled fibre (Pivnenko et al. 2016) and form a potential food safety concern for packages made from recycled board (Biedermann and Grob 2010).

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[25] *Cascadar recycling is circular recycling in which the quality of recyclate is slightly worse with each cycle of use and after several cycles the material is discarded.*

Table 29: Characteristics of the packaging recycling systems in the Netherlands with respect to the circular economy..

Packaging material	Feedstock	Characteristics	Issues and challenges	Applications
Paper & board	Renewable	Cascadar Dominated by non-packages	Raising responses Molecular pollution	Packaging and non-packaging
Beverage cartons	Renewable and fossil	Cascadar 100% packaging	Raising responses By-product recycling	Packaging and non-packaging
Plastic	Fossil	Mostly open loop Mostly packaging	Raising responses Plastic purity Particle pollution Molecular pollution	Mostly non-packaging
Glass	Fossil (A)	Circular 100% packaging	Raising responses Elementary pollution	Mostly packaging
Metal	Fossil (A)	Open loop Mostly packaging	Elementary pollution	Mostly non-packaging

A: the feedstocks for the glass and metal packages are minerals, hence not renewable.

The beverage carton recycling chain is relatively juvenile in the Netherlands. But the large scale adaptation of the PMD mixed collection system since 2015 by Dutch municipalities will probably boost the collection response. A special focus point will be on recycling the by-products.

Plastics

The plastic packaging recycling chain is still young in the sense that the responses are growing annually (Afvalfonds Verpakkingen 2015). It is a mostly open loop recycling system in which most of the plastic packages are recycled into granulates which are used in non-packaging applications, with the only exception of PET-bottle to PET-bottle and PET-tray recycling. But the amount of PET bottles is relatively small in comparison to the total collected amount of post-consumer plastic packaging waste (21 ktons of deposit refund sorted PET bottles compared to 130 ktons of sorted PPW) (van der Meulen). The molecular pollution of the non-PET post-consumer packaging plastics (mostly PE and PP) is so substantial that it limits their application to non-food packaging applications or non-packaging applications[26] (Palkopoulou et al. 2016). Odour and migration are the tell-tale consequences of this molecular pollution. Furthermore, the particle contamination and plastic purity of most post-consumer plastic recyclates limit their applicability, since it reduces the mechanical properties, causes grey discoloration, etc.

[26] *A few systems to recycle post-industrial PE and PP to food grade recyclates have been described, but these systems can only operate successfully with relatively clean post-industrial feedstock.*

Additionally, there is one striking difference with other material chains. The virgin plastic industry is hardly engaged in or with the recycling industry. Hence, the level of knowledge at the virgin and the recycling industry is very dissimilar. Additionally, the virgin plastic industry does not purchase recycled plastics to be blend in their virgin products, as is common with other materials and hence they also hardly influence the quality of recyclates.
According to the Ellen MacArthur foundation, the global plastic economy has to be redesigned completely (Ellen MacArthur Foundation 2016). They suggest a complex double-headed strategy for packaging plastics. On the one hand create an effective after use market for plastics and on the other hand improve the quality of the after use plastics. The latter strategy is often named design *for* recycling. The former strategy has recently been named design *from* recycling (Ragaert 2016)). Although they hint at the ingredients that are necessary for this change in the plastic economy, the roadmap towards this new plastic economy is still unclear. We are convinced that it will involve at least the following aspects:

- to raise the collection responses,
- to increase the plastic purity (by standardisation and simplification of the packaging designs and improved sorting techniques) and hence extend the applicability,
- to increase the technical and scientific understanding of the composition, processability and properties of recycled plastics and
- to promote the use of recycled plastics.

Such a redesign of the plastic (packaging) economy needs the active engagement of many different stakeholders of which the municipalities and collection agents are one. It will also require some form of coordination.
Due to the complexity of the composition of sorted plastic packages (with a variation of plastic packages present which all have a different composition of applied polymers) and the large effort required to determine polymer compositions of recycled plastics, the progress in recycling technology is limited. Hence understanding and controlling the polymer composition of recycled plastics is hence of central importance in order to improve the level of circularity. Therefore, the polymer composition of the recycled plastics will be further researched in TIFN SD002 task 4.2 .

<u>Glass</u>

The glass packaging recycling system is a mature collection and recycling system. Most glass packages are collected with drop-off containers and this yields roughly 80% of the packaging glass (Afvalfonds Verpakkingen 2015). The majority of the municipalities (~65%) has colour-separated glass collection containers. The packaging glass is sorted in which packaging components from different materials (corks, caps, labels, etc.), product residues and residual waste are removed. Almost all collected glass is also reused in packaging glass and some small amounts in various other applications (foam glass, thermal insulation, polishing powder, etc.). The sorting process for packaging glass is highly demanding, it requires the almost complete removal of all stone-like (stones, china, ceramics) impurities and all other glass-types with a different chemical composition. So laboratory glass (contains boron), crystal glass (contains lead) and thermal glass (contains zirconium) all have to be removed in sufficient amounts, to avoid unmolten glass lumps in the glass furnace upon reuse. Additionally, flat glass (elementary pure, hence free of B, Pb and Zr) is optionally added to the sorted packaging glass to further reduce the concentration of unwanted elements. A specific improvement point is further increasing the colour-separated glass collection over the mixed colour collection. The glass industry is able to accommodate more sorted glass cullets, especially clear cullets, so the level of circularity can still improve in the future. So, in essence the packaging glass recycling system is a true circular system, but even this system has its improvement points (raising the collection responses and mono-colour collection systems).

Metals

The metal packaging recycling system is a mature recovery and recycling system, but it is changing rapidly in a co-collection and recycling system. The existing recycling chain is based on the recovery of metals from the bottom ashes of incineration plants. These metal concentrates are sieved and sorted. The ferrous product is sold directly to local steel mills. These mills produce a large variety of products: machinery, construction beams, sheets for durable consumer goods, etc. This existing ferrous metal recycling chain is very efficient; having high recovery and sorting yields.

The non-ferrous product is subjected to density separation techniques to obtain aluminium products. These aluminium products are molten and the dross is separated. The obtained aluminium ingots are relatively rich in silicon and are primarily used to cast engine blocks. The existing non-ferrous metal recycling is slightly less efficient than the ferrous metal recycling, having a mediocre recovery yield and relatively good sorting and recycling yields.

Since 2015 a growing group of municipalities have implemented the co-collection system of plastic packages, beverage cartons and metal packages, named PMD-collection and in 2016 it appears to have become the major collection system in the rural areas of the Netherlands. Therefore, it is expected that a growing amount of the metal packages will now be recycled via the PMD-route. It is, however, unclear which technical process steps are taken in this recycling chain and in which applications the metals are re-used.

In short, the metal packaging recycling chain is characterised by relatively high recovery and sorting yields. The steel packages are reused in various steel products. The elemental composition of the aluminium material is slightly altered by the recycling chain, making the recycled aluminium more suitable for casting engine blocks. Therefore, this recycling chain is overall efficient and open-loop.

Circular packaging recycling

The current packaging recycling schemes in the Netherlands successfully reuse materials in various applications. Most recycling schemes have an open-loop nature. Glass packaging and PET-bottles are two examples of closed loop recycling schemes. Both closed loop recycling schemes rely on high collection responses, stringent sorting to remove contaminants and the partial input of pure material. This partial input of new material has two reasons: 1) to dilute the contaminants and 2) to replenish the losses of the recycling chain. Usually the first reason is dominant. In case some impurities cannot be removed easily (as for example with silicon in aluminium) the material is reused in a different market, for which this contaminant is not problematic or even beneficial. For porous materials (such as paper & board) and highly absorbing materials (such as polyethylene and polypropylene), molecular and/or particular contamination limits the applicability of the recycled materials.

6 Conclusions

A calculation model is presented which allows Dutch municipalities to gain insight in the type and amounts of secondary raw materials that are produced from separate collected and recovered packaging materials. The model allows municipalities to enter the amounts of MSW and separately collected (packaging) materials and subsequently calculate the amounts of secondary materials produced on behalf of that municipality. The results of this model are indicative, since the packaging material recycling chains are dynamic. Nevertheless, this model presents a typical result of what could have been produced. Furthermore, the results are intended to inform interested stakeholders and civilians of the benefits of their local collection and recovery services. The model was tested with two exemplary Dutch municipalities (Boxtel and Franekeradeel). The results revealed that for both municipalities the net collection yields are relatively mediocre and limit the net recycling yields. The net recycling yields of the applied recovery schemes are much higher, due to the relatively high net recovery yields. But not all materials can be recovered and not all municipalities have access to recovery facilities and hence there is still a substantial challenge towards achieving a more circular economy for the Dutch municipalities.

The qualitative analysis of the Dutch packaging recycling schemes showed that most are open-loop recycling schemes. Only packaging glass and PET bottle recycling are largely closed loop recycling schemes. These closed loop systems rely on high collection responses, stringent sorting to remove contaminants and the partial input of new materials to dilute the contaminants and replenish the recycling chain losses. In some open-loop recycling schemes some contaminants cannot be removed by sorting and the material is used in specific applications were these contaminants are not detrimental, but rather beneficial (as for example with recovered aluminium that is relatively rich in silicon and therefore well suited for casting engine parts). For porous materials (such as paper & board) and absorbing materials (such as polyethylene and polypropylene) the molecular contamination and particular contamination is so severe that it limits the application of the recyclates to non-food-contact utensils.

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List of abbreviations used

BC	Beverage cartons
CBS	Centraal bureau voor de statistiek
Film	Flexible plastic sorting product
LAMD	Level of attached moisture and dirt
LVP	German "Leicht Verpackungsmüll" similar to PMD
MP	Mixed plastics
MSW	Municipal solid refuse waste
MSWI	Municipal solid waste incinerator
PE	Poly ethylene
NMC	Net material content
PET	Poly ethylene terephthalate
PMD	Co-collection system for plastic packaging, metal packaging and beverage cartons
PNM	Papirfabrik Niederauer Mühle
PP	Poly propylene
PR	Packaging ratio
PRN	Papier Recycling Nederland
PS	Poly styrene
PVC	Poly vinyl chloride
P&B	Paper and board
RWS	Rijkswaterstaat
SRF	Secondary recovered fuel
SVR	Sorting value ratio
VPN	Vereniging papierindustrie Nederland

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Annex A

Levels of attached moisture and dirt to packaging materials and related non-packaging objects in MSW. MSW from Friesland Omrin Oude Haske, 11 September 2015.

	Gross weight, [g]	Net weight, [g]	LAMD, [%]
Glass packaging	4129	3820	7.5%
Glass non-packaging	192	175	8.9%
Fe metal packaging < 100 grams	2700	2036	24.6%
Fe metal packaging > 100 grams	2565	1452	43.4%
NF metal packaging < 100 grams	425	140	67.1%
NF metal packaging > 100 grams	1625	1042	35.9%
Paper & board packaging	15458	9250	40.2%
PET bottles clear, small, 10 pcs.	229	167	27%
PE Flasks, 10 pcs.	472	383	19%
PET non-bottle rigids, 10 pcs.	338	146	57%
PP rigids, 10 pcs.	227	137	40%
PE Film > A4, 10 pcs.	153	93	39%
Plastic packages weight averaged			40±5%

Annex B

The concentration of targeted plastic packages in the separately collected packaging waste and the sorting fractions as used in table 12 (paragraph 3.2.3.2).

Total concentrations of groups of plastic packages as present in Dutch separately collected plastic packaging waste, as derived from the database of 24 sorting analysis from different municipalities (Thoden van Velzen and Brouwer 2014).

$c_{target\ plastics}^{Input}$, [%]	Average	St.dev	Median	Min	Max
All PET bottles and flasks	9.1%	3.5%	9.0%	3.8%	17.9%
All rigid PE packages and objects	11.0%	3.0%	11.2%	5.9%	18.1%
All rigid PP packages and objects	13.2%	2.9%	13.2%	8.7%	18.4%
All flexible plastic objects (non PVC)	30.7%	5.9%	29.5%	22.3%	44.4%
All PET trays, black plastics, PS, other plastics	24.0%	6.2%	23.4%	17.6%	43.4%
PVC and residual waste	12.0%	8.5%	7.2%	1.4%	31.1%

The concentration of targeted plastic packages in the sorting products ($c_{target\ plastics}^{Sorted\ PET}$) and the concentration of plastics that contribute to the final recycling product ($c_{Sorted\ input}^{Contributing\ plastics}$) are listed here below per sorting product. The former is usually lower than the latter, since there are plastic objects that contribute to a recycling product, although not intended to be present in the sorting feedstock; for instance PE-film in the PP sorting product which is intended to contain PP rigids, nevertheless the PE will be incorporated in the rPP and contribute to the mass of recycled product.

Sorted PET, DKR 328-1

Sorting facility	$c_{target\ plastics}^{Sorted\ PET}$, [%]	$c_{Sorted\ input}^{Contributing\ plastics}$
A, 24 Oct 2011	80.5%	95.7%
B, 8 Feb 2012		
A, 20 June 2013	87.7%	92.0%
A, 1 July 2013	83.3%	92.6%
C, 15 July 2013	87.0%	89.5%
C, 13 June 2013		
A, 9 June 2014	99.9%	99.9%
Average	**88 ± 7%**	**94 ± 4%**

Sorted PE, DKR 329

Sorting facility	$c_{target\ plastics}^{Sorted\ PE}$, [%]	$c_{Sorted\ input}^{Contributing\ plastics}$
A, 24 Oct 2011	85.1%	93.9%
B, 8 Feb 2012	90.6%	97.5%
A, 20 June 2013	90.4%	96.8%
A, 1 July 2013	93.2%	96.7%
C, 15 July 2013	96.3%	100%
C, 13 June 2013	94.4%	96.3%
A, 9 June 2014	88.0%	95.0%
Average	**91 ± 4%**	**97 ± 2%**

Sorted PP, DKR 324

Sorting facility	$c_{target\ plastics}^{Sorted\ PP}$, [%]	$c_{Sorted\ input}^{Contributing\ plastics}$
A, 24 Oct 2011	94.5%	96.4%
B, 8 Feb 2012	93.5%	93.0%
A, 20 June 2013		
A, 1 July 2013	81.1%	87.5%
C, 15 July 2013	85.3%	97.0%
C, 13 June 2013	87.3%	96.0%
A, 9 June 2014		
Average	**88 ± 6%**	**94 ± 4%**

Sorted Film, DKR 310

Sorting facility	$c_{target\ plastics}^{Sorted\ Film}$, [%]	$c_{Sorted\ input}^{Contributing\ plastics}$
A, 24 Oct 2011	88.2%	90.1%
B, 8 Feb 2012	99.9%	93.5%
A, 20 June 2013	84.5%	87.8%
A, 1 July 2013	98.2%	98.5%
C, 15 July 2013	90.1%	91.7%
C, 13 June 2013	89.1%	91.4%
A, 9 June 2014	86.3%	89.0%
Average	**91 ± 6%**	**92 ± 4%**

Sorted Mixed Plastics, DKR 350

Sorting facility	$c_{target\ plastics}^{Sorted\ MP}$, [%]	$c_{Sorted\ input}^{Contributing\ plastics}$
A, 24 Oct 2011	37.0%	93.9%
B, 8 Feb 2012	33.0%	94.4%
A, 20 June 2013	29.0%	84.0%
A, 1 July 2013	84.0%	96.1%
C, 15 July 2013	35.8%	96.3%
C, 13 June 2013	23.1%	83.8%
A, 9 June 2014		
Average	**40 ± 22%**	**91 ± 6%**

Annex C

Total concentrations of groups of plastic packages as present in Dutch MSW, as derived from the analysis of three large samples of MSW from two different Dutch cities in 2011 and 2012 and a group of rural municipalities in 2013.

$c_{target\ plastics}^{Input}$, [%]	Average	St.dev	A	B	C
All PET bottles and flasks	0.9%	0.3%	0.68%	0.93%	1.19%
All rigid PE packages and objects	1.6%	0.7%	1.51%	0.91%	2.26%
All rigid PP packages and objects	2.2%	0.6%	1.79%	1.86%	2.86%
All flexible plastic objects (non PVC)	6.0%	0.1%	6.07%	6.06%	5.89%
All PET trays, black plastics, PS, other plastics	5.5%	2.1%	3.15%	6.35%	7.12%
PVC and residual waste	0.6%	0.2%	0.41%	0.80%	0.67%

The concentration of targeted plastic packages in the sorting products is listed here below per sorting product.

Sorted PET, DKR 328-1

Sorting facility	$c_{target\ plastics}^{Sorted\ PET}$, [%]	$c_{Sorted\ input}^{Contributing\ plastics}$, [%]
A, 26 Aug 2011	89.3%	99.3%
B, 14 July 2011		86.4%
C, 30 March 2012	97.4%	99.6%
D, 16 Feb. 2011		
E, 13 Feb 2013	90.1%	96.8%
F, 8 April 2011		
C, 16 sept. 2013	98.7%	99.2%
Average	**94 ± 5%**	**99 ± 6%**

Sorted PE, DKR 329

Sorting facility	$c_{target\ plastics}^{Sorted\ PE}$, [%]	$c_{Sorted\ input}^{Contributing\ plastics}$, [%]
A, 26 Aug 2011	93.3%	97.8%
B, 14 July 2011		91.0%
C, 30 March 2012	96.6%	98.5%
D, 16 Feb. 2011		
E, 13 Feb 2013	87.8%	93.4%
F, 8 April 2011		
C, 16 sept. 2013	99.7%	100%
Average	**94 ± 5%**	**96 ± 4%**

Sorted PP, DKR 324

Sorting facility	$c_{target\ plastics}^{Sorted\ PP}$, [%]	$c_{Sorted\ input}^{Contributing\ plastics}$, [%]
A, 26 Aug 2011	94.7%	97.0%
B, 14 July 2011	90.6%	94.8%
C, 30 March 2012	83.0%	89.1%
D, 16 Feb. 2011		
E, 13 Feb 2013		77.1%
F, 8 April 2011		
C, 16 sept. 2013	92.1%	94.9%
Average	**90 ± 5%**	**94 ±3%**

Sorted Film, DKR 310

Sorting facility	$c_{target\ plastics}^{Sorted\ Film}$, [%]	$c_{Sorted\ input}^{Contributing\ plastics}$, [%]
A, 26 Aug 2011	72.0%	92.6%
B, 14 July 2011		
C, 30 March 2012		
D, 16 Feb. 2011	81.0%	95.7%
E, 13 Feb 2013		
F, 8 April 2011	75.8%	89.3%
C, 16 sept. 2013		
Average	**76 ± 5%**	**93 ±3%**

Sorted Mixed plastics, DKR 350

Sorting facility	$c_{target\ plastics}^{Sorted\ MP}$, [%]	$c_{Sorted\ input}^{Contributing\ plastics}$, [%]
A, 26 Aug 2011	38.5%	92.3%
B, 14 July 2011	49.0%	88.3%
C, 30 March 2012	44.6%	97.0%
D, 16 Feb. 2011		
E, 13 Feb 2013	24.7%	68.6%
F, 8 April 2011		
C, 16 sept. 2013	32.9%	87.5%
Average	**38 ± 10%**	**91 ± 4%**

Annex D

Crudely estimated market distributions for each sorted plastic product originating from both separate collection and mechanical recovery. Based on dozens of interviews with incumbents of the recycling industries in 2010-2015.

Sorted PET, DKR 328-1

Sinking product	Separately collected	Mechanically recovered
Bottles	0%	0%
Trays	70%	60%
Fleece	10%	10%
Strapping	20%	30%

Floating by-product	Separately collected	Mechanically recovered
Plastic lumber	100%	100%

Sorted PE, DKR 329

Floating product	Separately collected	Mechanically recovered
Cable liner	20%	30%
Drainage pipes	30%	30%
Roll tubes	20%	20%
Road plates	20%	
Waste containers	9%	20%
Non-food bottles	1%	

Sinking by-product	Separately collected	Mechanically recovered
SRF	100%	100%

Sorted PP, DKR 324

Floating product	Separately collected	Mechanically recovered
Flower trays	50%	60%
Crates	20%	20%
Tree crates	15%	20%
Appliances	5%	
Pallets	10%	

Sinking by-product	Separately collected	Mechanically recovered

SRF	100%	100%

Sorted Film, DKR 310

Floating product	Separately collected	Mechanically recovered
Garden furniture	10%	10%
Drainage pipes	40%	50%
Road plates	40%	20%
Play sets	10%	20%

Sinking by-product	Separately collected	Mechanically recovered
SRF	100%	100%

Sorted Mixed plastics, DKR 350

Floating product	Separately collected	Mechanically recovered
Play sets	10%	10%
Traffic dividers	10%	10%
Embankment	10%	10%
Plastic lumber	30%	50%
Pallets	20%	20%
Mortar tubs	20%	

Sinking product	Separately collected	Mechanically recovered
Additive in Tarmac production	100%	100%

