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Title: **Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the Circular Economy**.

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Abstract

The Dutch post-consumer plastic packaging recycling network has been described in detail (both on the level of packaging types and of materials) from the household potential to the polymeric composition of the recycled milled goods. The compositional analyses of 173 different samples of post-consumer plastic packaging from different locations in the network were combined to indicatively describe the complete network with material flow analysis, data reconciliation techniques and process technological parameters. The derived potential of post-consumer plastic packages in the Netherlands in 2014 amounted to 341 Gg net (or 20.2 kg net.cap^{-1}.a^{-1}). The complete recycling network produced 75.2 Gg milled goods, 28.1 Gg side products and 16.7 Gg process waste. Hence the net recycling chain yield for post-consumer plastic packages equalled 30%. The end-of-life fates for 35 different plastic packaging types were resolved. Additionally, the polymeric compositions of the milled goods and the recovered masses were derived with this model. These compositions were compared with experimentally determined polymeric compositions of recycled milled goods, which confirmed that the model predicts these compositions reasonably well. Also the modelled recovered masses corresponded reasonably well with those measured experimentally. The model clarified the origin of polymeric contaminants in recycled plastics, either sorting faults or packaging components, which gives directions for future improvement measures.

Keywords

Post-consumer waste, plastic packaging, sorting, mechanical recycling, circular economy, compositional analysis

1. Introduction

One of the five priorities within the European Circular Economy package (European Commission 2015) is the reduction of plastic waste-to-landfill, in particular achieved by recycling of post-consumer plastic packaging waste (PPW), which has already been a legislative focal point since 1994 (European Parliament 1994). Although substantial amounts of PPW are now being collected in various member states, these recycling systems are still far from circular. Circularity is also a diffuse terminology. It is very much related to the cradle to cradle principle as defined by McDonough and Braungart (2002), more recently named closed loop recycling. Reality, however, is complex, and many technical and economic issues arise that result in deviations from this perfect circularity. The current state-of-the-art within recycling is therefore more related to open loop recycling, sometimes also called 'downcycling' or even 'upcycling'. For European households for example, the majority of plastic packages is still not collected (Plastics Europe 2015) and roughly 60% of the plastic packages that are collected for recycling within the EU are exported (Furfari 2016). Specifically for the Netherlands three PPW recycling systems are in place: separate collection from households, mechanical recovery from the mixed municipal solid refuse waste (MSW) and a deposit-refund system for large PET bottles for water and soda drinks. The latter is officially treated and registered as post-industrial packaging waste and excluded from this study. Polyethylene-terephthalate (PET) bottles are the only plastic packaging type that is being recycled in large volumes to produce rPET for new packaging applications (bottles and trays – which could be called closed loop recycling) as well as non-packaging applications (strapping, fleece fill textiles – which could be called open loop recycling) (Awaja and Pavel 2005; Welle 2011). The successful closed loop recycling of PET beverage bottles relies on three factors: a high polymeric purity, a low level of molecular contamination (i.e. absorbed single molecules causing odour and migration issues) and restoration of the polymeric chain lengths. The high level of polymeric purity for rPET can be achieved by mechanical recycling PET bottles of which the designs are optimal for recycling. The low level of molecular contamination and the restoration of the polymeric chain lengths can both be achieved for rPET with the solid state post-condensation (SSPC) treatment (Welle 2011). The most common plastic packaging materials are, however, polyethylene (PE) and polypropylene (PP) (Plastics Europe 2015). And although a few examples of post-industrial recycled PP in food packaging have been documented (EFSA 2014), in general the molecular pollution of both recycled PE and PP is so substantial that the legal migration limits for food packages are exceeded (Palkopoulou et al. 2016; Dutra et al. 2014). Therefore, their application is usually limited to non-food packaging and non-packaging applications. These are typical examples of open loop recycling. Moreover, recycled PE and PP are susceptible to thermal and thermo-oxidative degradation processes. Recycled PP is susceptible to chain scission and recycled PE is susceptible to both chain scission as well as cross-linking (Yin et al. 2015). However, there are no straight-forward technologies to restore their chain lengths and undo oxidative damage (Vilaplana and Karlsson 2008). Additionally, recycled PE and PP often contain polymeric contaminants which form immiscible blends and hence a profound particle contamination (Luijsterburg 2015). Hence the application of recycled PE and PP is often limited to non-transparent, non-white articles of a lesser mechanical strength (Meran et al. 2008; Pivnenko et al. 2015; Borovankska et al. 2012; Sjöqvist and Boldizar 2011).

In their much acclaimed report 'The New Plastics Economy', the Ellen MacArthur Foundation proposes to completely redesign the global plastic economy, in order to achieve the simultaneous creation of an effective after-use market for plastics and improved qualities of the recycled plastics (Ellen MacArthur Foundation 2016). However commendable, such strategic efforts at the policy level would at the very least require, in order to succeed, detailed predictive knowledge of the polymeric composition of (potentially recycled) waste plastics. This knowledge is currently lacking, which severely hinders the progress towards a more circular plastic recycling system. Hitherto, the composition of sorted plastic packaging products is described with broad specifications, of which the so-called DKR list of specifications is most commonly applied in Europe (Duales System Deutschland 2016). Compliance to specifications is determined by object-wise sorting of samples. For example, one of the nine quality aspects in the specification for PET product 328-1 demands that less than 0.1% (w/w) are PVC objects. Packaging objects are in almost all cases multi-material objects, though, yet being categorised on their main material. Thus, a PET bottle with a PP label and a PE cap is registered as a 100% PET object. This implies that compliance to a trading specification only renders a crude indication of the polymeric composition of the sorted product, as it only considers the sorting faults and not the packaging components made from different polymers. Moreover, polymeric contaminants are partially removed during the mechanical recycling process, yielding washed milled goods with unknown polymeric compositions. Since the processing options for and applicability of recycled plastics depends on their polymeric composition, there is a great need for methods to determine and describe the polymeric composition of recycled plastics.

Previous researchers have studied the polymeric composition of recycled plastics (Vilaplana and Karlsson 2008; Brachet et al. 2008; Borovankska et al. 2012; Hubo et al. 2014). Analyses have been performed on the level of washed milled goods, extruded granulates and injection moulded test specimen. Milled goods can be sorted automatically by near-infrared (NIR) based flake sorting machines. However, in our own experience with these machines, this yields 2-10% unknown materials, largely due to undesired light reflections of the irregular plastic particles. FT-IR (Fourier transform infrared) spectroscopy in ATR (attenuated total reflection) mode can be used to identify individual flakes and by repeating these measurements on hundreds of flakes the polymer composition can be obtained (Hubo et al. 2014). This is, however, tedious and laborious. FT IR–ATR spectroscopy can also be used to analyse the surface of test specimen made from recycled plastics. The concentration of polymeric contaminants in the test specimen can be determined if the concentration is roughly above 2%, but the concentration of these contaminants can be elevated at the surface as compared to the bulk (Luijsterburg 2015). DSC (differential scanning calorimetry) can be used to estimate polymeric contaminants from 1% on, as long as the polymers have clearly distinguishable phase transitions (Vilaplana and Karlsson 2008; Luijsterburg 2015; Borovankska et al. 2012). Again, multiple repetitions of the measurements can improve the level of accuracy. In any case, it has been proven difficult to determine the polymeric composition in the entire relevant range of 0.1-50% of polymeric contaminants in recycled plastics.

The current study has three objectives. First of all, this study aims to model the Dutch post-consumer plastic packaging network with material flow analysis (MFA) and data reconciliation techniques, from the household potentials to the produced amounts of washed milled goods. Secondly, the model is used to assess the end-of-life (EOL) fates of the 35 different plastic packaging types. Thirdly, the model derives the polymeric compositions of the produced milled goods. In order to estimate the polymeric composition of the milled goods this model needs to describe the network in an unprecedented level of detail, including a list of 35 different plastic packaging types and average material compositions per packaging type. In order to verify the model, milled goods made from Dutch sorting products will be analysed with manual NIR assisted sorting. Although NIR assisted sorting of milled goods is laborious and hence only single sample measurements have been performed, they have an indicative value and can be used to crudely verify the modelled composition of the milled goods. This MFA model explains the complex flow of plastic packages from the Dutch households to the produced milled goods. It clarifies the origin of polymeric contaminants in the recycled milled goods. This MFA model is dedicated for PPW and hence differs from more generic models that describe the flow of all plastics objects through specific countries, for instance Austria (Van Eygen et al. 2017). This dedicated MFA for Dutch PPW will be used in the near future to estimate the efficiency of industrial policy options –such as design-for-recycling measures and sorting policies- made by individual stakeholders on the amounts of washed milled goods and their polymeric composition. Since the latter parameter is indicative for the applicability of recycled plastics, this model can guide the redesign of the plastic recycling network towards a more circular economy.

2. Materials and methods

2.1 Origin of the data

A dedicated sorting team has determined the composition of 173 PPW samples taken at various locations in the recycling network in previous projects which were executed between 2010 and 2015. These compositions are described in data sheets, which categorise the material in terms of 35 different plastic packaging types, non-packaging plastics and 5 types of residual wastes. The data sheets have been combined to obtain averages and standard deviations, which are added as annex C and D. The composition of separately collected plastic packages has been determined for 26 different municipalities between 2010 and 2013 (annex C). The composition of plastic packages present in Dutch MSW was determined in two large sorting trials of MSW (2011, 2012) and ten smaller sorting trials with different municipalities (2013), see annex D. The compositions of the five plastic sorting products (PET, PE, PP, Film, Mix) made from the separately collected material were determined from in total 37 different sorting analysis. The composition of the sorting residue was determined with one sorting analysis, see annex C . The compositions of the five plastic sorting products (PET, PE, PP, Film, Mix) made from the recovered rigid plastic concentrate were determined from in total 87 different sorting analysis, see annex D. The composition of the non-recovered waste streams were calculated from the compositions of the waste products and their mass relations for three different sets of analysis.

The nationally accounted amounts of plastic packaging materials collected at households, sorted and mechanically recovered and sorted were derived from the national packaging materials monitoring report (Afvalfonds Verpakkingen 2015, annex B). The gross amounts of generated sorting products were derived from the total amounts of sorted PPW and sorting divisions, see annex F.

2.2 Mathematical modelling / Material flow analysis

A schematic structure of the Dutch PPW recycling system is given in figure 1. Roughly 6 sorting facilities are engaged in processing both the separately collected and the mechanically recovered PPW. In 2014 the sorting facilities had to produce at least five sorting products, which are named according to their DKR specification: PET (DKR 328-1), PE (DKR 329), PP (DKR 324), Film (DKR 310), Mix (DKR 350) and sorting residues. Under Dutch law all these sorted products have to be traded to approved and certified European mechanical recycling facilities (roughly 30).

The MFA of the Dutch post-consumer plastic packaging waste network was conducted in two models at two levels (packaging type level, material level). The first model described the separate collection of plastic packaging waste, the industrial separation into sorting products and the mechanical recycling into washed milled goods. The second model described the plastic packages present in the municipal solid waste (MSW), the mechanical recovery process of these packages from the MSW, the separation into sorting products and the mechanical recycling into washed milled goods. All steps in both models were described for the two levels, except for the last step; the washed milled goods were only described at the material level. The potential of plastic packages available at the Dutch households was derived by summing up the plastic packages present in the separate collection system and those present in the MSW, see Figure 1. In this calculation method of the potential, littering and public waste bins are excluded, since there is no reliable data available.

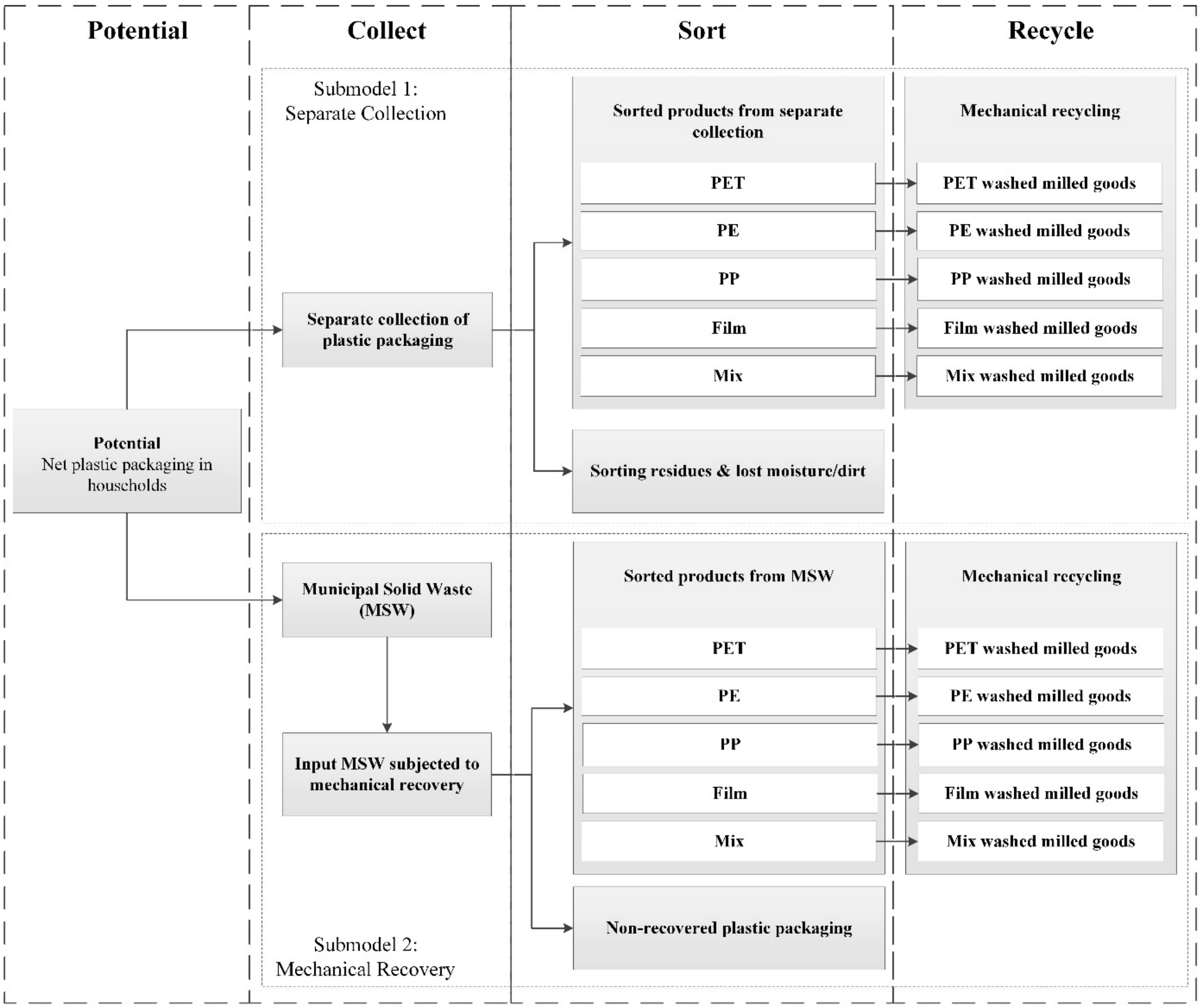

Fig. 1 Schematic overview of the two models used to describe the Dutch post-consumer plastic packaging recycling network.

2.2.1 Sub-model 1: separate collection

Datasets on the amounts and composition of the feedstock masses and the product masses were systematically entered into the data reconciliation software STAN (Uni. Vienna 2017 Stan-website) for both models (Brunner and Rechberger 2004; Laner, Rechberger and Astrup 2015; Fellner et al. 2011). The reconciled data was calculated and will be presented. The quality of the reconciled data was expressed in the software STAN with the Data Reconciliation Quality (DRQ) indicator (Cencic 2016).

The input data for the first model were the gross quantities of separately collected plastic packaging waste, the gross quantities of sorted products (PET, PE, PP, Film, Mix) and the average composition of all these input and output masses (annex B and C). The separately collected plastic packaging materials and the five sorted plastic products were considered as ‘goods’ in the terminology of STAN. These goods were described with the list of 35 packaging types, non-packaging plastics, 4 types of residual waste, attached moisture and attached dirt. These compositional categories were considered as ‘layers’ within STAN. All layers had mass fractions which added up to 100% to form the entire ‘good’. The data reconciliation was conducted in STAN for each layer separately. In a limited amount of cases, the reconciled data gave negative masses. This was obviously a flaw within STAN and occurred exclusively for layers with very low concentrations in the sorting residues. In order to avoid these negative masses, the standard deviations of these small mass fractions were manually set to zero and the data reconciliation procedure was repeated. The outcomes for the 42 layers were combined to obtain the reconciled result on the level of goods. In case the total net weight of a good after reconciliation differed from the original net weight, the levels of attached moisture and dirt were manually adjusted to let the total gross weights of a good after reconciliation be equal to the original gross weights.

In order to convert the reconciled composition of sorted products into a polymeric composition, a data sheet (annex F) was used with the average material composition for each packaging type and non-packaging plastic. This data sheet was obtained by disassembling packages found on the Dutch market in 2015, weighing each packaging component and analysing the plastic type with NIR or IR. This had already been performed in a previous study for PET bottles with 20 to 114 replicates per PET bottle type (Thoden van Velzen, Brouwer and Molenveld 2016). For all other packaging types at least 25 different packaging replicates were collected and analysed. In case labels could not be removed easily, the dry weight of the construct was determined, the label was removed by destructive scrubbing and the clean dry weight of the remaining object was determined. The weight of the non-detachable label was derived from the weight difference. The packaging type “Miscellaneous rigid PET packages” was too diverse and the material composition was determined for 11 sub-types with 25 replicates that were later averaged to the material composition for this packaging type. This data sheet is added as annex F.

Both models have conventional mechanical recycling as last step. This step was modelled and not analysed with data reconciliation techniques. The mechanical recycling step is comprised of milling, washing and float separation. The material composition of the sorted product was used as basis for the input for this part of the model (annex F and G). Since it was visually observed that roughly 35% of the bottles are incomplete, missing components like labels and caps, the material composition of the sorted products were corrected for this loss of bottle components, see annex I. The milling was modelled by assuming that all the materials remained in the form of loose flakes and that a part of the moisture and dirt was removed by evaporation and detachment of loose dirt. The fraction of moisture and dirt that was lost during the milling process was derived from the difference between the amount of attached moisture and dirt that was present in the sorted products as a result of the data reconciliation procedure and the amount of moisture and dirt that was present on freshly milled sorted fractions as experimentally determined, see annex K. These dirty milled goods were the feedstock for the further conventional mechanical recycling process that was comprised of washing and a float-separation process step. This part of the mechanical recycling process was described with transfer coefficients (annex A). These transfer coefficients describe for each constituent present in the feedstock the distribution in one of the three mechanical recycling products (floating product, sinking product and process waste). These transfer coefficients were determined in separate experiments, see annex A. The recovered masses of the three products were derived from the transfer coefficients by adding the weights of all the constituents (annex H). These recovered masses were compared with the previously published recovered masses for this part of the mechanical recycling process (Thoden van Velzen, Jansen, et al. 2016). The polymeric compositions of the floating and the sinking products were derived from this reconstitution of all the components and were compared with the NIR measured composition of both products.

2.2.2 Sub-model 2: mechanical recovery

Similarly, the input data for the second model were the gross quantities of MSW that were subjected to mechanical recovery of plastics (annex B), the gross quantities of sorted products (PET, PE, PP, Film, Mix) formed from these recovered plastics (annex B) and the average composition of plastic packages in the Dutch MSW and in the recovered sorting products (annex D). The compositions of the plastic packages in MSW, of the recovered, sorting products and of the non-recovered waste were derived from datasheets previously measured, see annex D. Again, mechanically recovered plastic packages and the five sorted plastic products were considered as goods and the same list of layers was used to describe these goods. The data reconciliation process was performed in the same manner as in the first model. The mechanical recycling step was modelled in the same manner as in the first model.

2.2.3 Output of both sub-models

The model results were reported in SI units, hence Gg, instead of the much more commonly used kiloton in both the trade and official monitoring reports. Additionally, denominators 'net' and 'gross' were added to stress the nature of the weight. The term net weight was only used to specify the dry and clean weight of plastics in waste materials. The reported net weights of plastic packages exclude the non-packaging plastics. The term gross weight implies that a part of the weight includes non-packaging plastics, residual waste and /or attached moisture and dirt.

Standard deviations were calculated on the level of layers (packaging types) as a result of the data reconciliation within STAN. Since there was substantial covariance between the layers, the standard deviations could not be added to obtain aggregated numbers such as 'total net plastic' or 'total net plastic packaging' since the dataset was reconciled.

Standard deviations could not be calculated on the level of materials within the constraints of this study. All input datasets with compositional data were averaged numbers with standard deviations. Especially the compositional datasets had relatively large levels of covariance, which in principle could have been resolved with software tools such as MATLAB. However, in both models the data was reconciled and hence, the error propagation laws cannot be applied and standard deviations cannot be calculated. Therefore, it was decided to present the modelling results as indicative values, without standard deviations.

2.3 Experimental verification of the model

The polymer composition of the milled goods was determined with an IOSYS SIRO NIR analyser to independently verify the MFA-based model. About 100-600 grams of plastic flakes (2-5 mm) were analysed for each sample. Each plastic particle was held with a tweezer in the light beam and was slowly rotated until the analyser gave a stable and clear result in terms of main polymer classes: PET, PE, PP, PS, PVC, PLA, PC, PMMA, ABS, etc. Black, dark-coloured and very small (< 2 mm) objects could not be identified and were categorised as residual / unidentified. Every sample of 100-600 gram took 2-7 working days of analysis; hence only single-point measurements and no replicates were performed. Most of the samples of milled goods were produced in our laboratory as part of the previous studies to determine the recycling yields (Thoden van Velzen, Jansen, et al. 2016) and two were obtained from local recycling industries (Sorted PP and Film from separate collection).

3. Results and discussion

The post-consumer plastic packaging recycling network and the most important masses derived from the material flow analysis are schematically shown in figure 2. A simplified Sankey diagram of only the plastic packages is added as figure 3. The DRQ indicator for model 1 (separate collection) was 0.95 and for model 2 (mechanical recovery) 0.94, indicating that the reconciled data matched well with the original data. The network is a diverging network from a product perspective; it starts with one waste stream and ends with 10 different types of milled goods. From the operator perspective, it is more or less a converging network, starting with about 7.7 million households, via approximately 400 municipalities to 5 - 6 sorting facilities and about 30 mechanical recycling facilities. Both the net and the gross annual amounts of plastic packaging materials are shown on the level of goods. The model estimates the net plastic packaging potential at the Dutch households to equal a mass of 341 Gg net in 2014 (or 20.2 kg net.cap^{-1}.a^{-1}). This net potential could be in reasonable agreement with the annual amounts of plastic packages placed on the Dutch market of 474 Gg net (Afvalfonds Verpakkingen 2015), which is the sum of the plastic packages used by civilians and companies with an unknown division. In case the industrial usage of plastic packages would amount to 133 Gg net, there would be a full match between net potential calculated by this MFA model and the nationally reported number. Although this estimate cannot be verified with official reported numbers, it nevertheless confirms the added value of MFA to estimate numbers that were previously not known.

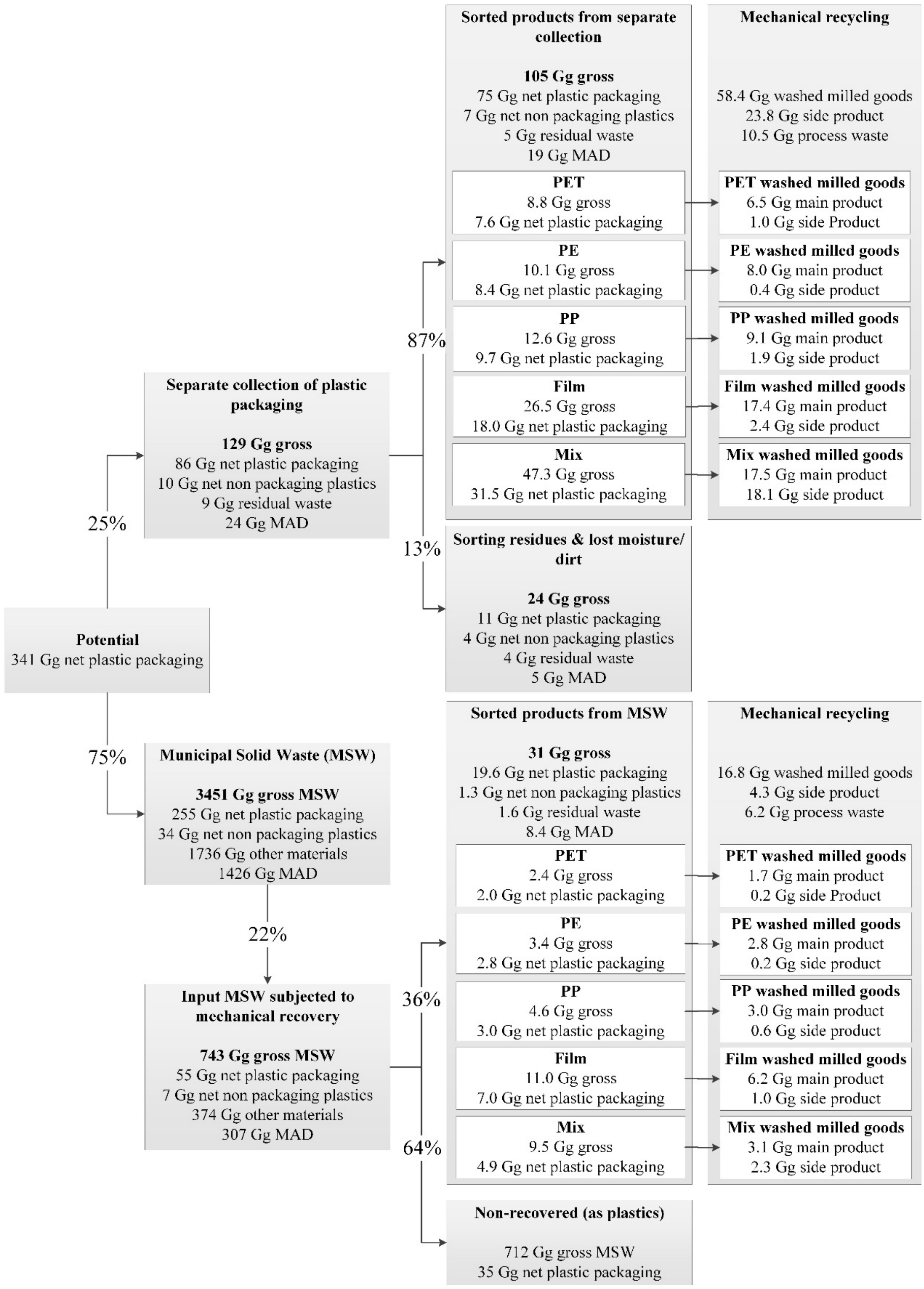

Fig. 2. The post-consumer plastic packaging recycling network described with modelled quantities of PPW for in the Netherlands in 2014. MAD means moisture and dirt. Within sub-model 2 the residual waste is named 'other materials' since also beverage cartons and metals are recovered from MSW.

From this net potential, 86 Gg net of plastic packages are separately collected together with 10.2 Gg non-packaging plastics, 9.0 Gg residual wastes and 23.9 Gg attached moisture and dirt. Together this adds up to the 129.1 Gg gross officially reported separately collected PPW in the Netherlands in 2014 (Afvalfonds Verpakkingen 2015). Hence, the net collection response equals 25%. This net response is smaller than the previously estimated number of 33% (Thoden van Velzen, Brouwer and Augustinus 2016), which was based on the slightly lower concentration of plastic packaging in MSW (8.8%) reported by Rijkswaterstaat (RWS) (Rijkswaterstaat 2015) than the reconciled concentration (12.6%) which is derived from the self-measured data used in this study. This difference relates to the applied definition of plastic packages. The data of RWS excludes plastic bags as a package and considers it a non-packaging object, whereas all our datasheets include plastic bags as packaging. According to RWS, Dutch MSW contains 5.0% non-packaging plastics of which 2.5% garbage bags, implying that the total concentration plastic bags in Dutch MSW varies between 2.5 and 5.0% (Rijkswaterstaat 2015). Hence, both datasets are in agreement and the lower net response rate can be understood by this difference in packaging definition. This emphasises the need to use this net response figure merely indicatively and interpret it in the right context and perspective.

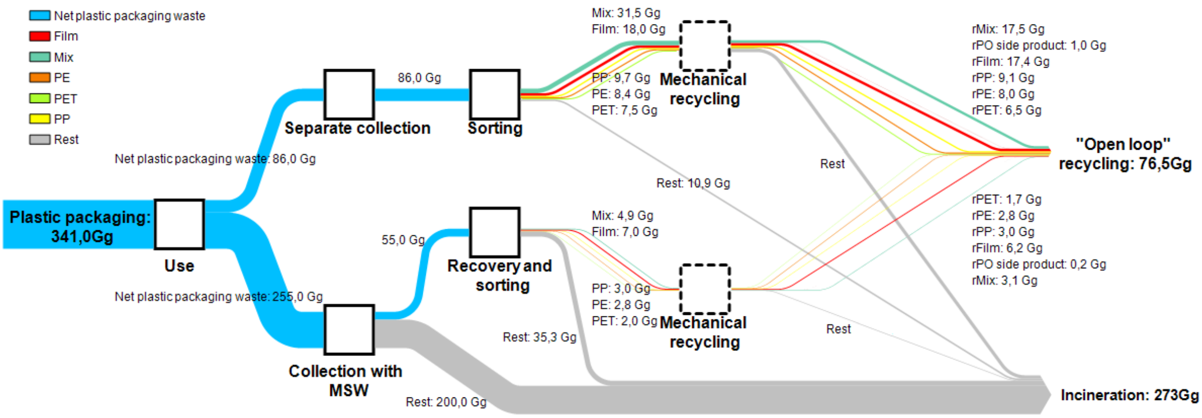

Fig 3. Graphical representation of the flow of only plastic packages through the PPW recycling network in the Netherlands in 2014. The numbers shown are net weights. Left from the mechanical recycling step (in dashed lines) these net weights indeed only relate to only plastic packages. Right from the mechanical recycling step, the difference between packages, non-packaging objects and residual waste can no longer be made and the numbers refer to the sum of them all. Therefore, the sum of 'open loop' recycled plastics and the incinerated plastics is also slightly higher than the household potential.

This separately collected PPW is subjected to sorting to render five different plastic sorting products, named PET, PE, PP, Film and Mix. The combined effort of at least four different sorting facilities is 105.4 Gg gross of sorted products, which contained 75.2 Gg net of plastic packages, 6.6 Gg net of non-packaging plastics, 5.1 Gg of residual wastes and 18.7 Gg of attached moisture and dirt. The division between the sorting products in gross weights is: 8.8 Gg PET, 10.1 Gg PE, 12.6 Gg PP, 26.5 Gg Film and 47.3 Gg Mix. These sorted products are traded with mechanical recycling facilities to yield in total 58.4 Gg net of the five main types of milled goods, 23.8 Gg net of side products and 10.8 Gg of process waste. The following milled goods are regarded as products: the sinking fraction of PET and the floating fractions of PE, PP, Film and Mix. As side products are regarded: the floating fraction of PET and the sinking fractions of PE, PP, Film and Mix.

The rest of the plastic packages (255 Gg net) are discarded with the MSW. The total amount of MSW equals 3451 Gg gross in 2014 (CBS 2014). Roughly 22% of the Dutch MSW (743 Gg gross) is subjected to mechanical recovery in 2014 in three recovery facilities. The mechanical recovery of plastics from MSW bears many different names in Europe, such as central sorting of recyclables from MSW (Cimpan et al. 2015), technical sorting (Feil et al. 2016) and mechanical biological treatment (Archer et al. 2005). This yields several intermediate products, which after the subsequent sorting process at two different facilities yields roughly 30.9 Gg gross of recovered and sorted plastics in total. The total mass of recovered and sorted plastics is composed of 19.8 Gg net plastic packages, 1.3 Gg net non-packaging plastics, 1.6 Gg of residual wastes and 8.4 Gg of attached moisture and dirt. The division between the sorting products in gross weights is: 2.4 Gg PET, 3.4 Gg PE, 4.6 Gg PP, 11.0 Gg Film and 9.5 Gg Mix. These sorted products are traded with mechanical recycling facilities to yield in total 16.8 Gg net of the five main types of milled goods, 4.3 Gg net of side products and 6.2 Gg of process waste. From this MFA a net combined recovery and sorting rate of 36% can be derived, see Figure 1. This relatively low number relates to the applied definition of plastic packaging, which includes plastic bags and would be higher when these bags would be excluded, as is also apparent from the EOL-fates for the recovered and sorted plastics in annex J.

The complete post-consumer plastic packaging recycling network yields 75.2 Gg net of plastic milled goods, 28.1 Gg net side products and 16.7 Gg process waste in 2014. Hence, the overall net recycling chain yield amounts to 22% in 2014 for the Netherlands, when exclusively post-consumer plastic packages are considered from households to recycled milled goods. This net recycling chain yield increases to 30.3% when also the side products are considered. However, this not realistic since only the side products from PET recycling are currently being recycled as materials, the other side products are incinerated due to the relatively high PVC concentrations. Since the input materials for the mechanical recycling process contain some non-packaging plastics and the flakes of this category cannot be distinguished in the milled goods, a correction for this partial input might be necessary depending on the desired perspective. This would reduce both net recycling chain yields slightly to 20.5% and 27.3%, respectively. There is no technical reason to exclude non-packaging plastics, since most of them are completely compatible with the packaging plastics.

These net recycling chain yields differ from officially reported recycling yield of 50% (Afvalfonds Verpakkingen 2015) for plastic packaging in the Netherlands in 2014. This is expected, since the underlying calculation method is completely different. The legal calculation method considers both post-consumer and post-industrial plastic packages, does not consider the mechanical recycling step, compares the gross weights of sorted plastic products to the net weights of plastic packaging placed on the market and finally does not include plastic bags as packaging type. This reconfirms that recycling yields should only be used with great care and full knowledge of their definition.

Figure 2 reveals the complexity of the PPW recycling network. Multiple types of plastic packages, together with non-packaging plastics and residual waste are simultaneously recycled into main and side products. Although, most of the residual waste is removed in the mechanical recycling step, some textiles, paper fibres and metals are nevertheless mixed into the recycling products. Current material flows and existing technologies thus do not allow for closed loop recycling. The main recycling products are applied in mostly non-packaging objects and some non-food packages. This could be regarded as open loop recycling, however, this perspective doesn’t account for the compositional complexity of the feedstock. Other conventional terminology to describe recycling chains, such as closed loop, cradle-to-cradle, upcycling, down-cycling and circular recycling also fail to accurately describe these complex recycling networks. Although this high level of complexity has previously been recognised by others (Ellen Macarthur Foundation 2016), this study provides a first detailed snapshot of such a complex PPW recycling network.

3.1 EOL-fates of packaging types

The MFA of the Dutch post-consumer plastic packaging network gives a detailed insight in the end-of-life fates of the various plastic packaging types. The indicatively calculated EOL fate distributions of 12 package types are listed in table 1, the complete list is added as annex J. The packages that are sorted in the correct sorting product will be recycled. The packages that are sorted in the faulty category will either cause polymeric contamination or be recycled in mixed plastics. The packages that are neither separate collected nor mechanically recovered nor sorted in one of the plastic products will end up in the MSW and/or the sorting residues and will be incinerated. Some packaging types are recycled to a larger extent than what could be expected on the crude average of roughly 30%, examples of these packaging types include: PET and PE bottles. Other packaging types such as PP flexible packages are recycled to a lower extent than average. Undesired packaging types such as for example PVC rigid packages and laminated flexible packages are hardly recycled at all, as intended. In general, the rigid packaging types are recycled reasonably well, whereas flexible packages are recycled to a lesser extent. The latter is related to the insufficiently discriminating nature of the wind sifting technologies to separate flexible packages (Jansen et al. 2015). Two types of rigid packages are recycled to a remarkable lower extent than average; PP beverage bottles and PE miscellaneous rigid packages. This is likely to be caused by the relative small object size of packages in these categories. In the Netherlands the first category is dominated by 12 cm high juice bottles and the latter category by 8 cm high chewing gum pots. Due to the relative small object size, the screening losses are likely to be relatively large.

Table 1: The approximated end-of-life fates for 12 types of plastic packaging in the Dutch post-consumer plastic packaging recycling network in %. N.A. implies not applicable.

Packaging types	**Ideal sorting fate**	**Correctly sorted**	**Faulty sorted**	**Not recycled**
PET bottle clear ≤ 0.5 litre	PET	34	11	55
PE beverage bottles	PE	43	7	49
PP beverage bottles	PP	12	2	86
PET non-beverage bottles	PET	31	12	57
PE non-beverage bottles	PE	40	4	56
PET other rigid packages	Mix	34	5	61
PE other rigid packages	PE	9	9	82
PP other rigid packages	PP	24	8	68
PVC other rigid packages	Rest	N.A.	15	85
PE flexible packages	Film	23	9	67
PP flexible packages	Film	8	17	75
Laminated flexible packages and blisters	Rest	N.A.	23	77

Average for all packaging types	**N.A.**	**21**	**8**	**71**

Substantial amounts of plastic packages (8%) are faulty sorted and most of these faulty sorted packages end up in the mixed plastics. This reconfirms the previously reported mediocre sorting efficiencies for PPW (Jansen et al. 2015).

3.2 Modelled polymer composition of milled goods

The indicatively calculated polymeric composition of the main milled goods made from the Dutch post-consumer plastic packaging waste is listed in table 2. The main milled goods are the sinking fraction of the PET sorting product and the floating fractions of the other sorting products. The main milled goods made from post-consumer PET bottles (DKR 328-1) are composed of primarily PET (98-99%) and percent to sub-percent levels of other polymers. The mechanical recycling processes for sorted PET is in the industrial reality often more complex, including process steps like wind sifting, fine sieving and automatic flake sorting. With these additional process steps the concentration of non-PET plastics can be further reduced (Thoden van Velzen, Brouwer and Molenveld 2016). For these advanced processes the concentrations of polymeric contaminants are reduced below 0.3% and hence these qualities of rPET do no longer need to be considered as blends.

Milled goods made from the polyolefines (sorting products: PE, PP and Film) are composed of one primary polymer in the 81-89% range, a secondary polymer in the 1-15% range and several other polymers in percent to sub-percent levels. Hence, milled goods made from PE (DKR 329) contain roughly 89-90% PE, 10-11% PP and sub-percent amounts of other polymers. Milled goods made from PP (DKR 324) contain roughly 87-88% PP, 8-10% PE and sub-percent amounts of other polymers. Milled goods made from Film (DKR 310) contain roughly 81-82 % PE and 9-15 % PP and sub-percent amounts of other polymers. These results compare well with previously determined compositions of post-industrial and post-consumer polyolefines (Luijsterburg and Goossens 2014; Brachet et al. 2008; Borovankska et al. 2012). The milled goods made from the floating fraction of the mixed plastics (DKR 350) contains 49-63% PE, 30-40% PP, 5-7% black plastics and small amounts of PS, PVC and PET.

Table 2: The modelled material composition of the main recycling products (washed milled goods) made from sorted products that originate from either separate collection (SC) or mechanical recovery (MR) in %. The material class 'other' refers to other types of plastics such as PLA, PC, PMMA and black plastics. The material class 'rest' refers to undefined objects, organic materials, textiles, wood, etc.

	PET	PE	PP	PS	PVC	Paper	Metal	Glass	Other	Rest
PET SC	98.6	0.1	0.1	0.5	0.1	0.1	0.2	0.0	0.2	0.1
PET MR	99.0	0.1	0.1	0.3	0.1	0.1	0.1	0.0	0.1	0.1
PE SC	0.0	89.1	10.0	0.1	0.1	0.0	0.0	0.0	0.7	0.0
PE MR	0.0	88.6	10.6	0.3	0.2	0.0	0.0	0.0	0.3	0.0
PP SC	0.1	8.2	87.6	0.6	0.9	0.0	0.0	0.0	2.6	0.0
PP MR	0.1	10.2	87.5	0.7	1.0	0.0	0.0	0.0	0.5	0.0
Film SC	0.0	81.3	14.5	0.5	0.5	0.0	0.0	0.0	3.1	0.0
Film MR	0.0	81.5	8.7	0.2	0.2	0.0	0.0	0.0	9.4	0.0
Mix SC	0.7	49.1	39.2	2.7	1.3	0.0	0.0	0.0	7.0	0.0
Mix MR	0.5	62.8	30.4	0.5	0.6	0.0	0.0	0.0	5.2	0.0

These recycled plastics made from post-consumer plastic packages should therefore all be regarded as blends. Hence, the processing methods should be adjusted to the blend composition to maximise the mechanical properties. These general changes in the processing methods include: raising the processing temperature in the extruder to above the melting temperature of the highest melting polymer present to avoid sharp edges of plastic particles inside the recycled plastic matrix, although the melt viscosity of the main polymer in the extruder could be abnormally low. Secondly, the hot recycled plastics should be cooled as fast as possible to avoid phase separation and freeze the blend structure. Such general adaptations of the processing methods could be considered as basic principles underlying the 'design from recycling' strategy (Ragaert 2016).

The polymer composition of the milled goods can be equal to the polymer composition of the extruded regranulate. However, in most cases the recycled plastic is melt-filtered with the primary intention to remove inorganic contaminants as sand, glass and metal particles etc. In case this melt filtration process is operated below the melting temperature of polymeric contaminants, these will partially be removed. The downside of melt-filtration is, however, that substantial material losses occur during either filter changes or back-flushes. During normal recycling operations with polyolefinic post-consumer plastics, the PET particles can be removed by melt filtration. As a consequence the polymeric purity level of the regranulate will improve slightly as compared to the polymeric composition of the milled good.

3.3 Origin of contaminants

The model of the post-consumer plastic packaging recycling network offers insights in the origin of polymeric contaminants present in the milled goods. The net material composition of the produced main milled goods is listed in table 3. These main milled goods are composed of four main constituents; the desired polymer from the intended plastic packages, the desired polymer from non-intended plastic packages, other polymers (the polymeric contaminants) and residual wastes. In case a PET product is taken as an illustration, than PET polymer from PET bottle bodies is an example of the first constituent, PET polymer from thermoformed packages and films are examples of the second type of constituent, PE polymer from bottle caps is an example of the third type of constituent and small pieces of glass and metal are examples of the fourth constituent. For the washed milled goods made from the floating fractions of the sorting products Film and Mixed plastics the intended polymers are less self-evident and were defined as PE and PP for both. As expected, the main recycling products made of sorted PET, PE, PP and Film do contain predominantly the desired polymer of the intended packages. Whereas, the recycling products made from sorting product MIX mostly contains the desired polymer of unintended packages, which is in agreement with the large portion of faulty sorted packages in this product.

Table 3: Modelled origin of materials in the main recycling products (washed milled flakes) made from sorted products that originate from either separate collection (top) or mechanical recovery (below) in % net weight / net weight.

SEPARATE COLLECTION	**PET**	**PE**	**PP**	**Film**	**MIX**
Desired polymer from intended packages	86	87	79	83	7
Desired polymer unintended packages	13	3	9	13	85
Non-intended plastics	1	11	12	4	8
Residual waste	0.37	0.00	0.00	0.00	0.00

RECOVERY FROM MSW	**PET**	**PE**	**PP**	**Film**	**MIX**
Desired polymer from intended packages	94	85	79	83	3
Desired polymer unintended packages	5	4	8	7	91
Non-intended plastics	1	11	13	10	6
Residual waste	0.36	0.00	0.00	0.00	0.00

The polymeric contaminants are the non-intended polymers in table 3. This group of polymeric contaminants can be further divided in four different types of polymeric contaminants, see table 4. These origins include two types of faulty sorted objects (those that are part of the collection portfolio and those that are not) and two types of packaging components that are made from different polymers (foreign polymers from intended and not-intended packages). The first two sources of contaminants are related to the sorting process and the latter two sources of contaminants are related to the packaging design. As is apparent from table 4, the main source of polymeric contaminants is most often design related, namely the packaging components from intended packages that are made from other polymers. Only in case of milled goods made from the floating fraction of PP the main source of polymeric contaminants are formed by the sorting faults of objects that should not have been collected or recovered. These observations are valuable for future policies.

Table 4: Modelled origin of polymeric contaminants in the main recycling products (washed milled goods) made from sorted products that originate from either separate collection (above) or mechanical recovery (below) in %.

SEPARATE COLLECTION	**PET**	**PE**	**PP**	**Film**	**MIX**
Components of intended packages	32	57	12	55	58
Components of unintended packages	8	0	0	0	1
Not intended objects, outside collection portfolio	13	9	44	22	12
Not intended objects, within collection portfolio	47	34	44	22	30

RECOVERY FROM MSW	**PET**	**PE**	**PP**	**Film**	**MIX**
Components of intended packages	55	59	11	54	75
Components of unintended packages	4	0	0	0	1
Not intended objects, outside collection portfolio	20	24	58	4	9
Not intended objects, within collection portfolio	21	16	31	41	14

3.4 Experimental validation of the model

The experimentally determined polymer compositions of single-samples of the main milled goods are listed in table 5. Besides the actually measured composition, also the absolute differences with the modelling results are given in italic print. The differences between the modelled and the measured composition are remarkably small, given the uncertainties in the model and the fact that only single samples could be studied. For the PET flakes the modelled PET concentration equalled the measured PET concentration within 1.5%. The single sample of PET flakes made from separately collected and sorted PET material contained a little bit too much PE. Most likely small pieces of PE cap were not completely removed during the simple mechanical recycling process. For the PE and PP flakes the measured concentration of main polymer was actually slightly higher in the single samples than what was modelled. Most likely more packaging components made from different polymers were lost during collection, recovery and sorting than what was modelled. The differences between the modelled and the measured polymer composition appear to be larger for Film. The measured single sample from separate collection contained a substantial amount of black PE and PP films, rendering a larger fraction of ‘other’ and a lower fractions of ‘PE’ and ‘PP’ in the sorting result. The measured single sample from mechanical recovery had been subjected to an additional NIR sorting step to concentrate PE in this film fraction and therefore, the PE measured PE concentration was higher than what was modelled without this concentration step. The difference between the measured and the modelled polymer composition was the largest for the Mix main product (Table 4), which was expected since in general the composition of this sorting product varies substantially on the object-level (see annex C and D) and only single samples were measured. Also in the Mix main product more black plastic flakes were found that what was expected based on the model.

Table 5: Experimentally determined material composition of the main recycling products (washed milled goods) made from sorted products which originate from either separate collection (SC) or mechanical recovery (MR) and the absolute difference between the modelled and measured composition in italic, %. The material class ‘other’ refers to other types of plastics such as PLA, PC, PMMA and black plastics. The material class ‘rest’ refers to undefined objects, organic materials, textiles, wood, etc.

	PET	**PE**	**PP**	**PS**	**PVC**	**Paper**	**Metal**	**Glass**	**Other**	**Rest**
PET SC	97.2	1.9	0.2	0.4	0.1	0.0	0.0	0.0	0.2	0.0
	1.4	*1.8*	*0.1*	*0.1*	*0.0*	*0.1*	*0.2*	*0.0*	*0.0*	*0.1*
PET MR	99.4	0.0	0.0	0.2	0.0	0.1	0.2	0.0	0.1	0.0
	0.4	*0.1*	*0.1*	*0.1*	*0.1*	*0.0*	*0.1*	*0.0*	*0.0*	*0.1*
PE SC	0.2	90.6	8.2	0.2	0.3	0.1	0.0	0.0	0.4	0.0
	0.2	*1.5*	*1.8*	*0.1*	*0.2*	*0.1*	*0.0*	*0.0*	*0.3*	*0.0*
PE MR	0.0	94.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
	0.0	*5.4*	*7.6*	*0.3*	*0.2*	*0.0*	*0.0*	*0.0*	*0.3*	*3.0*
PP SC	0.0	4.7	90.6	1.3	0.2	0.1	0.0	0.0	3.2	0.1
	0.1	*3.5*	*3.0*	*0.7*	*0.7*	*0.1*	*0.0*	*0.0*	*0.6*	*0.1*
PP MR	0.4	3.4	95.0	0.0	0.2	0.4	0.0	0.0	0.2	0.4
	0.3	*6.8*	*7.5*	*0.7*	*0.8*	*0.4*	*0.0*	*0.0*	*0.3*	*0.4*
Film SC	0.1	76.4	5.3	0.2	0.2	0.0	0.1	0.0	16.9	0.8
	0.1	*4.9*	*9.2*	*0.3*	*0.3*	*0.0*	*0.1*	*0.0*	*13.8*	*0.8*

Film MR	0.3	96.8	1.2	0.0	0.0	0.0	0.0	0.0	1.3	0.3
	0.3	*15.3*	*7.5*	*0.2*	*0.2*	*0.0*	*0.0*	*0.0*	*8.1*	*0.3*
Mix SC	6.5	32.6	30.9	2.8	1.9	5.9	0.0	0.0	19.0	0.4
	5.8	*16.5*	*8.3*	*0.1*	*0.6*	*5.9*	*0.0*	*0.0*	*12.0*	*0.4*
Mix MR	0.6	48.0	24.6	1.3	0.8	0.8	0.0	0.0	22.9	1.0
	0.1	*14.8*	*5.8*	*0.8*	*0.2*	*0.8*	*0.0*	*0.0*	*17.7*	*1.0*

3.5 Implications for the New Plastics Economy

The results above make it abundantly clear that recycled plastics made from post-consumer plastic packages with a conventional recycling process should be regarded as blends. Only in case the recycled plastic is produced with a more advanced recycling process which also involve wind sifting and flake sorting machines the concentration foreign polymers can approach such low levels that the recycled plastic does not have to be considered a blend anymore. For example, the concentration foreign polymers in rPET made from separately collected Dutch PPW made with a conventional recycling process and an advanced recycling process has been reported to equal 1.5% and 0.3%, respectively (Thoden van Velzen, Brouwer and Molenveld 2016). The indicative polymeric compositions of the post-consumer blends can be estimated with the MFA model, but will nevertheless vary between batches. Additionally, it should be stressed that within the polymer-class of 'PE', there are in fact a whole range of different types of PE present in the recycled plastic (LDPE, LLDPE, MDPE, HDPE, etc.), which cannot be differentiated form one another using NIR. These different types of PE do not automatically form miscible blends (Kukaleva 2003).

Although several researchers previously established that recycled post-consumer plastics are blends (Luijsterburg et al. 2015; Brachet et al. 2008; Borovankska et al. 2012), few have understood the ramifications for the processing methods and the mechanical properties (Hubo et al. 2014; Mehat and Kamaruddin 2011; Gu et al. 2014; Luijsterburg et al. 2016).

Mixed (recycled) polymers will typically form immiscible blends (Flory 1942); the difference in surface energy and viscosity between the composing polymers will lead them to separate in the melt phase, with a myriad of possible morphologies (Utracki 2002). This phase separation will have a tremendous effect on the mechanical properties of the resulting product (Litmanovich et al. 2002). The more 'chemically alike' the two polymers are, the more compatible they will be and the smaller this effect will be for the mechanical properties (Koning et al. 1998). Most properties of immiscible blends do not simply follow a proportional law, but display an antagonistic behaviour. Additionally, not every property behaves in the same way for the same polymer pair. For example, the tensile strength for a MPO-PP system follows the additive law, while the elongation at break displays the curve of a typical incompatible blend (Hubo et al. 2015). The elongation at break (describing ductility) and impact properties (describing toughness) are usually very sensitive to the distribution and dispersion of the second phase (Kordjazi et al. 2010).

A proposal towards such an indicative quality factor for mixed recycled plastics, based on (binary) blend composition and interfacial tension between the components, was recently made by one of the authors (Huysman et al. 2017). This system divides binary blends into 'compatibility' classes according to their interfacial tension, ranging from perfectly compatible to completely incompatible. Then, for each compatibility class, a quality curve is proposed which denotes the resulting loss in mechanical properties based on the amount of contaminating polymer. The method will require fine-tuning and further investigation, but the results from the current research clearly illustrate the usefulness such a system could have with regard to being a predictive quality model.

Equally important as the observed changes in properties for mixed recycled plastics, are the practical implications for the re-processing of such diverse materials. Given the fact that recycled PE, PP and Film are composed of a primary polymer-type in the 75-95% level, a secondary polymer-type in the 1-10 %-level and a small list of tertiary polymers in the percent to sub-percent level, it is important to adjust the processing method to this composition to maximise the mechanical properties.

A large spread can occur on the melting temperatures of the composing polymers in the blend, for example in the case of PE-PET blends, with a difference of nearly 100°C. Typically, a conventional converter will reprocess the blend at the processing temperature of the highest melting component, to ensure that everything is molten and no blockages occur in the process. This often leads to overheating and degradation of some lower melting components which in turn reduce the final properties. This is especially relevant for mixtures containing both PVC and PET, wherein the elevated processing temperatures used for PET will accelerate the dehydrochlorination of the PVC (Moller et al. 1995). The alternative is to accept that some parts of the blend will not melt. This is acceptable for bulky products, where a non-melting fraction can be extruded into a core without blocking any dies. Alternatively, the blend can be subjected to melt filtration. In the latter case, the difference in melting temperatures combined with the melting filter may even be used to clear the melt of these polymeric impurities, as these would inevitably reduce the quality and properties of the extrudate (Stenvall et al. 2016). Typically removed fractions include wood, paper, aged rubber particles and higher-melting polymers (e.g. PET in PP processed at 220°C) (Stenvall et al. 2013). Melt filters come in different mesh sizes. A smaller mesh size takes out more contaminations; it is more complex in production but will also lead to improved process stability and polymer quality (Luijsterburg et al. 2016). The downside of melt-filtration is, however, that substantial material losses occur during either filter changes or back-flushes. During normal recycling operations with polyolefinic post-consumer plastics, the PET particles can be removed by melt filtration. As a consequence the polymeric purity level of the regranulate will improve slightly as compared to the polymeric composition of the milled good.

The acknowledgement that conventionally recycled post-consumer plastics are currently blends is an important step towards a new plastic economy. Specifications for several applications of recycled plastics (PET bottle, PE tube extrusion products, PE sheet extrusion products, PP injection moulding products, Film blow moulding etc.) can now be defined in terms of maximally allowed concentrations of foreign polymers. A comparison between the concentration limits in these new specifications and the actually measured concentrations in the washed milled goods defines the applicability of the currently recycled milled goods. It clarifies the maximal level of recycled content for these applications. This is a first-order approximation of the maximum levels of recycled content, since degradation reactions, molecular contamination and waste particle contamination are not considered. For freshly collected and short-lived PPW, degradation reactions are not likely to have progressed so far to affect the properties of the recycled products noticeably. Furthermore, the molecular contamination of this material is perhaps significant from a food safety point of view; however, in our experience it seems to hardly affect the processing properties at the usual low concentrations. Thirdly, well-washed milled goods will hardly contain any attached waste particles. Therefore, the concentration of polymeric contaminants can be considered as a meaningful first-order quality indicator for the applicability of recycled PPW.

Specifications in terms of maximum allowed concentrations of foreign polymers are getting more common in PET bottle recycling (Snell et al. 2017) and are expected to spread towards other markets for recycled polymers. One of the issues delaying the application of concentration-based specifications is the impact of processing methods. In order to obtain the most realistic relationships between the concentrations of polymeric contaminants and the applicability of recycled plastics, the modalities that processing offers needs to be fully understood and exploited as well. This is the essence of design-from-recycling (Ragaert 2016) and holds promise to extend the application of recycled plastics beyond what would be deemed possible based on the polymeric composition.

The required efforts for attaining a more circular plastic economy can be derived from a comparison between the concentration limits in the specifications and the actual concentrations of polymeric contaminants in the milled goods. This mass flow model can be used to estimate the impact of improvement measures on the polymeric composition of the recycled plastics and hence on the applicability of the recycled plastics. This would be a major advance in understanding plastic recycling on a scientific level. It could for instance be used to determine which minimum mix of measures at three levels (packaging design, sorting and mechanical recycling) would be required to produce recycled plastics for circular applications. This renders insights in the required efforts of stakeholders to attain a more circular economy for post-consumer plastic packaging waste.

4. Conclusions and future research needs

A material flow analysis of the Dutch post-consumer plastic packaging recycling network in 2014 was conducted on the level of 35 different packaging types. From this analysis the net post-consumer plastic packaging potential of 341 Gg was indicatively derived and a net recycling chain yield of about 30% (from potential to washed milled goods) in case both the main products and the side products are taken into account. The results from this model can only be considered indicatively, since the standard deviations could not be derived within the limitations of this study. The end-of-life fates of the 35 packaging types can be approximated with the model, revealing that indeed several rigid plastic packaging types are more recycled than average and several undesired packaging types (PVC thermoforms, laminated flexible packaging and blisters) are indeed hardly recycled. The polymer composition of milled goods can reasonably well be modelled with MFA techniques and datasets. The single point measurements of the polymeric composition of milled goods crudely verify the compositions that were derived with the model. The model is currently used to study the impact of 'single industrial policy options' on the net recycling chain yield and the polymeric composition of the produced milled goods. Since the polymeric composition of recycled plastics renders a first order approximation of their applicability, this model is able to predict the effect of the industrial policy options on the approximated applicability of the recycled plastics. We intend to use this model in the near future to define which mix of industrial policy options will be required to achieve a more circular economy for plastic packages and quantify the consequences, such as amounts of side products formed.

The most important two factors limiting the net chain recycling yield are the low collection response and the relatively low portion of the MSW that is subjected to mechanical recovery. The third factor in order of relevance is the sub-optimal nature the sorting process, resulting in not only the loss of valuable plastic packages but also in polymeric contamination of sorted products. Nevertheless, the prime source of polymeric components is the packaging design; the packaging components that are made from different polymer types than the main plastic of the package. Most recycled plastics could best be considered as blends, and processing methods that are adjusted accordingly hold a promise to deliver better performing applications for recycled plastics.

This MFA was fed with compositional data from several projects on PPW in the last years. These projects, however, did not aim for this MFA. Hence, more recent data and especially more recent data on the composition of the milled goods and sorting residues is desired to achieve a more accurate analysis. With additional measurements, system changes after 2014, such as the combined collection of plastics, beverage cartons and metals, could also be modelled.

The model is currently being improved in three aspects. First, the reconciliation software can be improved by adding the constraint that output masses cannot be negative with software tools like MATLAB. Secondly, a constraint should be added that masses of goods should sum up to 100%, avoiding the need to make manual corrections. Thirdly, such a new tool could simultaneously assist in performing the error propagation analysis.

This model reveals the complex nature of the PPW recycling network in which multiple plastic packaging types, non-packaging plastics and small amounts of residual wastes are recycled into main products and side products. The complexity in the current recycling network thus makes 'cradle to cradle' or 'closed loop recycling' nearly impossible. Currently, the main products are mostly used in non-packaging applications and a few non-food packaging applications. The authors therefore believe that it is difficult to apply conventional terminology or frameworks such as cradle-to-cradle, closed loop, open loop, upcycling or down-cycling to the complex reality. Instead, analysing and predicting numbers and facts is essential in defining policy measures and steering technological innovation.

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Technical annexes

A. Transfer coefficients of mechanical recycling of sorted plastic packages.
B. Gross amounts of post-consumer plastic packaging waste in the Netherlands in 2014.
C. Composition of separately collected PPW and sorted fractions made thereof, both the averaged input data and the reconciled data.
D. Composition of the municipal solid waste offered to recovery facilities and the recovered, sorted plastic products, both the averaged input data and the reconciled data.
E. Average material composition per packaging type.
F. The material composition of the separately collected PPW and the sorted products made thereof.
G. The material composition of the municipal solid waste and the recovered and sorted plastic products made thereof.
H. The recovered masses for the mechanical recycling from sorted products to washed milled goods.
I. Correction factors for the losses of packaging components.
J. End-of-life fates of packaging categories after collection, sorting and recovery and sorting.
K. Levels of attached moisture and dirt for freshly milled (unwashed) goods.

A. Transfer coefficients for mechanical recycling of sorted plastic packages.

The transfer coefficients for the relevant plastics (PET, PE, PP, PS and PVC) in the mechanical recycling process (washing and floatation-separation) were separately measured. Losses of plastics to sludge (process waste) were neglected and only the distribution between the floating and the sinking products were considered and measured. Hereto mixtures of clean plastic milled goods with different polymers in different colours were composed to reflect either a sorted PP product or a sorted mixed plastic product. These mixtures were subjected to sink-float separation with cold tap water in a 200 litre laboratory set-up. The floating fraction was scooped up from the water surface. The sinking fraction was retrieved from the bottom-sluice. Both products were separately dried and the compositions were determined by colour-separating both fractions and weighing the polymeric components. The transfer coefficients were calculated from the weights of a specific polymer in both products and averaged between both experiments. For most polymers the standard deviation was less than 1%, only for PVC film and PS the standard deviations were substantial and rounded figures were used. The transfer coefficients for the residual waste components were estimated based on previous observations of waste sludge and sinking fractions.

Table A.1: Transfer coefficients used to describe the mechanical recycling process from dirty milled goods to washed milled goods, hence describing the washing and floatation separation steps, [%].

	PET	**PP**	**PE**	**PS**	**PVC**	**Paper**	**Metal**	**Glass**	**Other plastics, black plastics, etc.**	**Undefined, organic materials, incl. textiles**	**Moisture and dirt**
Sinking fraction	99%	2%	1%	83%	80%	5%	100%	100%	50%	50%	
Floating fraction	1%	98%	99%	17%	20%				50%		
Process waste						95%				50%	100%

B. Gross amounts of post-consumer plastic packaging waste in the Netherlands in 2014 (collection, recovery and sorting).

The total amount of separately collected post-consumer plastic packaging waste (PPW) in the Netherlands in 2014: 129 Gg gross, [Afvalfonds 2015]

The average sorting division for the separately collected PPW in 2015, calculated by dividing the weight of the sorted fraction by the total weight of the sorted fractions [% w gross/ w gross] is listed in Table B.1. [Thoden van Velzen, Brouwer and Augustinus 2016]

Table B.1: Sorting division for the separate collected PPW in 2015.

Sorting fraction name and specification	R_m, [%]
PET, DKR 328-1	7%
PE, DKR 329	8%
PP, DKR 324	10%
Film, DKR 310	21%
Mixed plastics, DKR 350	39%
Rest	15%

The loss of moisture and dirt during the sorting process was estimated to be 2% and was as first-order approximation uniformly distributed over the fractions.

The total amount of municipal solid waste in the Netherlands in 2014 was 3451 Gg. [CBS statline 2014] The amounts of MSW that were subjected to mechanical recovery at the three different facilities and the total amounts of sorted plastic produced on behalf of that MRF are listed in Table B.2.[Thoden van Velzen 2016] The sorting divisions for the recovered plastics are listed in table B.3.

Table B.2: The amount of MSW treated by the three MRF's and the amount of sorted plastic products produced in 2014.

Mechanical recovery facility	Amount of MSW feedstock in 2014, [$Mg.a^{-1}$]	Total amount of sorted plastic products, [$Mg.a^{-1}$]
Omrin Heerenveen	165845	12800
Attero-Noord	104332	7011
Attero-Wijster	472949	11127
Total	743127	30938

Table B.3: Sorting division for the recovered PPW at MRF's in the Netherlands in 2014. (The sorting for both recovery facilities of Attero are performed at one sorting facility). Sources: datasheets obtained from representatives of both facilities.

Sorting fraction name	Omrin 2015	Attero Wijster 2013
PET, DKR 328-1	6%	9%
PE, DKR 329	12%	11%
PP, DKR 324	11%	17%
Film, DKR 310	47%	28%
Mix, DKR 350	25%	35%

C. <u>Composition of separately collected PPW and sorted fractions made thereof, both the averaged input data and the reconciled data.</u>

The compositional data of the separately collected PPW and the sorted fractions made thereof was entered in the model is listed in C.1. This data was converted into amounts per layer (packaging type) and entered into the reconciliation software STAN. The output of the reconciliation is listed in table C.2. The listed parameter LAMD stands for the level of attached moisture and dirt.[Thoden van Velzen 2016]

Table C.1: Input data in STAN, the averaged compositional data that was based on 64 sorting analysis in previous projects.

		Separately collected PPW		**PET product - from separate collection**		**PE product - from separate collection**		**PP product - from separate collection**		**FILM product - from separate collection**		**MIX product - from separate collection**		**Sorting residue - from separate collection**		**Moisture and dirt that has been loosened and lost in the sorting process**	
Origin of data compositional data	# samples	26		8		8		7		6		8		1			
	Years	4x2010, 1x2012, 21x2013		2011, 2012, 2013, 2x2014, 3x2015		2010, 2011, 2012, 2013, 3x2014, 2015		2010, 2011, 2x2012, 2013, 2x2014		2011, 2x2012, 2013, 2x2014		2010, 2011, 2012, 2013, 4x2014		2014			
	Additional information	11 of the samples from 2013 are collected and sorted within the pilot beverage carton project, information excl. beverage cartons is used for composition of collected plastics.												Since only one such sample had been analysed, the standard deviation was set to 15%. In case negative masses in the reconciliation had to be avoided the standard deviation was set to 0%.			
Origin of LAMD	# samples	5		5		2		2		2		4					
	Years	4x2010, 1x2012		2x2014, 3x2015		2x2014		2x2014		2x2014		4x2014					
	Additional information													No measurements, used LAMD from MIX as default.			
		Average [%]	Stdev [%]	Average [%]	Stdev [%]	Average [%]	Stdev [%]	Average [%]	Stdev [%]	Average [%]	Stdev [%]	Average [%]	Stdev [%]	Average [%]	Stdev [%]	Average [%]	Stdev [%]
PET bottle clear ≤ 0.5 litre		2.6%	1.5%	27.5%	9.7%	0.2%	0.3%	0.3%	0.5%	0.1%	0.1%	1.7%	2.1%	1.8%	15%		
PET bottle coloured ≤ 0.5 litre		0.8%	0.6%	5.9%	3.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.4%	2.0%	15%		
PET bottle clear > 0.5 litre		1.3%	0.8%	13.2%	3.3%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.4%	0.3%	0.2%	15%		
PET bottle coloured > 0.5 litre		0.1%	0.2%	2.7%	5.6%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.0%	0%		
PE beverage bottles		1.8%	1.3%	0.0%	0.0%	19.2%	4.5%	0.2%	0.2%	0.0%	0.1%	0.6%	0.5%	0.7%	15%		

PP beverage bottles	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	1.1%	2.6%	0.0%	0.0%	0.0%	0.1%	0.0%	0%		
PS beverage bottles	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.1%	0.0%	0%		
Misc. beverage bottles	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.6%	0.0%			
PET non-beverage bottles	3.0%	1.2%	24.1%	7.7%	0.1%	0.1%	0.3%	0.2%	0.1%	0.2%	1.5%	1.2%	1.3%	15%		
PE non-beverage bottles	5.7%	2.2%	0.1%	0.3%	53.7%	5.8%	0.3%	0.3%	0.1%	0.1%	1.1%	0.9%	1.4%	15%		
PP non-beverage bottles	1.5%	0.7%	0.1%	0.1%	0.4%	0.3%	10.0%	5.4%	0.0%	0.0%	1.1%	2.4%	2.6%	15%		
Misc. non-beverage bottles	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	15%		
PET thermoforms	1.3%	0.9%	4.6%	11.7%	0.2%	0.2%	0.9%	2.0%	0.5%	0.4%	3.2%	3.3%	1.1%	0%		
PE thermoforms	0.2%	0.3%	0.0%	0.0%	0.1%	0.2%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	15%		
PP thermoforms	0.2%	0.2%	0.0%	0.0%	0.0%	0.1%	1.4%	1.0%	0.1%	0.1%	0.4%	0.6%	0.1%	0%		
PVC thermoforms	0.1%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.9%	15%		
PS thermoforms	0.2%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	0.0%	0%		
PET other rigid packages	9.2%	3.7%	7.5%	5.1%	0.8%	0.6%	1.4%	1.3%	1.8%	1.5%	16.6%	10.9%	1.8%	15%		
PE other rigid packages	1.1%	0.6%	0.3%	0.4%	2.9%	1.1%	0.1%	0.1%	0.1%	0.1%	0.8%	0.4%	0.2%	15%		
PP other rigid packages	7.0%	1.8%	0.5%	0.7%	2.1%	1.4%	53.2%	8.0%	1.1%	0.8%	10.1%	10.7%	1.9%	0%		
PVC other rigid packages	0.6%	0.5%	0.0%	0.0%	0.1%	0.2%	0.2%	0.3%	0.1%	0.2%	0.7%	0.4%	6.6%	15%		
PS other rigid packages	2.0%	0.8%	0.2%	0.2%	0.2%	0.2%	0.5%	0.4%	0.6%	0.5%	5.3%	3.1%	1.1%	0%		
Carriage bags (PE)	2.9%	0.9%	0.0%	0.1%	0.3%	0.2%	0.1%	0.1%	10.9%	7.6%	2.7%	2.2%	0.0%	0%		
PET flexible packages	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	0.0%	15%		
PE flexible packages	11.3%	4.3%	0.5%	0.9%	1.0%	0.6%	1.1%	0.8%	43.1%	11.7%	9.7%	6.7%	0.7%	0%		
PP flexible packages	3.7%	1.2%	0.2%	0.4%	0.3%	0.5%	2.4%	1.1%	4.3%	1.7%	4.7%	2.7%	1.1%	15%		
PVC flexible packages	0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.1%	0.1%	0.2%	0.1%	0.6%	15%		
PS flexible packages	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	15%		
Rigid packages made from non-NIR identifiable plastics	5.3%	3.9%	0.2%	0.4%	0.7%	0.7%	3.5%	5.0%	0.9%	0.8%	3.1%	1.9%	17.8%	15%		
Flexible packages made from non-NIR identifiable plastics	1.2%	1.2%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	3.1%	2.3%	1.7%	2.0%	0.8%	0%		

Misc. plastics (PC, PLA, etc.)	1.0%	2.5%	0.0%	0.1%	0.1%	0.1%	0.0%	0.0%	0.1%	0.2%	0.2%	0.3%	0.4%	15%		
Laminated flexible packages and blisters	2.4%	1.2%	0.1%	0.2%	0.3%	0.2%	0.6%	0.2%	2.9%	1.7%	3.4%	2.4%	1.6%	15%		
EPS trays	0.1%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	15%		
EPS blocks	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.2%	15%		
Silicone tubes	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.4%	0.4%		
Non-packaging plastics	8.0%	4.2%	0.3%	0.2%	1.4%	0.9%	10.6%	6.3%	7.7%	4.3%	6.1%	3.4%	18.9%	15%		
Organics & undefined	4.1%	4.8%	0.1%	0.1%	0.1%	0.1%	0.3%	0.3%	0.2%	0.2%	5.5%	5.7%	9.5%	15%		
Paper, cardboard & beverage cartons	4.1%	11.5%	0.0%	0.0%	0.1%	0.1%	0.2%	0.2%	0.4%	0.5%	3.3%	3.6%	4.0%	15%		
Metal	0.9%	1.3%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.0%	0.1%	0.7%	0.8%	6.3%	15%		
Glass	0.2%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	15%		
Moisture and dirt	15.8%	7.5%	11.5%	6.4%	15.2%	2.3%	10.8%	2.2%	21.3%	4.9%	13.7%	3.2%	13.7%	3.2%	100%	
Total	**100%**		100%		100%		100%		100%		100%		100%		100%	

Table C.2: Reconciled compositional data of separately collected PPW and sorted fractions made thereof. In order to avoid negative masses, a few standard deviations for layers in the sorting residue were manually set to zero for the reconciliation process to succeed, these are left blank.

	Separately collected PPW		**PET product - from separate collection**		**PE product - from separate collection**		**PP product - from separate collection**		**FILM product - from separate collection**		**MIX product - from separate collection**		**Sorting residue - from separate collection**		**Moisture and dirt that has been loosened and lost in the sorting process**	
	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]
PET bottle clear ≤ 0.5 litre	3427	1684	2416	839	21	26	34	60	17	29	830	999	108	1838		
PET bottle coloured ≤ 0.5 litre	1012	764	518	282	3	4	5	6	6	10	312	220	169	832		
PET bottle clear > 0.5 litre	1619	944	1171	295	1	2	6	10	1	4	176	169	264	990		
PET bottle coloured > 0.5 litre	162	191	88	201	6	12	1	3	0	0	67	74	0			
PE beverage bottles	2342	1469	3	4	1944	455	21	24	9	19	287	246	78	1511		
PP beverage bottles	106	166	1	3	0	0	89	167	0	0	15	25	0			
PS beverage bottles	80	45	0	1	1	1	2	2	2	3	72	45	3			
Misc. beverage bottles	0	0	0	0	0	0	0	0	0	0	0	0	0			
PET non-beverage bottles	3693	1333	2160	670	11	12	33	30	32	41	771	597	686	1490		
PE non-beverage bottles	6831	2031	13	23	5455	577	40	34	15	25	538	418	770	2033		
PP non-beverage bottles	2001	906	4	9	36	30	1253	669	5	13	474	1107	227	1437		
Misc. non-beverage bottles	9	31	0	0	0	0	0	1	0	0	0	0	8	31		
PET thermoforms	1929	977	247	919	19	23	107	250	136	115	1213	1119	209			
PE thermoforms	229	405	0	1	11	23	5	6	13	16	31	60	169	410		
PP thermoforms	293	168	2	3	3	6	152	122	35	37	85	186	15			
PVC thermoforms	141	377	0	0	1	3	0	0	3	7	31	84	105	386		
PS thermoforms	84	45	0	0	0	0	0	0	18	20	59	41	7			
PET other rigid packages	11129	3781	669	453	78	64	184	161	492	403	9111	3890	596	2648		
PE other rigid packages	1319	767	25	37	293	112	18	18	29	39	385	188	568	795		
PP other rigid packages	9600	2155	46	60	210	137	6615	995	274	220	2087	2314	368			

PVC other rigid packages	812	573	1	2	11	19	25	34	39	44	321	195	415	606		
PS other rigid packages	2757	830	22	17	25	19	63	48	161	130	2270	835	217			
Carriage bags (PE)	3885	1039	4	5	26	21	8	10	2591	1252	1246	985	9			
PET flexible packages	97	111	1	1	1	2	1	1	16	20	55	68	24	132		
PE flexible packages	15814	3515	44	76	106	60	140	100	11059	2798	4334	2920	132			
PP flexible packages	4581	1396	22	36	35	47	306	138	1166	458	2412	1234	641	1691		
PVC flexible packages	305	282	1	1	0	0	17	33	18	22	85	66	184	292		
PS flexible packages	28	28	0	0	0	0	2	3	1	1	16	24	9	37		
Rigid packages made from non-NIR identifiable plastics	5983	2627	22	38	71	71	451	631	241	225	1541	934	3658	2495		
Flexible packages made from non-NIR identifiable plastics	1727	912	1	2	2	4	7	11	789	570	781	831	147			
Misc. plastics (PC, PLA, etc.)	666	2135	3	6	5	13	3	6	33	49	96	142	525	2134		
Laminated flexible packages and blisters	3051	1418	11	15	32	19	70	25	777	460	1720	1132	441	1663		
EPS trays	111	200	0	0	0	1	1	4	8	11	7	8	95	201		
EPS blocks	83	140	0	0	1	1	1	2	4	5	61	54	15	150		
Silicone tubes	66	49	0	0	17	20	0	0	0	0	45	5	4	50		
Non-packaging plastics	10180	2991	22	18	138	94	1346	793	2055	1116	3006	1617	3613	2559		
Organics & undefined	4790	3358	9	11	8	11	43	40	41	47	2787	2608	1901	2622		
Paper, cardboard & beverage cartons	2668	3281	2	2	10	11	23	29	102	141	1672	1779	860	2794		
Metal	1301	1475	4	6	6	6	17	18	11	13	325	379	937	1497		
Glass	236	461	2	3	0	0	0	0	0	0	6	17	228	462		
Moisture and dirt	23851	9675	1316	566	1528	233	1553	278	6345	1301	7931	1578	2598	607	2580	9930
Total weight	**129000**		**8849**		**10114**		**12642**		**26548**		**47262**		**21005**		**2580**	

D. <u>Composition of the municipal solid waste offered to recovery facilities and the recovered, sorted plastic products, both the averaged input data and the reconciled data.</u>

The compositional data of the MSW offered to mechanical recovery facilities and the recovered, sorted products that was entered in the model is listed in D.1. This data was converted into amounts per layer (packaging type) and entered into the reconciliation software STAN. The output of the reconciliation is listed in table D.2.

Table D.1: Input data in STAN with respect to the averaged compositional data of the MSW offered to the mechanical recovery facilities and the recovered sorting products. This was based on 99 different sorting analyses in previous projects.

		MSW offered to MRF's for recovery		PET sorted product made- from recovered PPW		PE sorted product made- from recovered PPW		PP sorted product made- from recovered PPW		FILM sorted product made- from recovered PPW		MIX sorted product made- from recovered PPW		Rejects from the recovery facility & moisture and dirt	
Origin of data compositional data	# samples	12		10		20		21		15		21		3	
	Years	2011, 2012, 10x2013		2010, 2011, 2012, 4x2013, 2014, 2x2015		10x2010, 4x2011, 2012, 5x2013		9x2010, 5x2011, 2x2012, 5x2013		8x2010, 2011, 2012, 4x2013, 2014		9x2010, 5x2011, 2x2012, 5x2013		2011, 2012, 2013	
	Additional information	Samples from 2013 are from a pilot where a separate collection system was tested in combination with the recovery of PPW from MSW.												Based on the rest fraction from the recovery process (from mass balances in pilot studies).	
Origin of LAMD	# samples	1		4		1		1		1		1			
	Years	2015		2013, 3x2015		2013		2013		2010		2013			
	Additional information													Calculated based on other numbers	
		Average [%]	Stdev [%]	Average [%]	Stdev [%]	Average [%]	Stdev [%]	Average [%]	Stdev [%]	Average [%]	Stdev [%]	Average [%]	Stdev [%]	Average [%]	Stdev [%]
PET bottle clear ≤ 0.5 litre		0.1%	0.1%	35.8%	9.0%	0.2%	0.4%	0.3%	0.4%	0.2%	0.5%	1.7%	2.3%	0.1%	0.1%
PET bottle coloured ≤ 0.5 litre		0.0%	0.0%	6.7%	2.6%	0.1%	0.1%	0.1%	0.3%	0.1%	0.1%	0.5%	0.6%	0.0%	0.0%
PET bottle clear > 0.5 litre		0.1%	0.1%	13.0%	4.1%	0.0%	0.1%	0.0%	0.1%	0.0%	0.1%	0.4%	0.6%	0.0%	0.0%
PET bottle coloured > 0.5 litre		0.0%	0.0%	1.4%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.0%	0.0%
PE beverage bottles		0.1%	0.1%	0.0%	0.0%	10.0%	4.8%	0.2%	0.3%	0.1%	0.3%	0.4%	0.5%	0.0%	0.0%
PP beverage bottles		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PS beverage bottles		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Misc. beverage bottles	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PET non-beverage bottles	0.1%	0.1%	23.7%	9.5%	0.1%	0.3%	0.2%	0.3%	0.1%	0.3%	2.0%	2.5%	0.0%	0.0%
PE non-beverage bottles	0.3%	0.3%	0.1%	0.1%	60.2%	12.9%	0.7%	0.9%	0.3%	1.0%	0.9%	0.9%	0.1%	0.0%
PP non-beverage bottles	0.1%	0.1%	0.1%	0.2%	0.4%	0.6%	8.2%	4.2%	0.1%	0.2%	0.6%	0.8%	0.0%	0.0%
Misc. non-beverage bottles	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PET thermoforms	0.1%	0.2%	0.9%	2.1%	0.0%	0.2%	0.3%	0.8%	0.1%	0.3%	1.7%	2.4%	0.1%	0.1%
PE thermoforms	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.2%	0.3%	0.6%	0.5%	0.6%	0.0%	0.0%
PP thermoforms	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.5%	1.2%	0.0%	0.0%	0.2%	0.2%	0.0%	0.0%
PVC thermoforms	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PS thermoforms	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PET other rigid packages	0.6%	0.3%	2.8%	3.4%	0.3%	0.5%	1.4%	1.8%	0.5%	0.8%	12.0%	12.6%	0.4%	0.3%
PE other rigid packages	0.1%	0.1%	0.0%	0.1%	8.5%	7.8%	0.4%	0.6%	0.1%	0.2%	0.7%	0.7%	0.1%	0.1%
PP other rigid packages	0.6%	0.3%	0.2%	0.5%	1.1%	1.3%	50.6%	8.1%	0.9%	2.7%	5.4%	4.5%	0.5%	0.1%
PVC other rigid packages	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.2%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%
PS other rigid packages	0.2%	0.2%	0.1%	0.2%	0.0%	0.1%	0.3%	0.5%	0.2%	0.5%	0.4%	0.4%	0.2%	0.1%
Carriage bags (PE)	0.4%	0.3%	0.0%	0.0%	0.1%	0.2%	0.1%	0.4%	14.3%	7.6%	4.2%	3.7%	0.3%	0.4%
PET flexible packages	0.0%	0.1%	0.1%	0.2%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.2%	0.0%	0.0%
PE flexible packages	1.3%	0.6%	0.1%	0.1%	0.8%	1.1%	0.7%	1.7%	32.2%	8.7%	12.7%	11.2%	1.0%	0.9%
PP flexible packages	0.4%	0.2%	0.1%	0.1%	0.1%	0.1%	1.0%	1.1%	2.8%	2.8%	2.7%	2.0%	0.3%	0.1%
PVC flexible packages	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%
PS flexible packages	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
Rigid packages made from non-NIR identifiable plastics	0.8%	0.8%	0.1%	0.1%	0.1%	0.3%	0.5%	0.6%	4.5%	7.6%	2.6%	2.0%	0.8%	0.6%
Flexible packages made from non-NIR identifiable plastics	0.9%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	5.6%	7.1%	0.6%	0.9%	0.6%	0.5%
Misc. plastics (PC, PLA, etc.)	0.3%	0.5%	0.0%	0.1%	0.0%	0.1%	0.0%	0.1%	0.1%	0.4%	0.1%	0.2%	0.8%	2%

Laminated flexible packages and blisters	0.4%	0.1%	0.0%	0.1%	0.2%	0.7%	0.4%	0.4%	1.2%	1.4%	1.6%	1.2%	0.2%	0.0%
EPS trays	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%
EPS blocks	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%
Silicone tubes	0.0%	0.0%	0.0%	0.0%	0.5%	0.7%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.0%	0.0%
Non-packaging plastics	0.9%	0.4%	0.3%	0.6%	5.6%	8.6%	13.1%	8.4%	2.6%	3.9%	3.0%	2.7%	1.0%	0.7%
Organics & undefined	36.1%	10.4%	0.2%	0.2%	0.6%	1.0%	2.2%	3.6%	2.0%	3.8%	5.2%	6.5%	36.5%	5.9%
Paper, cardboard & beverage cartons	10.3%	4.0%	0.4%	0.5%	0.1%	0.3%	1.1%	1.7%	1.9%	1.8%	4.4%	3.6%	11.2%	4.6%
Metal	3.7%	1.7%	0.0%	0.1%	0.0%	0.1%	0.2%	0.2%	0.1%	0.2%	0.6%	1.0%	2.3%	1.1%
Glass	1.8%	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.4%	2.3%
Moisture and dirt	40.2%	10.4%	13.9%	3.0%	10.7%		17.1%		29.7%		34.5%		40.9%	11.0%
Total	**100%**		**100%**		**100%**		**100%**		**100%**		**100%**		**100%**	

Table D.2: Reconciled compositional data of the municipal solid waste offered to MRF's and the recovered, sorted products.

	MSW offered to MRF's for recovery		**PET sorted product made- from recovered PPW**		**PE sorted product made- from recovered PPW**		**PP sorted product made- from recovered PPW**		**FILM sorted product made- from recovered PPW**		**MIX sorted product made- from recovered PPW**		**Rejects from the recovery facility & moisture and dirt**	
	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]	Average [Mg]	Stdev [Mg]
PET bottle clear ≤ 0.5 litre	1328	508	822	209	8	14	11	17	18	54	137	216	332	505
PET bottle coloured ≤ 0.5 litre	278	134	146	61	2	5	5	14	7	16	34	59	84	132
PET bottle clear > 0.5 litre	507	193	305	95	1	3	2	5	5	14	39	60	156	170
PET bottle coloured > 0.5 litre	96	80	33	15	0	0	0	0	1	2	12	28	50	76
PE beverage bottles	632	206	0	1	345	161	8	14	14	37	38	45	227	120
PP beverage bottles	147	195	0	1	0	2	3	5	0	1	2	3	142	195
PS beverage bottles	11	12	0	0	0	0	0	1	0	0	1	3	10	12
Misc. beverage bottles	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PET non-beverage bottles	1088	373	562	220	5	11	10	14	10	33	190	234	312	220
PE non-beverage bottles	2584	455	2	3	2048	431	33	43	29	107	80	84	392	55
PP non-beverage bottles	630	270	3	4	12	19	354	182	6	22	52	71	203	239
Misc. non-beverage bottles	10	29	0	0	0	0	0	1	0	1	0	1	10	29
PET thermoforms	658	571	22	50	2	7	12	35	10	29	158	232	454	528
PE thermoforms	138	86	0	1	1	2	4	11	35	60	50	58	49	48
PP thermoforms	103	99	0	1	0	0	22	54	0	1	15	17	65	82
PVC thermoforms	39	52	0	0	0	0	3	13	0	0	1	4	36	51
PS thermoforms	25	53	0	0	0	0	0	0	0	0	0	1	25	53
PET other rigid packages	4129	1539	66	80	11	18	63	82	56	90	1165	1113	2767	1621
PE other rigid packages	1020	427	1	1	276	258	17	27	10	17	64	68	653	469
PP other rigid packages	6077	801	5	11	38	46	2274	366	76	294	464	418	3219	557

PVC other rigid packages	402	254	0	0	1	3	3	8	0	1	7	10	390	254
PS other rigid packages	1320	586	2	4	1	4	12	22	17	52	37	41	1252	584
Carriage bags (PE)	3455	1639	0	0	2	7	5	18	1527	816	389	351	1531	1699
PET flexible packages	102	101	2	4	0	1	0	0	8	11	13	18	78	99
PE flexible packages	10063	3476	1	1	26	37	33	79	3508	957	1157	1060	5336	3580
PP flexible packages	2987	718	1	2	4	5	46	50	297	301	256	191	2384	676
PVC flexible packages	94	24	0	0	0	0	1	3	2	3	8	10	83	22
PS flexible packages	25	16	0	0	0	0	0	0	3	9	1	1	21	15
Rigid packages made from non-NIR identifiable plastics	6115	3584	1	3	4	9	23	28	497	836	250	193	5339	3560
Flexible packages made from non-NIR identifiable plastics	5623	2627	0	0	0	1	1	4	657	770	53	86	4911	2605
Misc. plastics (PC, PLA, etc.)	2419	3659	0	1	0	2	1	3	11	44	10	22	2395	3659
Laminated flexible packages and blisters	2121	277	1	1	8	23	17	19	145	151	157	113	1794	212
EPS trays	110	73	0	0	0	0	1	3	1	1	4	7	103	72
EPS blocks	476	294	0	0	0	0	2	5	1	2	6	11	468	294
Silicone tubes	63	84	0	0	17	24	0	0	1	3	9	17	37	81
Non-packaging plastics	7222	2665	7	13	188	294	591	382	281	431	282	262	5874	2707
Organics & undefined	262306	36755	4	5	22	34	102	166	218	414	496	618	261465	36751
Paper, cardboard & beverage cartons	78235	22132	9	11	4	11	51	78	209	194	419	346	77544	22133
Metal	19307	6575	1	2	1	3	9	11	9	17	61	99	19226	6574
Glass	14042	7105	0	0	0	0	0	1	1	1	0	1	14041	7105
Moisture and dirt	307140	55149	370	71	410	0	844	0	3362	0	3419	0	298735	0
Total weight	743128		2370		3438		4564		11031		9536		712189	

E. Average material composition per packaging type

The average material composition was determined by disassembly of packages into their components and weighing all the separate components. This was repeated for at least 25 individual packages in a category and these results were averaged. Table E.1 lists these average material compositions per packaging category.

Table E.1: Average material composition per packaging category, [% w/w]

Packaging type	**PET**	**PP**	**PE**	**PS**	**PVC**	**Paper**	**Metal**	**Glass**	**Other plastics, black, etc.**	**Undefinable, rest incl. textiles**	**Source**
PET bottle clear ≤ 0.5 litre	85	4	10	0	0	1	0	0	0		PET recycling project WUR-FBR
PET bottle coloured ≤ 0.5 litre	88	1	10	0	0	0	0	0	0		PET recycling project WUR-FBR
PET bottle clear > 0.5 litre	90	2	7	0	0	1	0	0	0		PET recycling project WUR-FBR
PET bottle coloured > 0.5 litre	92	2	6	0	0	1	0	0	0		PET recycling project WUR-FBR)
PE beverage bottles	0	0	96	0	0	4	0	0	0	0	Waste 2 Plastic project WUR-FBR
PP beverage bottles	0	93	1	6	0	0	0	0	0	0	Measured
PS beverage bottles	0	0	4	96	0	0	0	0	0	0	Measured
Misc. beverage bottles										100	Are not in datasets
PET non-beverage bottles	78	17	3	0	0	2	0	0	0	0	PET recycling project WUR-FBR
PE non-beverage bottles	0	13	84	0	0	1	0	0	1	0	Measured
PP non-beverage bottles	1	95	2	0	0	2	0	0	0	0	Measured
Misc. non-beverage bottles										100	Are not in datasets
PET thermoforms	86	0	10	0	0	3	0	0	0	1	Measured
PE thermoforms	9	3	85	1	0	2	0	0	0	0	Measured
PP thermoforms	12	73	12	2	0	2	0	0	0	0	Measured
PVC thermoforms	0	0	0	0	100	0	0	0	0	0	Measured
PS thermoforms	0	0	0	100	0	0	0	0	0	0	Measured
PET other rigid packages	90	1	5	0	1	4	0	0	0	0	Measured
PE other rigid packages	0	2	95	0	0	1	0	0	0	2	Measured
PP other rigid packages	6	89	1	0	2	1	1	0	0	0	Measured
PVC other rigid packages	0	0	0	0	99	1	0	0	0	0	Measured
PS other rigid packages	1	2	1	86	0	8	1	0	0	0	Measured
Carriage bags (PE)	0	0	99	0	0	1	0	0	0	0	Measured
PET flexible packages	97					3					Estimate based on the other film sample measurement
PE flexible packages	0	0	98	0	0	2	0	0	0	0	Measured
PP flexible packages	0	96	0	0	0	3	0	0	0	0	Measured
PVC flexible packages	0	1	0	1	96	1	0	0	0	0	Measured
PS flexible packages	0	0	0	100	0	0	0	0	0	0	Measured

Rigid packages made from non-NIR identifiable plastics									100		All black/non-NIR sortable
Flexible packages made from non-NIR identifiable plastics									100		All black/non-NIR sortable
Misc. plastics (PC, PLA, etc.)									100		Mainly other plastics
Laminated flexible packages and blisters	10	57	20	0	6	0	7	0	0	0	Measured + calculated
EPS trays	0	0	0	100	0	0	0	0	0	0	Measured
EPS blocks	0	0	0	100	0	0	0	0	0	0	Measured
Silicone tubes	0	0	100	0	0	0	0	0	0	0	Measured
Non-packaging plastics	3	33	29	18	16	0	0	0	0	0	Calculated based on market division

For non-packaging plastics we chose to model 100% of the main material. As these are not typical objects.

F: The material composition of the separately collected PPW and the sorted products made thereof.

The material composition of the separately collected PPW and the sorted products made thereof were calculated by performing matrix multiplication of the reconciled compositions in terms of packaging categories with the average material compositions per packaging category, see Table F.1. This renders insight in the overall material composition of these intermediate plastic products. Nevertheless, one should bear in mind that such a material composition is an abstract figure, since these intermediate products are composed of many different multi-material objects.

Table F.1: Material composition of the separately collected PPW and the sorted products made thereof.

	PET	**PP**	**PE**	**PS**	**PVC**	**Paper**	**Metal**	**Glass**	**Other plastics, black plastics, etc.**	**Undefined, organic materials, incl. textiles**	**Moisture and dirt**
Separately collected PPW	17%	17%	26%	4%	3%	3%	1%	0%	7%	4%	18%
PET sorted product	69%	6%	7%	0%	0%	1%	0%	0%	0%	0%	15%
PE sorted product	2%	10%	69%	1%	0%	1%	0%	0%	1%	0%	15%
PP sorted product	6%	64%	6%	3%	3%	1%	1%	0%	4%	0%	12%
Film sorted product	3%	10%	54%	2%	2%	2%	0%	0%	4%	0%	24%
Mix sorted product	24%	15%	18%	6%	2%	5%	1%	0%	5%	6%	17%

The material composition of all the milled goods produced from the separately collected and sorted PPW is listed in table F.2.

Table F.2: Material composition of all milled goods produced from the separately collected and sorted products, [%]

FLAKES	**MAIN PRODUCTS**										
		PET	**PP**	**PE**	**PS**	**PVC**	**Paper**	**Metal**	**Glass**	**Other plastics, black, etc.**	**Rest**
PET	Sinking fraction	98%	0%	0%	1%	0%	0%	0%	0%	0%	0%
PE	Floating fraction	0%	13%	86%	0%	0%	0%	0%	0%	1%	0%
PP	Floating fraction	0%	88%	8%	1%	1%	0%	0%	0%	3%	0%
Film	Floating fraction	0%	15%	81%	1%	1%	0%	0%	0%	3%	0%
Mix	Floating fraction	1%	39%	49%	3%	1%	0%	0%	0%	7%	0%
FLAKES	**SIDE PRODUCTS**										
PET	Floating fraction	5%	45%	48%	1%	0%	0%	0%	0%	1%	0%
PE	Sinking fraction	37%	5%	16%	14%	8%	2%	5%	0%	13%	1%
PP	Sinking fraction	41%	9%	0%	15%	17%	0%	4%	0%	12%	1%
Film	Sinking fraction	32%	2%	6%	19%	15%	1%	3%	0%	22%	1%
Mix	Sinking fraction	63%	1%	0%	13%	5%	1%	3%	0%	7%	8%

G: The material composition of the municipal solid waste and the recovered and sorted plastic products made thereof.

The material composition of the municipal solid waste and the recovered, sorted plastic products made thereof are listed in table G.1.

Table G.1: Material composition of the MSW and the recovered, sorted plastic products made thereof.

	PET	**PP**	**PE**	**PS**	**PVC**	**Paper**	**Metal**	**Glass**	**Other plastics, black, etc.**	**Rest**	**Moisture and dirt**
Composition of MSW	1%	2%	3%	0%	0%	11%	3%	2%	2%	35%	41%
PET sorted product	70%	6%	6%	0%	0%	1%	0%	0%	0%	0%	16%
PE sorted product	1%	11%	71%	1%	1%	1%	0%	0%	1%	1%	12%
PP sorted product	5%	58%	7%	3%	3%	2%	1%	0%	1%	2%	18%
Film sorted product	1%	5%	47%	1%	1%	3%	0%	0%	11%	2%	30%
Mix sorted product	17%	10%	21%	1%	1%	5%	1%	0%	3%	5%	36%

The material composition of all the milled goods produced from the mechanically recovered and sorted PPW are listed in table G.2.

Table G.2: Material composition of all milled goods produced from the mechanically recovered and sorted products, [%]

FLAKES	**MAIN PRODUCTS**									
		PET	**PP**	**PE**	**PS**	**PVC**	**Paper**	**Metal**	**Glass**	**Other plastics, black, etc.**	**Rest**
PET	Sinking fraction	99%	0%	0%	0%	0%	0%	0%	0%	0%	0%
PE	Floating fraction	0%	14%	86%	0%	0%	0%	0%	0%	0%	0%
PP	Floating fraction	0%	87%	10%	1%	1%	0%	0%	0%	0%	0%
Film	Floating fraction	0%	9%	82%	0%	0%	0%	0%	0%	9%	0%
Mix	Floating fraction	1%	31%	63%	1%	1%	0%	0%	0%	5%	0%
FLAKES	**SIDE PRODUCTS**										
PET	Floating fraction	5%	46%	48%	0%	0%	0%	0%	0%	1%	0%
PE	Sinking fraction	24%	5%	15%	22%	16%	1%	3%	0%	6%	8%
PP	Sinking fraction	39%	8%	0%	17%	19%	1%	5%	0%	2%	8%
Film	Sinking fraction	13%	1%	5%	6%	5%	1%	2%	0%	57%	11%
Mix	Sinking fraction	69%	1%	1%	4%	3%	1%	3%	0%	7%	11%

H: The recovered masses for the mechanical recycling from sorted products to washed milled goods.

The recovered masses for mechanical recycling process from sorted products to washed milled goods have recently been measured in detail. (Thoden van Velzen et al. 2016, submitted to AIP Conference Proceed.) These experimental determined recovered masses are compared to those that MFA predicts based on the material composition of the feedstocks and the transfer coefficients, see table H.1.

Table H.1: The recovered masses of the washed milled goods predicted by the MFA and compared to the published values. [% w dm /w dm].

SEPARATELY COLLECTED	Floating product	Sinking product	Process waste
PET Modelled	12%	84%	4%
PET Measured	11±1%	83±2%	6±4%
PE Modelled	90%	5%	6%
PE Measured	94±2%	3±1%	3±2%
PP Modelled	79%	16%	5%
PP Measured	90±1%	7±1%	4±1%
Film Modelled	83%	12%	6%
Film Measured	90±6%	4±4%	6±3%
Mix Modelled	43%	44%	13%
Mix Measured	64±12%	32±11%	5±1%
RECOVERED FROM MSW	Floating product	Sinking product	Process waste
PET Modelled	11%	81%	8%
PET Measured	10±2%	84±2%	6±4%
PE Modelled	88%	5%	7%
PE Measured	93±2%	2±2%	5±4%
PP Modelled	71%	15%	14%
PP Measured	83±2%	3±2%	14±4%
Film Modelled	73%	12%	15%
Film Measured	83±15%	4±2%	13±13%
Mix Modelled	45%	34%	21%
Mix Measured	65±4%	28±1%	7±3%

I: Correction factors for the losses of packaging components.

Sorted plastic bottles are often not complete packages; roughly one third of the components (labels and caps) has loosened and is no longer part of the bottle. To accommodate for these component losses in the model, correction factors were applied that describe the level at which components remain part of the packaging in the sorted products, see table I.1.

Table I.1: Correction factors used to describe the loss of packaging components in the sorted products. It is defined as the level of packaging components that remain in the sorted product. Hence a factor of 100% means that all material remains in the sorted products and a factor of 65% implies that 35% of this material is lost, [%].

	PET [%]	PP [%]	PE [%]	PS [%]	PVC [%]	Paper [%]	Metal [%]	Glass [%]	Other plastics, black, etc [%]	Rest [%]
PET bottle clear ≤ 0.5 litre	100	65	65	65	65	99	65	65	65	65
PET bottle coloured ≤ 0.5 litre	100	65	65	65	65	99	65	65	65	65
PET bottle clear > 0.5 litre	100	65	65	65	65	99	65	65	65	65
PET bottle coloured > 0.5 litre	100	65	65	65	65	99	65	65	65	65
PE beverage bottles	65	65	100	65	65	99	65	65	65	65
PP beverage bottles	65	100	65	65	65	99	65	65	65	65
PS beverage bottles	65	65	65	100	65	99	65	65	65	65
PET non-beverage bottles	100	65	65	65	65	99	65	65	65	65
PE non-beverage bottles	65	65	100	65	65	99	65	65	65	65
PP non-beverage bottles	65	100	65	65	65	99	65	65	65	65
Misc. non-beverage bottles	65	65	65	100	100	99	65	65	65	65
PET thermoforms	100	99	99	99	99	99	99	99	99	99
PE thermoforms	99	99	100	99	99	99	99	99	99	99
PP thermoforms	99	100	99	99	99	99	99	99	99	99
PVC thermoforms	99	99	99	99	100	99	99	99	99	99
PS thermoforms	99	99	99	100	99	99	99	99	99	99
PET other rigid packages	100	99	99	99	99	99	99	99	99	99
PE other rigid packages	99	99	100	99	99	99	99	99	99	99
PP other rigid packages	99	100	99	99	99	99	99	99	99	99
PVC other rigid packages	99	99	99	99	100	99	99	99	99	99
PS other rigid packages	99	99	99	100	99	99	99	99	99	99
Carriage bags (PE)	99	99	100	99	99	99	99	99	99	99
PET flexible packages	100	99	99	99	99	99	99	99	99	99
PE flexible packages	99	99	100	99	99	99	99	99	99	99
PP flexible packages	99	100	99	99	99	99	99	99	99	99
PVC flexible packages	99	99	99	99	100	99	99	99	99	99
PS flexible packages	99	99	99	100	99	99	99	99	99	99
Rigid packages made from non-NIR identifiable plastics	99	99	99	99	99	99	99	99	100	99
Flexible packages made from non-NIR identifiable plastics	99	99	99	99	99	99	99	99	100	99
Misc. plastics (PC, PLA, etc.)	99	99	99	99	99	99	99	99	100	99
Laminated flexible packages and blisters	100	100	100	100	100	100	100	100	100	100
EPS trays	100	100	100	100	100	100	100	100	100	100
EPS blocks	100	100	100	100	100	100	100	100	100	100
Silicone tubes	100	100	100	100	100	100	100	100	100	100

Non-packaging plastics	100	100	100	100	100	100	100	100	100	100
Organics & undefined	100	100	100	100	100	100	100	100	100	100
Paper, cardboard & beverage cartons	100	100	100	100	100	100	100	100	100	100
Metal	100	100	100	100	100	100	100	100	100	100
Glass	100	100	100	100	100	100	100	100	100	100

J. End-of-life fates of packaging categories after collection, recovery and sorting.

The end-of-life (EOL) fates can be calculated by the MFA at any desired cross-section of the recycling network. In table 1 of the paper the EOL-fates of 12 packaging types are given. Here in table J.1 the complete overview is given.

Table J.1: Approximated end-of-life fates of plastic packaging types in the Dutch post-consumer plastic packaging recycling network. [%]

Packaging types	Ideal sorting fate	Correctly sorted	Faulty sorted	Not recycled
PET bottle clear ≤ 0.5 litre	PET	34	11	55
PET bottle coloured ≤ 0.5 litre	PET	29	16	55
PET bottle clear > 0.5 litre	PET	37	6	57
PET bottle coloured > 0.5 litre	PET	20	14	66
PE beverage bottles	PE	43	7	49
PP beverage bottles	PP	12	2	86
PS beverage bottles	Mix	55	4	41
PET non-beverage bottles	PET	31	12	57
PE non-beverage bottles	PE	40	4	56
PP non-beverage bottles	PP	33	12	55
Misc. non-beverage bottles	Rest	N.A.	2	98
PET thermoforms	Mix	28	11	61
PE thermoforms	PE	1	16	83
PP thermoforms	PP	23	18	59
PVC thermoforms	Rest	N.A.	12	88
PS thermoforms	Mix	29	9	62
PET other rigid packages	Mix	34	5	61
PE other rigid packages	PE	9	9	82
PP other rigid packages	PP	24	8	68
PVC other rigid packages	Rest	N.A.	15	85
PS other rigid packages	Mix	26	3	71
Carriage bags (PE)	Film	21	8	71
PET flexible packages	Film	4	13	83

PE flexible packages	Film	23	9	67
PP flexible packages	Film	8	17	75
PVC flexible packages	Rest	N.A.	18	82
PS flexible packages	Film	3	13	84
Rigid packages made from non-NIR identifiable plastics	Mix	5	4	91
Flexible packages made from non-NIR identifiable plastics	Film or Mix	8	0	92
Miscellaneous plastics (PC, PLA, etc.)	Mix	1	0	99
Laminated flexible packages and blisters	Rest	N.A.	23	77
EPS trays	Mix	2	2	96
EPS blocks	Mix	3	0	97
Silicone tubes	Rest	N.A.	25	75
Average for all packaging types	**N.A.**	**21**	**8**	**71**

N.A. stands for Not Applicable.

In order to express the efficiency of collection, the EOL-fates of the separate collected plastic packages are calculated, see table J.2.

Table J.2: EOL-fates of the packaging categories at the moment of collection, expressing the efficiency of separate collection with regard to the packaging categories.

	Ideal fate	Correctly Collected
PET bottle clear ≤ 0.5 litre	Separately collected	36%
PET bottle coloured ≤ 0.5 litre	Separately collected	44%
PET bottle clear > 0.5 litre	Separately collected	41%
PET bottle coloured > 0.5 litre	Separately collected	27%
PE beverage bottles	Separately collected	44%
PP beverage bottles	Separately collected	13%
PS beverage bottles	Separately collected	61%
Misc. beverage bottles		N.A.
PET non-beverage bottles	Separately collected	42%
PE non-beverage bottles	Separately collected	36%
PP non-beverage bottles	Separately collected	41%
Misc. non-beverage bottles	Separately collected	16%
PET thermoforms	Separately collected	39%
PE thermoforms	Separately collected	26%
PP thermoforms	Separately collected	38%
PVC thermoforms	Separately collected	44%
PS thermoforms	Separately collected	42%
PET other rigid packages	Separately collected	37%

PE other rigid packages	Separately collected	22%
PP other rigid packages	Separately collected	25%
PVC other rigid packages	Separately collected	30%
PS other rigid packages	Separately collected	31%
Carriage bags (PE)	Separately collected	19%
PET flexible packages	Separately collected	17%
PE flexible packages	Separately collected	25%
PP flexible packages	Separately collected	25%
PVC flexible packages	Separately collected	41%
PS flexible packages	Separately collected	19%
Rigid packages made from non-NIR identifiable plastics	Separately collected	17%
Flexible packages made from non-NIR identifiable plastics	Separately collected	6%
Misc. plastics (PC, PLA, etc.)	MSW	N.A.
Laminated flexible packages and blisters	MSW	N.A.
EPS trays	MSW	N.A.
EPS blocks	MSW	N.A.
Silicone tubes	MSW	N.A.

The separately collected plastic packages are subsequently sorted in sorting facilities. In table J.3 the EOL-fates of the sorting process are shown.

Table J.3: EOL-fates of sorting for separately collected packages.

	Ideal sorting fate	**Correctly sorted**	**Faulty sorted**	**Not recycled**
PET bottle clear ≤ 0.5 litre	PET	71%	26%	3%
PET bottle coloured ≤ 0.5 litre	PET	51%	32%	17%
PET bottle clear > 0.5 litre	PET	72%	11%	16%
PET bottle coloured > 0.5 litre	PET	54%	46%	0%
PE beverage bottles	PE	83%	14%	3%
PP beverage bottles	PP	84%	16%	0%
PS beverage bottles	Mix	90%	6%	4%
Misc. beverage bottles	Rest	N.A.	N.A.	N.A.
PET non-beverage bottles	PET	58%	23%	19%
PE non-beverage bottles	PE	80%	9%	11%
PP non-beverage bottles	PP	63%	26%	11%
Misc. non-beverage bottles	Rest	N.A.	3%	97%
PET thermoforms	Mix	63%	26%	11%
PE thermoforms	PE	5%	22%	74%
PP thermoforms	PP	52%	43%	5%
PVC thermoforms	Rest	N.A.	25%	75%
PS thermoforms	Mix	69%	22%	8%
PET other rigid packages	Mix	82%	13%	5%
PE other rigid packages	PE	22%	35%	43%
PP other rigid packages	PP	69%	27%	4%
PVC other rigid packages	Rest	N.A.	49%	51%
PS other rigid packages	Mix	82%	10%	8%
Carriage bags (PE)	Film	67%	33%	0%
PET flexible packages	Film	16%	59%	25%
PE flexible packages	Film	70%	29%	1%
PP flexible packages	Film	25%	61%	14%
PVC flexible packages	Rest	N.A.	40%	60%
PS flexible packages	Film	4%	63%	33%
Rigid packages made from non-NIR identifiable plastics	Mix	26%	13%	61%
Flexible packages made from non-NIR identifiable plastics	Film or Mix	91%	1%	8%
Misc. plastics (PC, PLA, etc.)	Mix	14%	7%	79%
Laminated flexible packages and blisters	Rest	N.A.	86%	14%
EPS trays	Mix	7%	8%	85%
EPS blocks	Mix	74%	8%	19%
Silicone tubes	Rest	N.A.	94%	6%
Average EOL fate (for packages that should be sorted into a sorted product)		*55%*	*25%*	*20%*

The EOL-fates of plastic packages that are present in the MSW and that are subjected to mechanical recovery and subsequent sorting are listed in table J.4.

Table J.4: EOL-fates of plastic packages present in MSW that is subjected mechanical recovery and sorting.

	Ideal sorting fate	**Correctly sorted**	**Faulty sorted**	**Not recycled**
PET bottle clear ≤ 0.5 litre	PET	62%	13%	25%
PET bottle coloured ≤ 0.5 litre	PET	53%	17%	30%
PET bottle clear > 0.5 litre	PET	60%	9%	31%
PET bottle coloured > 0.5 litre	PET	35%	13%	52%
PE beverage bottles	PE	55%	10%	36%
PP beverage bottles	PP	2%	2%	96%
PS beverage bottles	Mix	9%	2%	89%
Misc. beverage bottles	Rest	N.A.	N.A.	N.A.
PET non-beverage bottles	PET	52%	20%	29%
PE non-beverage bottles	PE	79%	6%	15%
PP non-beverage bottles	PP	56%	12%	32%
Misc. non-beverage bottles	Rest	N.A.	7%	93%
PET thermoforms	Mix	24%	7%	69%
PE thermoforms	PE	0%	64%	35%
PP thermoforms	PP	22%	15%	63%
PVC thermoforms	Rest	N.A.	9%	91%
PS thermoforms	Mix	1%	0%	99%
PET other rigid packages	Mix	28%	5%	67%
PE other rigid packages	PE	27%	9%	64%
PP other rigid packages	PP	37%	10%	53%
PVC other rigid packages	Rest	N.A.	3%	97%
PS other rigid packages	Mix	3%	2%	95%
Carriage bags (PE)	Film	44%	11%	44%
PET flexible packages	Film	8%	15%	77%
PE flexible packages	Film	35%	12%	53%
PP flexible packages	Film	10%	10%	80%
PVC flexible packages	Rest	N.A.	11%	89%
PS flexible packages	Film	12%	4%	84%
Rigid packages made from non-NIR identifiable plastics	Mix	4%	9%	87%
Flexible packages made from non-NIR identifiable plastics	Film or Mix	13%	0%	87%
Misc. plastics (PC, PLA, etc.)	Mix	0%	1%	99%
Laminated flexible packages and blisters	Rest	N.A.	15%	85%
EPS trays	Mix	4%	2%	94%
EPS blocks	Mix	1%	1%	98%
Silicone tubes	Rest	N.A.	42%	58%
Average EOL fate (for packages that should be sorted into a sorted product)		*26%*	*10%*	*64%*

K. Levels of attached moisture and dirt for freshly milled (unwashed) milled goods.

The levels of attached moisture and dirt (LAMD) have experimentally been determined for the fresh milled goods. These are the unwashed intermediate products produced by the coarse mill. These unwashed milled goods are the feedstocks of the mechanical recycling process. Their LAMD-levels are important, because they define the losses of moisture and dirt that occur during the milling step.

Table K.1: Experimental determined moisture content, dirt content and LAMD for the freshly milled sorted fractions that are feedstocks for the mechanical recycling processes, expressed in percentages of dry weights divided by gross weights: % (w net / w gross).

Separately collected			
	Moisture content	Dirt content	LAMD
PET	5±4%	2.2±1.9%	7±5%
PE	4±4%	4±2%	8±5%
PP	1.4±0.2%	4±2%	5±3%
Film	4±4%	4±3%	8±4%
Mix	1.8±0.3%	4±1%	6±1%
Mechanical recovered			
	Moisture content	Dirt content	LAMD
PET	13.1%	8.4%	21.5%
PE	3.9%	4.8%	8.7%
PP	9.0%	9.4%	18.4%
Film	8.2%	9.5%	17.7%
Mix	13.0%	8.7%	21.7%