Commingled Waste Collection as Chance for Technical Separation: Alternative Collection Systems

Adele Clausen, Malte Althaus, and Thomas Pretz

Abstract The most relevant parameter for the profitability of a deposit is its raw materials concentration. With the view on secondary raw materials from municipal solid waste (MSW), the concentration depends on the population density and the specific waste generation rate. To recover a secondary raw material from MSW, collection is the first step and at the same time, the bottleneck, as typically the efficiency of the separate collection of recyclables decreases with increasing population density. Also, the effort of collecting many different recyclables as a single fraction, with each of these fractions making up a small specific amount per household, often only leads to collection costs being too high to be compensated by revenues from recycling or waste fees. As a compromise between losing recyclables due to high degrees of contamination when collected in mixed household waste, and exploding collection costs for too many single fractions, recyclables are often collected as a commingled fraction of selected materials, which can technically be efficiently separated, and then be directed to recycling plants. Local waste management structures, such as contractual periods and distribution of responsibilities, lead to specific collection and treatment systems with individual efficiencies, which is demonstrated by different examples, as implemented in Europe.

Keywords Commingled collection, Municipal solid waste, Recyclables, Separate collection, Sorting

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Contents

1 Introduction

The basis for assessing the profitability of mining activities of a specific deposit is the concentration of a resource, e.g. the metal concentration of an ore, compared to the technical effort to get access to the ore. In general, the situation is similar for materials recycling from waste streams: The waste needs to contain a certain concentration of the target material. Thus, several standards have been established by industry defining acceptance criteria for the input material of recycling processes. The European metal industry applies the *European Steel Scrap Specification* [1] for ferrous metals and the *General Terms of Metal Trading* [2] for non-ferrous metals. Both precisely describe different qualities. The same applies to the paper [3], as well as the plastics recycling sector [4].

The standards are always related to quality requirements and the maximum share of impurities that are accepted within a certain quality group. Typically, purity greater than 90% is demanded. As a result, the separate collection of mono fractions is implemented for many production wastes.

If no general trading standards are defined yet, as is the case in the mass sector of construction and demolition (C&D) waste, the recycler directly sets purity demands for the waste flows that he accepts. Driven by economic considerations, the goal of the recycler is the maximum yield of valuables related to a minimum of technical effort.

Also in the field of post-consumer waste, separate collection has been installed for different mono fractions. In Europe, hollow glass is the most dominant example of the implementation of successful single collection.

Even though it is well accepted that recycling requires clean, high quality input materials, commingled collection systems are widely disseminated as well. When commingled collection systems are used, different valuables are gathered in one mixed (commingled) material stream instead of the separate collection of high quality mono fractions. Accordingly, the purity for each of the valuables contained in the commingled material flow is low when compared to materials from a mono collection system. In the following, opportunities and challenges related to commingled collection systems are discussed and evaluated.

2 Collection Systems for Post-consumer Recyclables

When discussing optional collection systems for post-consumer recyclables, the first question to be answered concerns the *valuables* that arise as *waste* in a consumer's household and that are applicable for materials recycling.

In Europe, the amount of municipal solid waste (MSW) typically lies somewhere at about 450 kg per capita per year. MSW includes material groups such as biowaste, paper, wood, textiles, plastics, metals, glass and inert materials such as stone, porcelain or ceramics. Furthermore, waste electric and electronic equipment (WEEE) and bulky waste are part of MSW. A last group to mention contains all materials which cannot be assigned to any of the above. Figure 1 as an example shows the average annual generation of said MSW material groups per capita in Germany.

In terms of evaluating the resource potential of MSW, the decisive number is not the percentage of a valuable material in the total waste material, but the amount of that valuable waste fraction produced per capita [kg/(cap·a)]. This is because the resource must be recovered from the complete settled area and not from a point source, as would be the case for recycling from post-production waste. This means not only that there is a very high number of waste sources, but also that a very high number of individual consumers are participating in the system. Thus, the specific amount per area varies significantly, e.g. due to the varying population density or consumer behaviour.

Typical statistics include total areas. However, the number of people living in the different settlements is much more relevant for the collection task. Figure 2 shows the population density in Europe and in the German federal state of North Rhine-Westphalia.

There are two fundamentally different systems available to gather and collect recyclables, which are called *kerbside collection* and *bring systems*.

Kerbside Collection The consumer provides the generated waste either in bags or in bins at a household level at the kerbside. Depending on the system, the waste is to be gathered as mixed or separated according to different waste types (separation at

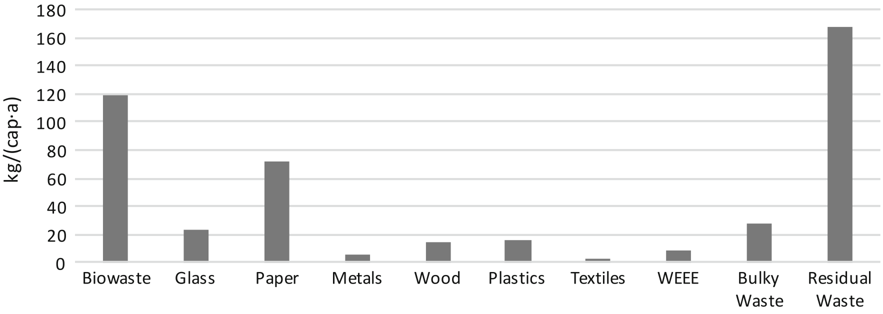

Fig. 1 Average material group distribution in German household waste, 2015 [5, 6]

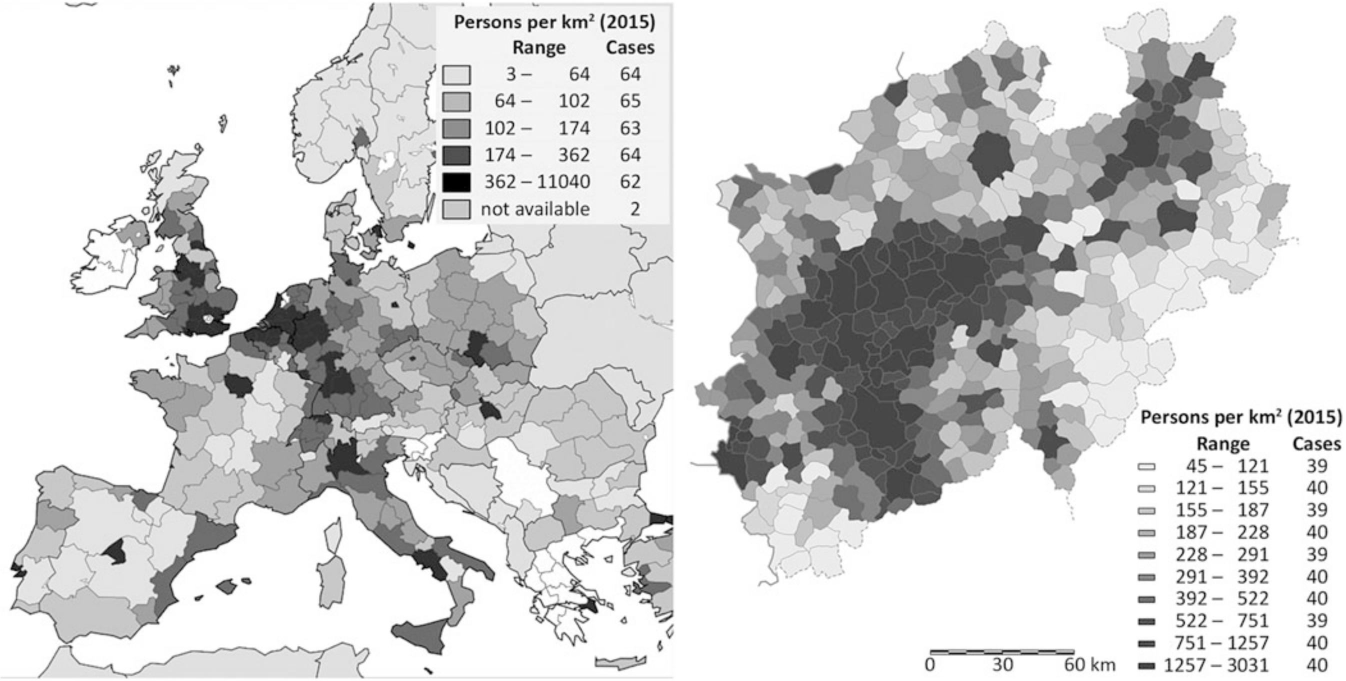

Fig. 2 Population density in Europe by NUTS 2 regions (*left*) [7] and in North Rhine-Westphalia, Germany (*right*) [8]

the source). Typically, different sizes of bins are available according to the settling structure. In densely populated areas with apartment houses, several households typically use bins jointly. Some countries also provide decentralized collection points with bins for several houses (e.g. France, Greece, Spain), so that the consumer has to walk a certain distance to reach the bin. Thus, kerbside collection systems show high variations in terms of user-friendliness.

Bring System Collection points with big containers for recyclables (e.g. 1.1 m^3 containers or depot containers) are installed in decentralized locations for a large number of inhabitants of typically more than 500 up to several thousand. The consumer has to organize the transportation of the waste. The utilization of the system strongly depends on the motivation of the consumer to contribute to a recycling system.

Both kerbside collection and bring systems for pre-sorted recyclables require the participation of informed citizens. The participation rate increases with higher social control, which again is higher the lower the population density is. Accordingly, the separate collection of clean recyclables can be implemented more successfully in rural areas and comes along with lower efficiencies in urban structures. In this case, systems applying technical separation instead of separation at the source can provide an alternative option for implementing pre-sorting. The development of adequate technologies allows not only the recovery of raw materials from highly concentrated yielding of a mono collection, but to also consider waste flows with lower concentrations of valuables, or even mixed MSW (MMSW) as a source of secondary raw materials.

As already mentioned, the key criterion in terms of implementing the separate collection of household waste is the specific waste generation expressed as kilograms per capita and year [kg/(cap·a)]. The second important number is the bulk density of the waste to be collected (kg/m^3). Both information is of special importance for economic considerations. Example data is given in Fig. 3.

3 Commingled Systems

The idea of commingled collection is based on a cost-benefit assessment, whereby an efficient collection of a certain amount of waste per area is evaluated against the remaining technical effort required for technical separation.

When applying mono collection, low specific amounts per inhabitant and year do cause a large collection effort. Also, practical limitations must be considered for the implementation of such systems. A large number of separately collected materials are related to a large number of bags or bins that must not only be stored in the household (Fig. 4, A1/2), but also be placed near the street to be provided for collection by collection trucks (Fig. 4, A3). Both need space to be implemented.

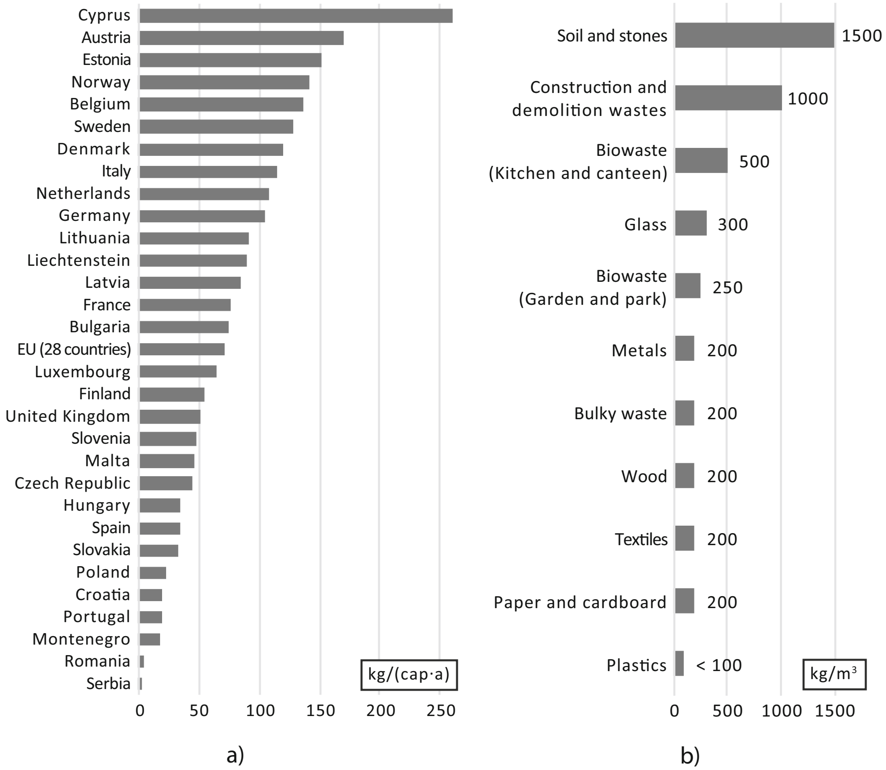

Fig. 3 (**a**) Amounts of recyclables per capita in the EU in 2014 [9]. (**b**) Bulk densities of source-separated recyclables

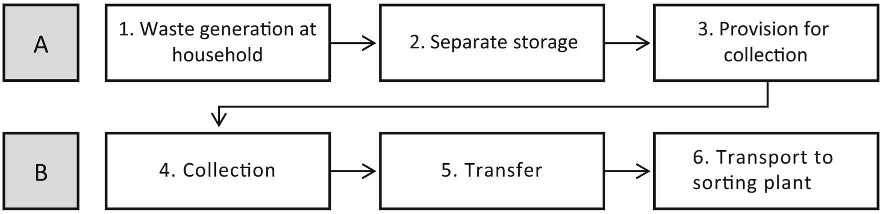

Fig. 4 Process steps of kerbside collection

Hence, part A shown in Fig. 4 is dominated by acceptance and technical feasibility, which is limited especially in high population density, urban areas. Part B, in contrast, can be evaluated solely based on economic considerations.

In order to understand the quantitative contribution of single waste material groups, in the following, the example of *product responsibility* as it is valid for the German packaging market is discussed. Table 1 lists the inhabitant-specific amount

Table 1 Specific amounts of packaging waste

DKR spec.	Name of material fraction	Share in packaging waste (kg/Mg)	Maximum share of impurities (%)	Waste generation[a] [kg/(cap·a)]	Waste generation net[b] [kg/(cap·a)]	Minimum recycling rate[c] (%)	Specific potential [kg/(cap·a)]
320	Plastic bottles	24	6	0.67	0.63	60	1.1
311	Foils >A4	48	8	1.34	1.24	60	2.1
410	Tinplate	106	18	2.97	2.43	70	3.5
420	Aluminium	22	10	0.62	0.55	60	0.9
510	Beverage carton	60	10	1.68	1.51	60	2.5
350	Mixed plastics	204	10	5.71	5.14	60	8.6

[a] Based on an average packaging waste generation of 28 kg/(cap·a)

[b] Content of pure recyclable material assuming the material concentrate contains the maximum of accepted impurities

[c] As defined in the German Packaging Ordinance 07/2014

of waste that is produced and distinguished according to types of packaging. The data are derived from contracts between the operators of sorting facilities and the *Dual System*, which executes the producer's responsibility. To protect from competition, these data are not public. Thus, the data in Table 1 are to be considered as an educated guess.

The share of single material fractions shows considerable deviation depending on specific national consumption patterns. One example is the fraction of beverage cartons. In 2014, the use amounted to 176,000 Mg in Germany, which equals 2.15 kg/(cap·a). After consumption of the content, beverage cartons still contain moisture, and a part of the product typically remains in the packaging as well. On average, these impurities add up to about 25% of the net weight of the beverage carton. As a result, the waste generation rate can be expected to be 2.15 kg/(cap·a) × 125% = 2.7 kg/(cap·a). For simplification, a value of 2.5 kg/(cap·a) is presented in Table 1.

In the Netherlands, a beverage carton is not only used as packaging for beverages, but also for pasty foods, such as yoghurt or pudding. In 2010, the use of a beverage carton in the Netherlands amounted about 70,000 Mg equalling 4.1 kg/(cap·a). As it is more difficult to completely empty a beverage carton with pasty contents, the share of moisture and remaining product in the beverage carton waste fraction adds up to about 100% compared to the net weight of the beverage carton. Hence, the waste generation rate can be assumed to be as high as 8.2 kg/(cap·a).

The fraction of paper waste, which includes both packaging from paper and printed products, is also subject to national variations in terms of its consumption.

As demonstrated in Fig. 5, which shows the specific paper consumption as well as the specific gross domestic potential (GDP) in different European countries, there is no clear correlation between economic conditions and paper consumption.

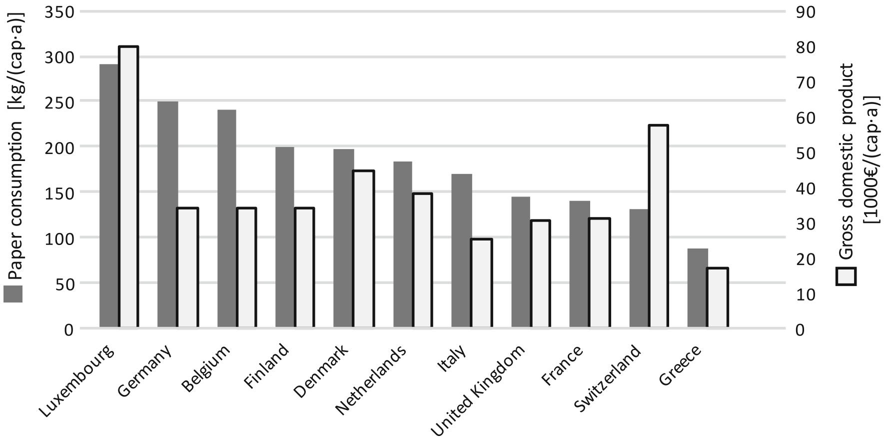

Fig. 5 Paper consumption and GDP per capita in selected European countries, 2014 (Data from paperonweb.com, ec.europa.eu/eurostat/)

In the field of waste paper collection, no differentiation is made between paper packaging and printed products. Also, considering the fact that most of the other types of packaging waste show an even lower bulk density than waste paper, the amount of waste paper available for recycling measures is comparably high.

When developing commingled collection systems, the objective is to combine the operation of a sorting plant under economic conditions with justifiable transport distances.

Mixed packaging waste including printed products shows a low bulk density, which can be assumed to be in a range between 50 and 100 kg/m^3. To avoid long transportation distances with materials having a low bulk density, the first technical process step is organized on a decentralized level.

Under European conditions, the smallest capacity of a sorting plant that is needed to run under economically efficient conditions can be assumed to be at an annual throughput of 100,000 Mg [10]. Applying a decentralized concept, it means that this sorting plant must be reachable by waste collection trucks avoiding a transfer station. The low bulk density of waste packaging material limits the load per waste truck. As a result, from an economic perspective, the radii of collection areas of more than 50 km can hardly be covered. Table 2 demonstrates the area that is required to collect 100,000 Mg/a of input material from an urban and a rural area for both material flows, lightweight packaging (LWP) according to the German system and commingled waste as collected in the UK. At least in rural areas, the waste generation rate per area is too low for an economical collection of LWP.

The example calculations prove the importance of commingled collection systems. They enable the collection of highly inhabitant-specific quantities. In order to implement highly specific collection quantities, paper has to be included in the collection concept as shown in Fig. 6, which compares commingled concepts excluding paper (Germany) and including paper (UK).

Table 2 Required radii of waste collection areas for profitable sorting plants

Collection system	Spatial category	Population density (cap/km^2)	Waste generation [kg/(cap·a)]	Inhabitants generating 100,000 Mg/a (cap)	Radius of required area (km)
LWP Germany	Rural	250	40	2,500,000	56
	Urban	2,000	10	10,000,000	40
Commingled UK	Rural	250	80	1,250,000	40
	Urban	2,000	50	2,000,000	18

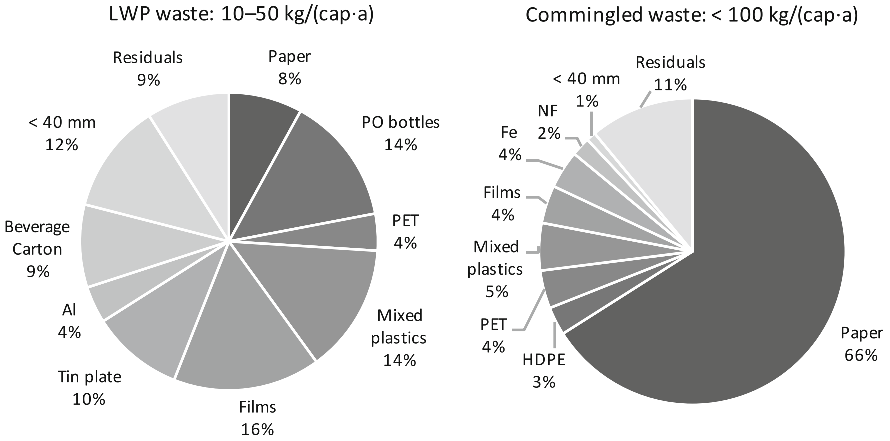

Fig. 6 Amounts and shares of mixed waste collection excluding paper (Germany, *left*) and including paper (UK, *right*)

4 Sorting Technology

The design of sorting plants for mixed waste with a high share of packaging waste always follows the scheme of disintegration first, conditioning second and sorting third. The process of disintegration has to loosen the material mix that has been compacted during collection. Also, packs like bags must be opened. The process of sorting uses particle characteristics. Therefore, relevant particle characteristics may not get lost during the process of comminution. Furthermore, the loosened material mix has to be supplied to the separation processes as an evenly distributed volume flow.

Modern sorting plants for lightweight packaging waste or material recovery facilities (MRF) with a capacity of 100,000 Mg/a realize material throughputs of at least 22 Mg/h. After loosening the material, this mass flow shows a bulk density of between 50 and 100 kg/m^3. Correspondingly, volume flows of 220–240 m^3/h must be processed.

The step of conditioning functions as preparation of the material for the decisive sorting processes. The volume flow is reduced by separating oversized particles.

Screening technology and ballistic separation are applied for that purpose. Furthermore, fine particles are to be removed by screening. This is due to two aspects. The low mass per particle of the fine fraction creates a disproportionally high technical effort per mass to be sorted on the one hand. On the other hand, the share of impurities such as dirt, organics and humidity increases with decreasing particle size. Finally, there are also demands in terms of the particle size distribution and the distribution of the mass per particle of material flow that yield from the separation technology that the material is supplied to in the last steps of the process chain. Thus, the partition of the material into particle size groups is another task that has to be fulfilled during the process step of conditioning.

Special conditions are related to the sorting of packaging waste that contains a high share of paper. In this case, material characteristics such as the stiffness of cardboard and cartons are linked to the particle size. This means that classifying into particle size groups leads to a concentration of materials with similar characteristics in a specific particle size group. Using the example of paper, it is known that the separation of a material flow at a size of DIN A3 (300 × 400 mm) directs most of the carton into the oversize fraction, and newspaper and journals into fraction <A3. Thus, a separation into material fractions takes place in addition to the separation into particle size groups. Particles of packaging based on metal, paper compounds or plastic that are part of the waste material flow are spread into both intermediate concentrates. A pre-concentration by classifying as described for the group of newspapers and journals and the group of cartons does not take place. Accordingly, these recyclables have to be recovered from different intermediate material flows. Thereby, the parameterization of a sorting process yields from the quality requirements related to the material that dominates the mass flow, e.g. high purity of <1.5 m-% impurities in paper. The separation of material groups that hold a minor share of mass is therefore always conducted in two steps. The objective of the first separation step (*rougher*) is to ensure a maximum yield of the low concentrated target material (e.g. PET), which at the same time functions as a cleaning step for the dominating target material (e.g. paper). The second separation step (*cleaner*) separates impurities. The objective is a high-quality concentrate. This kind of process always yields a loss of target material. This effect can be reduced by applying a third separation step (*scavenger*), which picks the valuables from the rejected material flow. A graphical representation of this separation process is provided in Fig. 7.

If the separation steps described are conducted for all material groups of the material mix, complex process flow charts are derived involving a high amount of sorting equipment.

The most important technology used for comingled sorting today is sensor-based sorting. Modern sensor-based sorting technology separates single particles, which implies that volume flows must be supplied to the sorting equipment as a monolayer of particles to enable individual treatment. This equipment conducts detection, interpretation and separation as three decoupled sub-processes. The interpretation of data allows the application of filters, which again allows the recovery of different qualities.

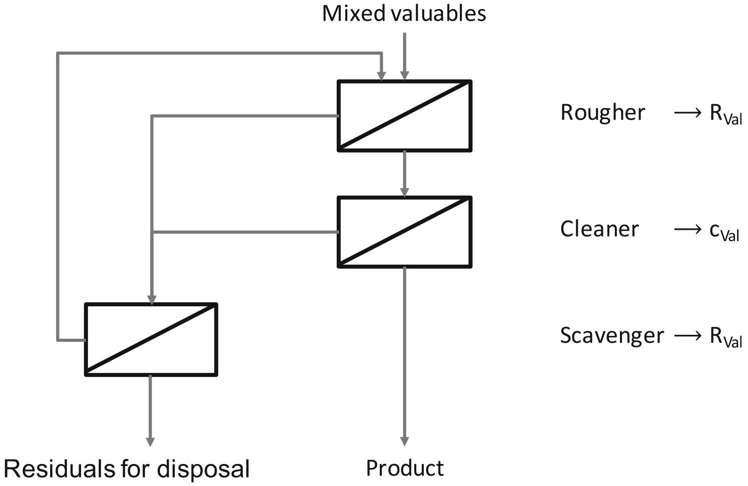

Fig. 7 Separation stages for material groups with small mass fractions

Separation processes based on physical principles combine the identification of a material characteristic with the ejection of the related particle(s). Here, it is possible to modify the product quality by, e.g., adjusting the ejection unit as it can be done for eddy current separators. All separation equipment has the demand that the relation of maximum and minimum particle size in the material flow to be treated in common and is limited to 3:1. The conditioning must ensure the limitation of the grain size range as well as a consistent material distribution in monolayers.

Well-designed treatment processes that are supplied with a mix of pre-sorted recyclables, such as the material collected from commingled systems, enable the realization of high performance parameters. The performance is evaluated by the mass recovery R_M and the yield of valuable target material R_V.

Today, a yield of target material of 90% can be realized for material groups with a particle size of >50 mm if the above-described multi-step sorting processes are applied. The mass recovery quantifies the share of the input material that is recovered as a valuable recyclable product flow and that can be directed to the next stage of the recovery process chain. These recyclable product flows contain impurities according to the accepted maximum.

In contrast to impurities, moisture, product that remained in closed packaging and dirt that is attached to the surface of particles are classified as part of the valuables. Recycling quotas are calculated based on the mass flow that is provided for recycling and also published that way. Hence, a reliable statement about the effectively recycled mass flow cannot be derived from these recycling quotas. Considering the different conditions described, the purity of the recyclable product flows on average adds up to $\geq$90%, with the exception of paper and tinplate. The purity requirements for paper products can be as high as 99.5% [3]. Tinplate products, in contrast, may contain as much as 33% impurities [4].

5 Techno-Economic Performance

Generally, available technologies allow the separation of recyclables from mixed material flows with a high yield and a high quality that is sufficient for a downstream recycling of the separated recyclable concentrates.

However, quality requirements are often not met or the mass recovery is significantly lower than what the available technology can realize. The reasons are the economic conditions under which commingled sorting plants are operated. They are described in the following:

1. Investment in technical plants or equipment is justified only if a return on investment can be expected. This requires long-term perspectives for a sufficient supply for the sorting plant with an adequate waste material flow, a condition for deciding on an investment. However, the European waste management sector shows a wide spectrum in terms of waste management contracts and durations. These range between 2 years (Germany) and 20 years (Greece), and are accordingly related to a high and, respectively, low supply risk.
2. The demands in terms of quality and quantity aspects of sorting technology are, on the one hand, politically motivated by related laws and directives. On the other hand, they are driven by markets and the markets' demands.

   However, frequent changes in legal demands always trigger technical and operational adaptations in sorting plants, which effect the economic performance of the plant. For example, in Germany the legislation that regulates the recovery of lightweight packaging was revised seven times between 1991 and 2014.

   During the depreciation time of up to 25 years, all processes that take place downstream to sorting were affected by development. At the same time, the input material for sorting plants is subject to changes due to technical developments and consumption patterns. As a result, the quality requirements put on recyclable concentrates are continuously being modified. One example is paper printed with water-soluble ink, which is not permitted to enter a material flow of deinking quality. To fulfil such requirement, a technical adaptation is absolutely necessary.
3. The position of plant operators in recovery chains shows considerable differences. Plant operators can function simply as service providers who are paid per unit at an agreed-on price. The recyclable concentrates remain the property of the customer. However, the disposal of residual waste fractions generated during the sorting process has to be paid. Since the disposal is typically part of the plant operator's service, the costs are covered by the service fee paid by the customer. As a result, the plant operator's motivation to improve the product quality is low, as a higher purity of the product material flow is related to increased mass flows of residual materials and consequently increased disposal costs.

   In contrast, plant operators can hold full economic responsibility for marketing the recyclable concentrates that they produce, as they have to set up bilateral contracts with recyclers, and they have to fulfil the recycler's individual quality demands.

6 Conclusion

One of the main challenges of recycling in the field of post-consumer waste is the fact that a high number of different recyclables are generated with

– a low bulk density
– a low purity
– a low punctual generation rate
– a very high number of sources (=number of inhabitants) that are widespread in the area.

In EU, the sector of packaging waste management is regulated by the EU Directive on Packaging and Packaging Waste [11] which calls for recycling quotas that must be fulfilled applying the approach of producer responsibility. With the private sector being the main player in this business, market mechanisms dominate technical feasibility. The benefit of the separation of recyclables at the source on a household level, which can reduce the required technical effort for sorting, is weighed against the additional effort of separate collection of small quantities with a low weight per volume and resulting huge collecting areas to gather mass flows that justify the operation of a treatment plant. As a compromise, the commingled collection of a mix of selected recyclables is implemented, followed by technical separation. Technically, the separation of mixed recyclables into highly pure mono fractions of valuables with a high mass recovery is feasible. However, again the technical effort realized is driven by market mechanisms. Key elements influencing market conditions are the organization of responsibilities in terms of proving the compliance with quotas, the marketing of recyclable concentrates, the disposal of residual material flows and, crucial for any decision related to investment in technology, the duration of contracts guaranteeing a certain material supply. Short contracts are said to increase competition. However, in the field of household waste recycling, this can also inhibit the implementation of technical development when the economic risk in a volatile market becomes too high for investments.

The design of a commingled collection system is a result of the framework conditions for downstream sorting and recycling activities, which vary greatly in different countries, even among EU countries under the same legislation. High technical efficiency in terms of quality and quantity of recycling is feasible. However, due to different emphases on different values, high technical efficiency is not necessarily what a society may or want to provide a framework for. Therefore, it is crucial to understand how exactly a society defines success in terms of recycling to design adequate framework conditions.

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