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1 INTRODUCTION

The global generation of municipal solid waste is estimated to be two billion tons per year. It is expected to rise by 30% by 2030 and 70% by 2050, leading to up to 3.4 billion tons of waste generated worldwide in 2050 (Kaza et al., 2018). This already staggering number only includes municipal waste, excluding other major solid waste sources like construction and demolition waste or post-industrial waste.

All waste needs to be collected and processed correctly to avoid further environmental pollution. The increasing amount of waste, combined with the increasing complexity and variety of end-of-life products and materials, is putting heightened pressure on the recycling industry. At the same time, manufacturers are increasing their requirements toward secondary raw materials resulting from the recycling process. These increased requirements are due to continuously rising consumer expectations and stricter legislation concerning the composition of materials used during production, for example, REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) or POP (Persistent Organic Pollutants) directives. Additionally, the EU and multiple national governments are increasing the recycling quotas, meaning that more secondary raw material needs to be produced from the products and material that are discarded by consumers. To cope with these challenges, a joint effort of all actors involved in the treatment of waste is necessary.

Currently, there are substantial differences between the treatment process of different end-of-life products and materials. Some product types are collected and treated systematically in a well-managed supply chain. Many other products, however, cannot be disposed of in a dedicated waste stream. They are therefore collected with household waste and are mostly incinerated or landfilled, despite containing valuable materials that could be recovered. This report analyses five reverse cycles for different end-of-life products from the collection of the waste until the use of the secondary raw material. Our analysis focuses on identifying best practices and challenges concerning the network setup, design and management of the supply chain.

We analyse reverse cycles that are systematically collecting and treating waste to recover secondary raw materials. In our analysis, we focus on the post-consumer waste streams of waste from electrical and electronic equipment (WEEE), plastics packaging, glass, paper, and construction and demolition. Post-consumer is defined as end-of-life products generated by consumers as well as businesses. Its primary source is the packaging of food and other non-durable goods. Durable goods like information and communication technology or other products like furniture or even buildings can also be the source of post-consumer waste. Post-industrial waste, however, is generated by companies during production (e.g. runners from injection moulding), transport of parts, or finished goods (e.g. packaging material).

To be able to compare the activities in the different reverse cycles, we developed six steps that apply to the recycling process of all the waste streams (see Figure 1). (i) The *Collection* comprises all the activities necessary to collect and transport the waste from its origin to the first treatment facility. (ii) During the *primary treatment,* the end-of-life products are prepared for further treatment, e.g. depollution (applies only to end-of-life products). (iii) *Material recovery* is the dismantling and fractionizing of multi-material waste streams, e.g. recovery of Fe-metals, non-Fe-metals, and plastics from WEEE (applies only to multi-material waste streams). (iv) *Material purification* is the different cleaning activities carried out to remove contamination from one fraction. The output is a single material containing as little contamination as possible, e.g. PET flakes with a purity of 99%. (v) The *secondary raw material production* is the activities necessary to make a material that is used in the production process of a manufacturing company, e.g. the regranulation of the PET flakes. (vi) The last activity we describe are activities related to the *use of the secondary raw material* by the manufacturing company.

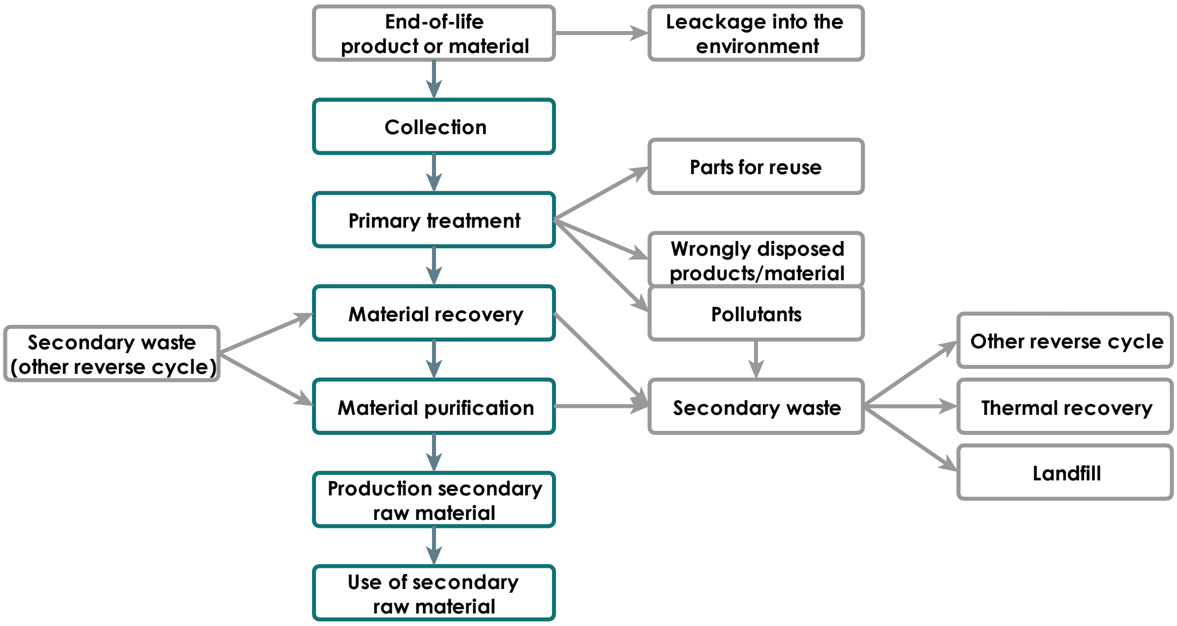

Figure 1: General treatment steps of reverse cycles

For the analysis, we used different types of data as input (see Figure 2). First, we reviewed stakeholder reports, scientific publications, and company publications like press releases, websites, or videos. This review gave us an initial overview of the peculiarities of the treatment steps and yielded some first challenges and best practices. Second, we conducted 36 semi-structured expert interviews to gain deeper insights into the reverse cycles. They took place between August 2019 and May 2020, either face-to-face, via telephone, or video calls. The average duration of the interviews was 64 minutes with the shortest interview lasting 36 minutes and the longest 100 minutes. Our sample contains companies from all reverse cycles studied in this report. They are active in all treatment steps from the collection of the end-of-life products and materials, and the material recovery, to the use of the secondary raw material (SRM). Additionally, we interviewed experts from extended producer responsibility (EPR) schemes and associations. Our experts come from nine EU-member states. Figure 3 gives an overview of our sample. Third, we conducted two in-depth case studies of EPR-schemes, one from WEEE and one from packaging.

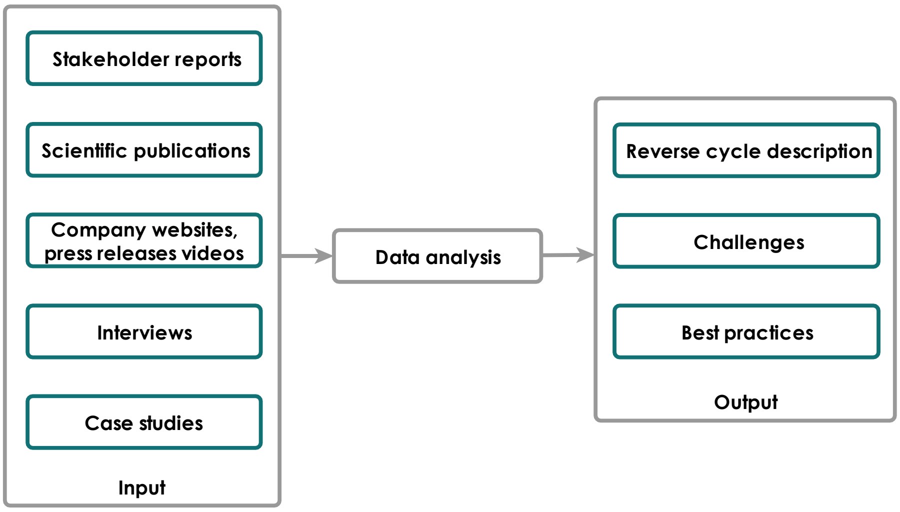

Figure 2: Overview of the methodological approach

We analysed the three data sources using the qualitative content analysis proposed by Mayring (2010). First, we identified and grouped all relevant information in the data sets related to reverse cycle logistics. Second, we assigned the information to different topics that were identified a priori or during data analysis. Then, we compared and synthesised all information for each topic (e.g. best practices for a specific reverse cycle). The goal of the analysis was to structure the data and thereby understand the specifics of the reverse cycles. Additionally, we identified a set of challenges and best practices that were mentioned repeatedly during the interviews or in the other data sources. The list of challenges and best practices is therefore not exhaustive, but a result of our sample and data set.

Reverse cycle	Number of interviews
WEEE	18
Plastics packaging	10
Construction and demolition	5
Glass	2
Pulp and paper	2

Treatment step	Number of interviews
Collection	8
Primary treatment	8
Material recovery	13
Material purification	16
SRM production	12
SRM use	9
Other	9

Country	Number of interviews
Austria	1
Belgium	13
Croatia	1
France	1
Germany	11
Italy	3
Netherlands	4
Spain	1
Sweden	1

Figure 3: Overview of the interview sample[1]

The CREAToR project aims to develop new processes that can first identify plastics containing bromated flame retardants and then remove the flame retardants from the plastics by using continuous extraction technologies. Waste streams, which are currently incinerated, can be converted into valuable secondary raw materials using the CREAToR process. The implementation of this new process will create a new reverse cycle that will include existing and new actors. The insight from this report on challenges and best practices in other reverse cycles will be exponentially valuable during the design and implementation of the CREAToR reverse cycle.

[1] Numbers may not add up to total number of interviews as some companies are active in more than one waste stream or multiple treatment steps.

2 WASTE ELECTRICAL & ELECTRONIC EQUIPMENT REVERSE CYCLE

Waste from electrical and electronic equipment (WEEE) is one of the fastest-growing waste streams in Europe. In 2017, 8.9 Mt electrical and electronic equipment was placed on the market. In the same year, 3.7 Mt of WEEE were collected (Eurostat, 2020). WEEE is a unique waste stream that contains many different materials and components, including several hazardous substances. A separate collection of WEEE is therefore essential. The European Union introduced a directive to control the correct disposal, collection, and recovery of the materials. It first entered into force 2003 and is updated regularly. The directive makes the producers and retailers of the products responsible even beyond their lifetime. Hence, the directive ensures that WEEE is collected as a separate waste stream with free-of-charge disposal for consumers.

The exact material composition of the waste stream varies significantly between the product categories. Metals and plastics dominate the waste stream. Iron and steel are the most common materials found by weight and account for almost half of the WEEE weight. The second-largest fraction is plastics, accounting for roughly 21% of WEEE. Non-ferrous metals, including precious metals, represent another 13% of the total weight (with copper accounting for 7%) (Ongondo et al., 2011). We therefore focus our analysis on metal and plastics treatment. The primary sources of waste by weight are large household appliances (53%), such as freezers, dishwashers and washing machines, consumer equipment and photovoltaic panels (15%), IT and telecommunications equipment (14%), and small household appliances (10%) like coffee machines and toasters (Eurostat, 2020).

In this chapter, we first give a short overview of the reverse cycle of WEEE by describing the necessary treatment steps and their distribution among the actors. We then highlight challenges and best practices in the WEEE reverse cycle that were identified during the analysis.

2.1 TREATMENT STEPS AND ACTORS

During our analysis, a clear pattern concerning the structure of the reverse cycle across the different countries emerged. We will describe this generic supply chain focussing on the main sub-streams of WEEE and its materials. However, there are also various smaller sub-streams splitting the main WEEE stream. In these streams, highly specialised companies are treating, for example, only hard drives to recover precious metals. Our analysis focuses on identifying best practices and challenges concerning the reverse cycle logistics like network setup, design, and management of the supply chain.

The WEEE reverse cycle contains the general treatment steps described in Figure 1. However, there are some differences between the EU-member states. They mostly pertain to the implementation of the WEEE directive and the setup and management of the system. We base our description on the most common setup, which builds on municipal collection points and EPR schemes. This way, the WEEE directive is translated into national law in most countries. Germany has chosen a different approach. Here, producers and retailers are responsible for the management of the reverse cycle. However, this has no real impact on treatment activities. To give more detailed insights into the activities of an EPR scheme, we introduce the case of *Recupel,* a Belgian EPR scheme.

2.1.1 COLLECTION

The extended-producer responsibility starts when a consumer decides to discard electrical and electronic equipment (EEE). Multiple channels for WEEE collection exist. The three primary ones are municipal collection points, retailers, and producer take-back. The majority of EPR schemes use municipal collection points as the central point of return. There is a dense network of ten thousand collection points all over Europe. The return of the product to the collection points is free of charge for consumers. Returning a product to the retailer or producer is, in most cases, free as well. However, it might be on the condition of a new purchase. These services are set up to ensure high collection rates.

In most countries, the collection is carried out in separate containers for each product category. Product categories are groups of applications that have similar properties (e.g. screens, heating/cooling appliances, or lamps). In some countries, all WEEE is collected in one container and separated during primary treatment. The transport from the collection point to the next processing facility is mostly organised by the EPR schemes. As soon as a container is filled, the scheme is notified. It then arranges the transport to a treatment facility and the replacement with an empty container.

2.1.2 PRIMARY TREATMENT

After collection, the WEEE is transported to companies that handle the primary treatment. This treatment includes several actions that are mandatory due to the legislation but also efforts to prepare the products according to the requirements of the next treatment step. From a logistical perspective, the sites of the primary treatment facilities act as hub for the WEEE. Thus, the facilities act as satellites for large shredding facilities. The small quantities arriving from the collection points are treated and then stored until a truckload ships to the next treatment step. Companies carrying out the primary treatment for the large dismantling sites are usually rather small. Most of the work has to be done manually. The throughput of these facilities is, therefore, low.

During the primary treatment, the WEEE first undergoes a visual inspection, and wrongly discarded products and materials are separated. Then, the products are depolluted. Hazardous substances, such as batteries, toner cartridges, LCDs, and chemicals like chlorofluorocarbons from fridges are removed. Also, other unwanted materials like wood or vacuum cleaner bags are removed. This makes manual pre-treatment necessary, especially for monitors and cooling appliances. Monitors are dismantled by hand so that the screens do not break and the hazardous substances cannot leak out. Cooling appliances are treated manually to retrieve the hazardous cooling liquids safely. Monitors and cooling appliances are therefore usually treated separately from the other WEEE in dedicated facilities.

The rest of the equipment is then sent to a shredder for dismantling and size reduction. Depending on their customers, the primary treatment facilities also sort the WEEE based on their primary materials. The goal is to align the product mix with the target materials of the material recovery facility. Large household appliances would be the best choice if they are looking to recover steel. Material recovery facilities focusing on precious metals, however, are interested in information and communication technology equipment.

2.1.3 MATERIAL RECOVERY

Electronic products contain many different materials. To recover the individual materials, the product needs to be dismantled and reduced in size. Shredders dismantle the majority of the WEEE. These shredders crush the products into small pieces using spinning hammers or blades. The result is a uniformly fragmented scrap.

After the dismantling, the output material is separated into at least three material fractions. A ferrous metal fraction containing materials like steel and iron is separated using an overband magnet. The second fraction contains non-ferrous metals like copper, brass, or aluminium and is separated using an eddy-current separator. Depending on the facility and its customer, the rest remains in the shredder light fraction or is further separated. This shredder light fraction, therefore, contains a broad range of materials like plastics, rubber, wood, textiles, some cables, and metal pieces. A possible further separation step is electrostatic sorting that allows separation of e.g. ABS and PS. Another possible separation step is an all-metal inductive sensor that separates circuit boards and cables from the fraction.

The resulting fractions are still impure and a mix of different materials. Sources of the impurity include, for example, materials that are still adhering to the target material due to incomplete disintegration or other process-related contaminants. The fractions are therefore sent to the next processing, where they are purified and separated into more specific fractions.

2.1.4 MATERIAL PURIFICATION

During this step, the still impure material coming out of the dismantling facility is broken down into several cleaner fractions containing, if possible, only one target material. This means that the material is sorted further to obtain a higher level of purity. First, the material is shredded to achieve a higher level of disintegration of the different materials in the fraction. Then, sorting equipment is used to separate the target materials from the fraction. Common separation technologies are density separation to identify specific metals or plastics based on their intrinsic density. Other equipment is sensor-based, using near-infrared, x-ray, or cameras to separate particular materials based on their spectroscopic properties or image. The more separation steps executed, the higher the quality of the output material. The number of sorting steps therefore varies depending on the value of the target material. Also, the material requirements of the producer of the secondary raw material play a key role. The remainder of the material, which is not the target material, can either be processed by another company to recover other materials or is sent to incineration.

The recovered and purified material, which is the output of this treatment step, is the input for the production of secondary raw material. It is therefore essential to obtain a stable quality. The stability of the input material is important to the producers of the secondary raw material because they are obliged to produce a product of stable quality. The recovered material is, therefore, regularly tested by the recycler as well as by its customer. The testing procedure depends on the price and the requirements of the customer as well as the legislation. For high-quality plastic fractions, samples are taken and sent to a lab for testing. It is crucial to obtain a good mixture of the material by grinding it down into a fine granulate and mixing of the whole batch to spread out any contamination as much as possible across the batch. The result of this process is a homogenous material that can be used in the production of (secondary) raw material. The process for metal recyclates is different. High-value metal recyclates like copper fractions are also tested in the lab. For steel fractions, on the other hand, a visual inspection is often sufficient. Metal recyclates are homogenised by adding them to the production process of primary raw material (e.g. at the copper smelter or steelworks).

2.1.5 SECONDARY RAW MATERIAL PRODUCTION

At the final stage of the recycling process, the purified material is used to produce a secondary raw material. This raw material can contain 100% recycled material, or it can be mixed in the production with primary (virgin) raw material. The advantage of mixing a certain percentage of recycled and virgin content during the production is that the mechanical performances of the recycled plastics will be enhanced thanks to the addition of the virgin plastic. For metal production processes, it is common to add metal scrap to the production process. This means that the produced raw material always contains a certain share of scrap material without negatively influencing its properties. Steel, copper, and precious metals are considered to be the most easily recyclable materials (Martens & Goldmann, 2016). This means that they are easy to separate from other materials in the recovery process. Also, the production process using the recyclates is not as prone to impurities as other processes.

The production of secondary raw material from plastics is usually carried out in batches. The material in one batch can ultimately be traced back to one material source. This enables companies that use the secondary raw material to properly test the mechanical and chemical properties of the product before using it in their product. The secondary raw material is produced by regranulation and readditivation of the material. During the extrusion of the plastics, the melt is filtered one last time, and additives can be added to fine-tune the properties of the plastic.

2.1.6 SECONDARY RAW MATERIAL USE

For the metal, there is no difference in using scrap-based and non-scrap-based materials because, as described above, most of the metal production processes today use scrap as one of the material inputs during production. This is, however, different from the use of recycled plastics. On the one hand, there is still reluctance among EEE producers to use recycled plastics. The reasons are an increased effort in finding suppliers that can deliver material in the desired quality and quantity, and the remaining risk of contamination with substances of high concern. The manufacturer needs to perform tests to show that the products using recycled material to demonstrate that the material meets the relevant requirements under the applicable product legislation (e.g. POP, REACH). They have to pass the same test concerning product quality – like the drop and durability tests – but also concerning hazardous substances (further information in deliverable 1.7). On the other hand, there are many suppliers of secondary raw material that have difficulties in finding buyers for their recycled plastics, especially if oil prices and therefore the price for virgin material is low. This indicates that there is still a need for improved management to better match supply and demand in terms of quantity and quality.

2.1.7 MANAGEMENT

The WEEE directive is placing physical and financial responsibility on the producers of EEE. The producers are held responsible for the transport of all collected WEEE to authorised treatment facilities and the establishment of measures to treat the WEEE using the best available technology (Cahill et al., 2011). In most European countries, the management of these responsibilities is taken over by EPR schemes, which are financed by the producers. As a result, a specialised recycling industry has developed, working in close cooperation with the EPR schemes.

Up to the point of material recovery, the producer responsibility schemes manage the WEEE reverse cycle. On a strategic level, their task is to conclude contracts with all the companies involved in the WEEE recycling process like treatment facilities or logistics companies to ensure the proper treatment of all the WEEE collected. On an operational level, they manage the pick-up of containers from the collection points, their transport to treatment facilities, and similar activities. Furthermore, they ensure that the collection and recovery targets are met, and the treatment is executed following to the regulations. This means that they need to audit the recyclers, carefully control the reports from the recyclers, and communicate the numbers to the local governments. The whole process is paid for by the producers of the EEE, often by imposing a fee on the consumers.

After the step of material recovery, the involvement of the producer responsibility schemes stops, and this part is less regulated than the previous steps. This means that the companies producing the recyclate and the secondary raw material need to work closely together to provide the quality and quantities requested by manufacturing companies to ensure the economic efficiency of their operations. Mostly, the manufacturing companies are interested in long-time contracts with the suppliers of the secondary raw material. This allows them to establish a relationship and build trust with the suppliers.

Case study I: Recupel

(WEEE EPR scheme, Belgium)

The WEEE directive includes an extended producer responsibility, which holds the manufacturers and retailers of EEE responsible for their product even after the end-of-life. The companies, therefore, have to register the appliances with the national register, declare how many products of which type they put on the market, organise and finance the collection, transport, and recycling of their end-of-use products and report on these operations. In most European countries, these activities are not carried out by the manufacturers themselves. Instead, EPR schemes take care of these activities for the companies. In Belgium, this is the non-profit organisation *Recupel,* founded in 2001.

Recupel is an administrative and coordinating organisation. They do not collect, transport, or recycle any WEEE themselves. Instead, they purchase these activities from subcontractors. These companies have to follow strict rules concerning their operations. For example, the logistics companies get explicit instructions about the type of container for the transportation of the appliances. The recycling entities follow strict rules concerning depollution, as well as specific recycling targets for the different product groups. All the recyclers have to follow the European Standard EN50625. They need to report their activities to *Recupel*. This allows *Recupel* to make sure that the recyclers are complying with the regulations set by the EU and the Belgian government.

The contracts for the subcontractors are put out for tender every three years. The tender contains details on the volumes collected during the last year. These values, however, are just an orientation, and the companies are not guaranteed to receive those amounts. The companies can then bid on volumes of the different product groups. *Recupel* pays them for the collection and transport activities. The price per tonne depends on the value of the materials inside the appliances. Certain groups of appliances are more valuable, such as large household appliances that have large metal and low pollutant content. The recyclers offer money for these appliances to *Recupel*.

Customers pay a contribution when they purchase a new appliance that finances *Recupel's* activities. The "*Recupel* contribution" is included in the sales price, varying by product group. It ranges from 0.05 € for small household appliances like toasters to 10.00 € for freezers and fridges. The consumers pay this fee to the manufacturer or retailer, who then uses it to pay *Recupel* for the recycling of their products. The companies have to report quarterly on how many products they have put on the market and are billed accordingly by *Recupel*. *Recupel*'s subcontractors charge *Recupel* based on the volumes they have collected, transported, or recycled.

Recupel closely collaborates with the regional authorities that are responsible for overseeing the system. The authorities are involved with *Recupel* activities in multiple ways as (i) they sit as observers on *Recupel*'s Board of Directors, (ii) they need to approve the "*Recupel* contribution," (iii) they are involved in the selection of the subcontractors, and (iv) they play a role in all major decisions made at *Recupel* like approving the annual budget.

Recupel's network comprises 7283 points of return, mostly retail shops. By law, any shop that is selling EEE also needs to take back WEEE. These shops can be used by consumers to hand in their old EEE. However, the main points of return are the 564 municipal collection points that cooperate with *Recupel*. In 2017, this network collected over 117,000 tonnes of WEEE.

Further information: **www.recupel.be**
Sources: (Recupel, n.d., 2015, 2016)

2.2 Challenges

In this chapter, we highlight challenges related to the logistics and management of the WEEE reverse cycle. We indicate which steps of the reverse cycle are influenced by this challenge, followed by a short description. The examples given result from the analysis of our sample and data set and are not exhaustive.

2.2.1 WEEE does not enter the correct reverse cycle

Every year, consumers in Europe discard millions of tons of old EEE. Nevertheless, there is still a lot of WEEE not entering the WEEE system. This is a problem because if old EEE enters a different waste system like household waste, it cannot be adequately treated, and valuable materials contained in the products cannot be recovered. There are multiple reasons why old EEE does not correctly enter the WEEE system.

First, the consumer is wrongly discarding the WEEE. Even though the collection is carried out at a large number of collection points and is free of charge for the consumer, the barriers for many consumers to return the WEEE correctly are still too high. For example, they might not be willing or able to reach a collection point and return their appliances. Another option is that the consumers are not aware of the correct treatment of their obsolete EEEs and therefore discard them via the wrong bin. One of our interview partners told us that in the Netherlands, 2 kg per capita of WEEE are still discarded as household waste every year. Additionally, consumers tend to hoard old EEE. Instead of discarding their old equipment, they keep it at home. This might happen because the consumer cannot access a proper return channel. Another reason is the reluctance to return the equipment, which contains files of personal value like old pictures or messages. In this case, the devices are often kept to retrieve these files in the future.

Second, the WEEE might be returned to other channels that also have an interest in the equipment. For example, these include scrap dealers who are interested in the big household appliances, such as washing machines and dishwashers, containing a lot of metal components. Scrap dealers tend to sell these materials outside of the official WEEE system. The result of this activity is often an inferior treatment that does not follow the WEEE regulation. Another activity that is taking place and hindering effective WEEE collection and treatment are illegal exports out of Europe. The WEEE is collected within Europe and then sent under the pretence of secondary use to other countries. In these countries, often within Africa, the waste is treated in an improper but very cheap way, greatly harming the people carrying out the treatment and the local environment (Schluep et al., 2011; Umweltbundesamt, 2019).

2.2.2 WEEE is damaged during the transport

Due to inadequate methods of transport, a significant number of discarded products get damaged, making the following treatment more difficult, expensive, or even impossible. Our interviewees told us that in their experience, roughly one-third of the screens that the primary treatment facilities receive are damaged in a way that makes it impossible to dismantle them manually. Instead, they have to shred them using highly specialised tools, which is more expensive and does not yield the same pure ABS fraction that is obtained when the screens are dismantled manually.

This problem exists due to poor regulation concerning the collection and subsequent transportation. The WEEE is usually collected in large containers, which is then loaded onto a truck. During handling and transportation, the products can easily be damaged. Neither the collection points nor the transportation companies have any incentives to deliver the WEEE undamaged to the primary treatment facility.

2.2.3 MORE PRODUCTS CONTAIN BATTERIES

More and more products designed and marketed today contain batteries. It is often not apparent from the outside that a product includes batteries or where the batteries inside the product are located. If the batteries are not removed, this causes difficulties for the next treatment steps. The dismantling facilities have to deal with the risk of explosion and fire when they shred products that might still contain batteries. The steps further downstream also suffer from this problem because they need to get rid of the hazardous substances that leak out when the batteries are shredded. To overcome this challenge, better communication between the manufacturers and the recyclers needs to be established (Ollion et al., 2020).

2.2.4 DISMANTLING IS DOMINATED BY LARGE UNIVERSAL SHREDDING FACILITIES

At the moment, large (car) shredding facilities treat a lot of the WEEE. These are large plants that can dismantle vast volumes of various product types and materials in a short time. This allows the plants to operate cost-efficiently if they have a high throughput. WEEE treatment on these large shredders, however, poses two significant challenges: first, the plants treat a lot of other products in addition to WEEE, like cars or furniture. This leads to cross-contamination of the material recovered from WEEE with other materials like wood. This contamination is a major challenge for the treatment steps further downstream. During material purification, the contamination has to be removed in a costly process to produce high-quality secondary material. Second, the large equipment in the expansive shredding facilities is not dedicated to WEEE treatment. The method used for dismantling like metal hammers turns part of the material to dust instead of dismantling it gently, which would allow recovery. For this reason, recovery rates are often not optimal because part of the plastics and other non-metal materials get lost during the process and can only partly be recovered (further explanation see 2.2.5). If the dismantling step were optimised, e.g. by treating WEEE separately with dedicated equipment, the quality and quantity of the recovered material could be improved (see 2.3.4)

2.2.5 METAL IS THE MAIN TARGET MATERIAL IN WEEE RECYCLING

Currently, the primary target material in WEEE recycling is metal scrap, as well as precious metals. Thus, sorting and material recovery processes gear towards recovering the maximum amount of metal. The predominant role of metal recovery is mostly due to the historical development of the WEEE. The metal used to be and still is more valuable than the plastics fraction. Also, metal recycling has been carried out for much longer than plastics recycling, which just started to develop during the last 20 years. Material recovery operations at many plants are therefore geared towards metal recovery. This is often carried out using multiple recovery steps. With every extra sorting step that is taken for the non-metal fractions, non-metal material is lost due to wrongful separation (e.g. of adhesive material or material turned into dust during dismantling). The non-metal fraction coming from these plants often need to be incinerated because further treatment is no longer economically feasible.

Currently, three trends make a more holistic approach towards the recovery of all materials in WEEE interesting. First, the plastics content in the products is steadily rising, meaning that it is becoming more interesting to target this material and more costly to incinerate the growing portion. Second, plastics recycling technology is improving, which results in better quality and higher prices for secondary raw materials. Third, the rising recycling quotas for WEEE can no longer be reached if only the metals are recovered from the waste.

2.2.6 TIME LAG OF RETURN OF END-OF-LIFE PRODUCTS

Another challenge in WEEE recycling is the time-lag between the production of the products and their recycling. This time-lag differs between the product groups. A study of the usage time of different EEE in Germany found the average usage time of a laptop to be five years, while the average usage period of a fridge is 16 years (Prakash et al., 2016). These numbers, however, only indicate the averages. Thus, there are fridges already discarded after four years, while some will not be returned after more than 25 years. This is a challenge for WEEE recycling because the different times of return combined with the vast portfolios of the manufacturers result in an enormous variety of products being returned at any point in time. This also means that many of the returned products were produced a long time ago, and in most cases, there is little to no information about the products available. Current labelling standards, for example, might not have been in place yet, leading to difficulties when trying to identify the (hazardous) contents of the product. At the same time, any legislation that is put into place now or improvements in the design of the products for recycling will only take effect in a few years.

An especial challenge is the time lag for plastics recycling. The legislation on hazardous substances is continuously adapted by the EU, introducing stricter thresholds for different substances. If the plastics from a TV-set from 20 years ago are recycled today, it cannot be used as a secondary raw material in a new TV because the hazardous substances would exceed the threshold in the REACH directive. Another challenge resulting from this is the uncertainty for recyclers. The constant changes in legislation create an environment of uncertainty for the actors in the industry. The recyclers are less willing to invest in new technology which can treat WEEE following current legislation. If the legislation is changed again in one or two years, the technology might not be sufficient anymore. For this reason, especially small and medium-sized recyclers are hesitant to invest in new technology when the investment depends on the legal consistency.

2.2.7 PRODUCERS ARE HESITANT TO USE PLASTICS SECONDARY RAW MATERIAL

Manufacturers of EEE are currently hesitant to use plastic secondary raw material from WEEE for reasons linked to quality, quantity, price, and the risk of hazardous substances. Various manufacturers told us during the interviews that the quality of the recycled material which they can procure is worse than that of the virgin plastics. At the same time, they stated that the price of recycled material is often higher than the price of virgin plastics. Additionally, they told us that it is hard to procure plastics with sufficient batch sizes. There is also the risk of variation in quality between the different batches. The batch size is essential because every batch has to be tested individually for quality and hazardous substances. Thus, small batches become more expensive because of the higher testing costs per ton of material. Manufacturers also state that they usually need to work together with recyclers for a long period until the recyclers can provide them with a material that fulfils their specifications. This contrasts their usual relationship with the suppliers of virgin materials, where they simply order a certain quality from the product portfolio. The most pressing concern for the manufacturers we talked to, however, was the contamination of the secondary raw material with hazardous substances. All of them are concerned that the recycled plastics contain hazardous substances when they are used in their products, making them as the manufacturer liable to lawsuits and bad press. Some manufacturers stated that a lot of trust in the processes and a lot of testing is necessary until they are confident enough to use recycled plastics from WEEE in their final products. One manufacturer, however, stated that they do not trust the current system of WEEE recycling at all and that they are not thinking about using recycled plastics from WEEE due to the fear of contamination with hazardous substances.

2.3 Best practices

In this chapter, we highlight best practices related to the logistics and management of the WEEE reverse cycle. We indicate which steps of the reverse cycle are influenced by this best practice, followed by a short description. The examples given result from the analysis of our sample and data set and are not exhaustive.

2.3.1 Making the WEEE disposal more convenient for the consumer

Different EPR schemes are implementing improved collection processes to make the return of used EEE more comfortable for the consumer. WEEE NL, for example, is running a pilot that allows consumers to hand in small EEE free of charge and without pre-registration to the postman whenever a package is delivered to their door (WEEE Netherlands, 2018). This makes it easier for the consumer to discard the WEEE correctly and not hoard it at home. EPR schemes we talked to stated that they are also testing or have implemented collection containers in the streets or stores. The collection in the streets is more comfortable to access for the consumer and the waste management companies. However, such open collection points are prone to theft.

2.3.2 Reducing the input variety of the waste stream

One significant challenge for plastics recycling in WEEE is the great variety of plastics in the waste stream. Similar properties like the same density of different plastics depending on the used additives make it very hard to separate them. During the interviews and the review, we identified three best practices that help to make the sorting of the plastics easier. These three best practices reduce variation in the input, which results in fewer different plastics in the resulting waste stream. First, manual dismantling, as found in the dismantling of screens, results in a very clean plastics fraction, which can be treated rather easily. The result is a very clean ABS secondary raw material that many manufacturers are interested in. Second, small and clearly defined sub-streams also allow for high-quality recycling. Due to the necessity to treat all the cooling appliances manually, they are separated at the primary treatment facility. This sub-stream is also treated separately in the following steps, yielding a very clean and high-quality plastic fraction from the inside of freezers and fridges. Third, closed-loop recycling is another way to reduce the variation in material sub-streams. Philips, for example, with its partners Veolia and Coolrec, collects and recycles its own vacuum cleaners to use the plastics for the production of a new series of vacuum cleaners (Philips, 2017). Thus, the OEM has a good knowledge of the input fraction and knows what to expect from the output.

Smaller sub-streams lead to less variance of materials that have similar mechanical properties. An example are different polymers with a similar density that are used in different applications. After being shredded into small pieces they are hard to separate by techniques like flotation. If the applications, however, are kept separate before shredding when they are still easy to identify visually prevents a mixture of the plastics. This makes the identification of the polymers much easier after shredding. Therefore, limiting the variation of materials by reducing the input into the sub-streams ensures a higher quality of the output material, especially in plastics recycling. However, the downside of these practices is higher processing cost due to high cost for manual labour or sensor-based equipment, increased number of transports, and separate collection.

2.3.3 Standardised waste fractions in scrap

For steel recycling, steel scrap specifications exist. These standards are used to communicate the quality of the batches, which are set by the European Ferrous Recovery and Recycling Federation. Having a set of standards to refer to makes it easier for the companies producing and using the fractions. Company A knows that it can produce certain material classes that will be demanded by other companies when planning their production. Company B also knows that there are certain material classes available that it can procure when designing its products. It is, however, necessary that these standards are used by a wide range of companies in the industry to obtain network effects. These effects will only be reached if the defined standards are establishing useful properties of the materials. They are only useful if the standards can be fulfilled by Company A supplying the material fraction so that there is a reasonable supply of this standardised material at a reasonable price. However, the standard also needs to be strict enough that the resulting material is useful for Company B buying the fraction. Similar standards are currently missing in the plastics recycling industry. However, there are efforts to establish such standards by the European Plastics Alliance.

2.3.4 Use of equipment specifically designed for the waste stream

When using large dismantling equipment to disintegrate the WEEE, this causes multiple difficulties (see 2.2.4). The French recycling company Paprec is using equipment specifically designed for the disintegration of small household appliances. "The smasher" from Paprec dismantles WEEE by putting it into a large turning drum (like a large washing machine). Instead of being smashed by metal blades, the force of other equipment crushing into it disintegrates the equipment. This is a gentler disintegration process that allows for a higher recovery rate because less material is disintegrated beyond recovery. There is also less contamination of the output because the machine is only used for IT and small household appliances (Paprec, n.d.).

2.3.5 Vertical integration and collaboration along the supply chain

To be able to supply the manufacturers with a recycled plastic grade which matches their expectations, a close collaboration along the supply chain is necessary. This means that the individual companies need to have elite knowledge about the specifications of the secondary raw material as well as about the treatment process of their supply chain partners. Only then can they know how to fine-tune their output so that the actors downstream can achieve the best results. Our interview partners told us that today, all recyclers need to have good compounding skills to prepare a product from WEEE, which can be used in WEEE again. This does not necessarily mean that this knowledge is possessed by a person inside the company. Close collaboration and input from another supply chain member are also sufficient. There are also several companies like MGG recycling which have all the processing steps of WEEE recycling in-house, which enables easy knowledge transfer among the different units.

The interviews have also shown that there is a need for manufacturing companies to demand recycled plastics. Only if they are actively approaching the compounders and ask for a high-quality plastic will they start to work on producing one. None of the experts from producing companies stated that they were able to procure a secondary raw material that was offered by a compounder that immediately fulfilled their requirements towards a high-quality plastic. Rather, it was the process of jointly developing the specifications and setting up the required supply chain to obtain the right material to match the desired specifications.

2.3.6 Planning for the use of recycled material in the design phase

Companies should plan to use recycled plastics during the design phase. Often, secondary raw materials, especially in plastics, have inferior material properties to virgin material. Thus, if a product is designed with virgin materials in mind, the substitution with recycled plastics might not be possible. Despite the worse properties of recycled plastics, designers can work with them if they are aware of the specifications during the design phase. Otherwise, they can specifically point out which requirements the material needs to fulfil. Many virgin materials used in the products are over-specified, which means that the specific material is bought to fulfil a particular set of properties. However, the same material also comes with other high-quality "features," which would not be necessary for this specific application. If the recycler knows exactly which specification is needed to fulfil to fit the needs of the product, it is easier than just trying to match the specification of a virgin grade.

3 Plastics packaging reverse cycle

Plastics packaging is currently the second most used packaging material after paper. Especially in food packaging, it is in high demand due to its many favourable properties. Plastics packaging is flexible and adaptable to allow the brand owners to customise it according to their needs. It is lightweight, which reduces the logistics cost and the storage space needed. It protects the product inside very well, thus enabling outstanding increases in the shelf life of food and beverages over the last decades. At the same time, it is very cheap and easy to use for any kind of company irrespective of their size.

In 2018, the European packaging industry used 20.5 Mt of plastics in the production of packaging material. In the same year, 17.8 Mt of plastic packaging material was collected (Plastics Europe, 2019). Many different applications can use plastics packaging. Most commonly, it is used for protecting consumer products in the form of food packaging, shampoo bottles, or packaging for other products used every day. Plastics packaging is also used in a commercial setting, e.g. as protection when goods are transported from one company to the next.

The current recycling rate of plastics packaging is 42% in the EU, on average. In 2005, it was only 26%. The differences between the member states, however, are large. While Malta only recycles 24%, Lithuania is already recycling 74% of the packaging used. The waste framework directive by the EU sets rules on how municipal waste should be handled in the EU. The directive was first introduced in 2008 and requires a separate collection of plastics packaging in all EU member states by 2015. The amended version of the framework also sets the target of a minimum recycling rate of plastics packaging of 55% by 2030. This ambitious goal is currently only reached by five EU member states (Eurostat, 2019).

3.1 Treatment steps and actors

The following description of a plastics packaging reverse cycle captures the essential characteristics of the reverse cycle. Our analysis focuses on identifying best practices and challenges concerning reverse cycle logistics like network setup, design, and management of the supply chain. The implementation of every supply chain in the plastics packaging reverse cycle is different in some way. Nevertheless, the main activities described below are carried out.

The reverse cycle of plastics packaging follows the treatment steps described in Figure 1. However, for plastics packaging, there is no primary treatment, which is usually only carried out for products. Differences exist between the EU-member states regarding the implementation of the packaging directive. We base our description on the German system that has been adopted by several other countries (see case study 2).

3.1.1 Collection

The EU member states have translated the Packaging Directive differently into national legislation. The collection of plastic packaging waste is therefore handled differently depending on the country. Dubois et al. (2020) analyse the collection systems for different household waste streams. They show that the most common collection systems in the European capitals for plastic packaging waste are either door-to-door collection or require bringing to collection point schemes. Both systems are designed to be convenient for the consumer because the collection is taking place near the consumer. The waste is collected directly in front of the consumers' door or at a collection point within walking distance. Both systems are operated by waste management companies that pick-up the waste either within a regular interval (e.g. every one or two weeks) or whenever the container is full.

The collection systems also differ regarding the allowed content in the bins. The Netherlands and Germany have collection systems that have a broad allowance for different kinds of lightweight packaging, including all plastics and metal. On the other hand, Belgium's collection system only has a limited allowance. The bags only allow packaging waste from solid bottles used for water, soft drinks or shampoo, metal cans used for a drink or canned food as well as carton drink packaging. This system excludes any soft fraction like foils or plastics bags (Ragaert et al., 2017). Currently, an improved collection system is being rolled out over Belgium that allows the collection of more types of plastics waste. It will be in operation for most of Belgium by 2021.

One other source of plastic packaging waste is deposit systems for drink bottles. Many European countries, such as Germany, Denmark, or Sweden, have these systems in place. Whenever a consumer is buying a plastics bottle made out of PET, she has to deposit a small amount of money (15-25 cents in Germany). Later, she can return the bottle to any shop selling them. Upon return, she gets her deposit back. There are two kinds of deposit systems. The Reuse-System uses sturdy bottles that are checked after the return and, if possible, cleaned and refilled. If they cannot be reused because they have been contaminated or damaged, they are recycled. In the Single-Use-System, the bottles are directly sent to recycling.

Another source of plastics packaging is post-industrial collection. All types of manufacturing companies, as well as retailers, use plastics packaging, e.g. corner protection or foils to protect goods during transport. These are also collected separately by the companies. In many European countries, the regulation for the collection of waste by companies is strict. They are obliged to collect multiple different waste fractions separately at their sites.

Kerbside collection is the most common collection method for packaging waste. Garbage trucks pick up the waste one by one at the different disposal points like bags or bins in front of the consumers' doors or public collection points in the street. Packaging waste is usually not very dense and contains a lot of air. Garbage trucks therefore have a hydraulic press that allows them to compress the waste to be able to fit more waste into the truck. The waste is then brought to the site of the local waste management company. From this site, the waste is transported to a sorting facility.

3.1.2 MATERIAL RECOVERY

At the waste treatment plant, the collected waste undergoes a series of sorting steps to recover valuable material and separate it from material that does not belong in the waste stream. The primary target materials for the sorting facilities are usually HDPE, PP, and PET in the solid fraction and LDPE in the foil fraction. If the collection system also contains metals, these are recovered, as well. For the sorting, different identification and separation steps are taken for the different types of target materials and contaminants in the waste stream. The sorting plants are, in many cases, fully automated, but also manual sorting is still applied in the facilities. There are thousands of these facilities all over Europe. Germany alone has 1121 sorting facilities (BDE et al., 2018).

The exact number and type of sorting and recovery steps are different for every facility. Thus, we will describe a typical plant layout, which includes all the main processing steps. The first step of the material recovery process is a sack opener. This machine rips open all the bags which are used by consumers to collect their packaging waste. The waste is then separated by size in a rotary sieve to harmonise the material stream. The small fraction (0-40 mm) is residue. The medium (40-120 mm) and large (120-22 mm) fractions are further processed in the facility. The next step is a wind sifter, which separates the foil and hard plastic fraction. While the foil fraction is already one “final” fraction, the hard-plastic fraction is treated further. The first step of the treatment of the hard-plastic fraction is the recovery of ferrous metal, using an overband magnet. Then, using optical sorting technology, drink cartons are separated. Non-ferrous metals like food cans made from tinplate are separated using an eddy-current separator. Finally, a ballistic separator again removes foils from the stream. The remaining stream is further separated by NIR technology. This equipment can detect the plastic used in the different pieces of packaging by analysing the IR-spectrum reflected by the object. The fractions mainly separated are HDPE, PP, PET.

Finally, the different plastics fractions press into bales for transport to the next processing step. At this point, in the reverse cycle, there are two options. One is to use the plastic fraction as it comes from the material recovery as a secondary raw material. These fractions are usually referred to as mixed plastics fractions because they still contain some impurities like plastics packaging made of different polymers. This kind of material is used as input for the production of garden furniture, outdoor flooring, or flower pots, for example (Ragaert et al., 2017). The other option is further purification to produce higher-quality secondary raw materials.

3.1.3 MATERIAL PURIFICATION

The purification of the material involves the steps of size reduction by shredding, washing, and further sorting. The shredding is usually the first step of the process used to reduce the size of the material further. The flakes are washed to remove contaminants like labels (e.g. made of paper), dirt, or glue by using a rotating drum washer with water. To remove organic waste stuck to the material, a second washing step using friction washing can be applied. Afterwards, the material can be sorted further, for example, using an optical colour sorter to obtain a recyclate of a specific colour, or flotation or x-ray sorting to purify the waste stream further.

3.1.4 SECONDARY RAW MATERIAL PRODUCTION

Depending on how the secondary raw material is used, the flakes coming from the material purification are directly used as input for the production process. They can also be regranulated again. The flakes are melted if they are regranulated, and this melt is filtered to remove further impurities like wood, rubber, and paper, which are still solid in the plastic melt. The melt is then extruded. During this process, further additives can be added to adjust the properties of the secondary raw material if necessary. Finally, the extruded material is cooled and pelletized into granulates. For further transportation, the secondary raw material is usually stored in big bags. This also allows a specific allocation of the individual big bags to a particular processing batch.

3.1.5 SECONDARY RAW MATERIAL USE

Numerous applications can use secondary raw material. Closed-loop applications include, for example, packaging of soap or cleaning products (see 3.3.3). The PET coming from the deposit system can even be used to make bottles again (see 3.3.2). There are also a lot of open-loop applications for the secondary raw material from plastics packaging — these range from outdoor furniture and flowerpots to the use of electronic equipment. In comparison to recycled plastics from WEEE, recycled plastics from packaging are free of any hazardous substances because they are usually food-grade plastics (even in non-food packaging).

3.1.6 MANAGEMENT

The management of the reverse cycle of plastics packaging is very different throughout the EU. In some countries, waste management companies are collecting waste and charge a fee to the consumer (e.g. as a "pay-as-you-throw" fee for every bag). In other countries, the management is carried out by an EPR. In case study 2, we describe the EPR *Grüner Punkt,* which is the oldest EPR scheme for packaging in Europe. The management of the reverse cycle of plastics packaging is very challenging because large volumes of waste have to be collected across the whole country. This results in many companies being active in the reverse cycle and also more local supply chains in comparison to WEEE recycling.

Case study: Grüner Punkt
(Packaging EPR, Germany)

In Germany, there are ten extended producer responsibility schemes for packaging. The German law on packaging (VerpackG) makes it obligatory for all packaging directed at private consumers to be part of an EPR scheme. *Duales System Deutschland (DSD)* is the oldest and most commonly known EPR scheme for packaging in Germany. Its trademark sign is the *Grüner Punkt* (Green Dot), which is used to label sales packaging. This sign indicates that the brand owner of the product is fulfilling its legal obligation according to the packaging law. There are over 25 *Grüner Punkt*-systems modelled after the German example all over Europe using the same sign to label the products. In Germany, it is no longer necessary to label the packaging as due to the VerpackG, all packaging of consumer products needs to be registered with one of the 10 EPR schemes. These EPR schemes, in turn, take care of the collection and treatment of the packaging waste.

Grüner Punkt is active as an EPR scheme for all consumer packaging. It is, therefore, responsible for the collection and recycling of light-weight packaging made from plastics, multi-layer material, aluminium, or tinplate, as well as packaging made from paper and glass.

The idea of the EPR implemented in the packaging law is to hold product manufacturers and retailers responsible for the packaging of the products they sell even after their end-of-life. The EPR schemes are taking over the responsibility of the product manufacturers. Fees finance an EPR scheme, which the manufacturers have to pay. These fees depend on the weight, the material, and the recyclability of the packaging they use. This incentivises the companies to make their packaging lighter and to optimise it for a material that is easier to recycle. The steering effect of the German packaging law can be explained using the example of a yoghurt cup. The average weight of a yoghurt cup has been reduced from 7,2 g in 1991 to 4,7 g in 2016.

Grüner Punkt is the link between manufacturers, retailers, waste management and the recycling industry, as well as consumers. It organises the collection, sorting and treatment of packaging waste. *Grüner Punkt* therefore has contracts with waste management companies all over Germany and coordinates the logistics necessary for the collection of waste in the municipalities. Due to the EPR, the collection costs are paid for by the manufacturers. The disposal of packaging waste is therefore free of charge for the consumers in Germany. Besides the collection management, *Grüner Punkt* also coordinates the treatment of the waste. They own and operate a treatment plant while they also have contracts with treatment plants all over Germany. After the waste has been processed, the EPR schemes are no longer responsible. Through contracts with the processing plants, they need to ensure that the recycling quotas set in the packaging law are met.

Today *Grüner Punkt* is vertically integrated into the reverse cycle of post-consumer packaging. The Duales System Holding GmbH & Co. KG is not only active as an EPR scheme but is itself or through its daughter companies active in most of the steps in the reverse cycle. *Grüner Punkt* also consults companies on how to design their products effectively for recycling. It offers national and international logistics services, including storage and the transportation of waste from one facility to the next. Additionally, DSD Deutschland is active in the processing of light-weight packaging waste, as well as the production, the research and the development of secondary raw material (see 3.3.3). Under its trademark *Systalen*, *Grüner Punkt* sells secondary raw material made from post-consumer packaging waste.

Further information: **www.gruener-punkt.de/en**
Sources: (Grüner Punkt, n.d., 2016)

3.2 Challenges

In this chapter, we highlight challenges related to the logistics and management of the plastics packaging reverse cycle. We indicate which steps of the reverse cycle are influenced by this challenge, followed by a short description. The examples given result from the analysis of our sample and data set and are not exhaustive.

3.2.1 Keep it clean from the start

One major problem in the recycling of post-consumer light-weight packaging is the contamination of the separate collection system of plastics or light-weight packaging. In Germany, the rate of wrong disposals in the light-weight packaging collection system is 30% in some regions, or sometimes even up to 60% (BVSE, 2020). These high rates of wrong disposals have two sides. On the one hand, people are intentionally putting non-packaging household waste in the bags or bins intended for light-weight packaging because the disposal of these is cheaper or even free of charge. On the other hand, people are wrongly discarding products because they do not understand how the system works. The systems usually only target packaging waste and no other plastics or metal components, which is often not known to the consumers. This leads to the disposal of complex plastic products in this waste stream, which cannot be appropriately treated but are also hard to separate automatically by the machines.

Therefore, the correct separation needs to be carried out by the public. However, many people do not gain any advantage from separating correctly because it is hard for waste management companies to incentivise or punish individuals based on their separation performance. The population needs to be repeatedly sensitised and informed about why waste separation is necessary and how to do it properly.

3.2.2 Low recyclability of packaging

Large amounts of packaging produced today cannot be recycled in existing recycling systems. Even though packaging material only has a short lifetime, a high percentage of packaging materials used today are not designed to be easily recyclable. The current design of the packaging is usually not optimised for recycling. Multi-layer packaging in the form of pouches, foils, or beverage bricks is especially hard to recycle. At the same time, multi-layer packaging is becoming increasingly popular due to its superior properties regarding flexibility as well as optics. As each of the different layers of the multi-layer packaging consists of another kind of material, they need to be separated first before they can be recycled appropriately. While it is possible to separate the different layers, e.g. by delamination or selective dissolution, this process is costly. As a result, most multi-layer packaging is sent to incineration (Kaiser et al., 2017).

Also, most of the other packaging used today is not designed to be recycled. The packaging therefore contains a mix of materials, such as different plastic types, paper wrappers, or labels. All these are contaminants that must be removed using complex processes to create a clean, high-quality secondary raw material.

3.3 Best practices

In this chapter, we highlight best practices related to the logistics and management of the plastics packaging reverse cycle. We indicate which steps of the reverse cycle are influenced by this best practice, followed by a short description. The examples given result from the analysis of our sample and data set and are not exhaustive.

3.3.1 Using the internet to improve bin collection operation

Modern information technology, like the Internet of Things, real-time data exchange, or mobile devices, are increasingly used to improve waste collection operations. They are the first indicators of how digitalisation could change the waste management industry. One example is the use of notifications via mobile devices to inform the waste management company to empty a full garbage container. Instead of having to call the company, the user can simply use an app on her mobile device. The waste disposal company accepts the order automatically and schedules it for the next suitable tour. The customer is notified of the scheduled date and after the container has been emptied (BDE et al., 2018).

Another example is the use of the Internet of Things to continually monitor the filling level of the container at all times. For example, Veolia has developed bins that are equipped with ultrasonic sensors that measure the level in the waste containers in real-time. This data is then transmitted to the site of the waste management company. Here, the data is used for the automatic route planning to empty the containers. This smart and environmentally friendly solution saves unnecessary journeys and thus reduces CO_2 emissions and disposal costs (BDE et al., 2018; Smartbin, n.d.; Veolia, n.d.-a).

3.3.2 PET bottle deposit system

The PET bottle deposit system is an example that shows nicely how the separation of PET into an individual waste stream has a positive effect on the whole PET reverse cycle. Due to the use of a deposit system, PET bottles are collected separately from other plastic packaging types in many European countries. Before entering the waste stream, every bottle is individually checked either by a person or a machine to make sure that it is part of the deposit system. Only if it is part of the deposit system, the deposit is paid back, and the bottle is allowed to enter the system. The recycler therefore knows the content of the waste stream to 100%. The collection at the store is fully separated from any other waste collection. This separation ensures that the waste is also collected free from contamination by organic material. Since only one type of packaging is targeted and no other material is allowed to enter the stream, the waste stream resulting from the deposit system is pure PET.

This highly defined waste stream is an excellent basis for the production of high-quality secondary raw material. For example, Veolia has developed a system that allows the production of two types of recyclate based bottles coming from the PET deposit system. The first recycling steps of this process include manual sorting, shredding, hot washing, flotation sorting, and wind sieving of the PET-bottles. The recyclate resulting from this process can be used for non-food applications. For the production of food-grade secondary raw material, further processing steps are necessary. Multiple cleaning steps using sodium hydroxide solution and vacuum cleaning are used to remove the surface of the pet flakes and with it any contamination and odour. After the material is dried, further sorting steps, including colour and LIBS separation, are used to remove any remaining impurities. The result of this process can be used in different countries for packaging of food, including PET-bottles, creating a closed-loop for plastics packaging. Every year, over 1 billion PET-bottles are processed in a plant in Rostock operated by Veolia. Using their process, PET recycling saves 83% of energy and 70% of CO_2 emissions compared to PET produced from virgin materials (EuRIC, 2020; Veolia, n.d.-b).

3.3.3 Closed-loop recycling of packaging waste

Werner and Mertz, a German manufacturer for cleaning, care, and conservation products, have been very active in the use of recycled materials in their products. In 2010, they were the first brand in the industry to use recycled PET for plastic packaging. The clear PET bottles they use for the packaging of cleaning products consist of 80% recycled PET bottles from the deposit system and 20% from recycled plastics from the light-weight packaging collection. To develop a process to recover the right material in the right colour from the post-consumer waste stream, Werner and Mertz is working closely together with the EPR scheme Grüner Punkt.

In 2016, they developed an HDPE bottle using only material from post-consumer light-weight packaging. To achieve this goal, they developed an improved colour separation targeting natural and white flakes. They also developed an optimised washing process and an additional decontamination step integrated into the process to obtain high-quality HDPE secondary raw material. This material is now 100% closed-loop because the packaging made from it will be put into the same collection system as the secondary raw material from which it was made.

In 2019, Werner and Mertz improved their process further. The company is now able to produce cosmetics packaging exclusively from post-consumer packaging waste. Two main barriers were producing a material that is safe to use from a medical perspective, and that is free of any smell. The producer of recycling equipment EREMA has developed an extruder system with the so-called ReFresher module designed to meet the challenges of processing plastic waste from post-consumer packaging waste. This process eliminates odours through a thermal-physical process. (Werner & Mertz, 2016, 2019)

3.3.4 Future-proof design of the sorting plant

The composition of the light-weight packaging waste stream is continuously changing due to innovation in the packaging industry as well as different consumer preferences. However, the recycling companies want to be sure that the equipment they are investing in today can be used for a long time. Equipment manufacturers therefore have to make sure that their equipment is also compatible with future waste streams with a different composition than that of the current waste streams.

Lobbe Holding in Germany operates one such future-proof light-weight packaging sorting plant. To be able to stay up to date, changes due to extensions in the types of packaging collected and new packaging materials are already taken into account in the process technology, and the plant can be quickly converted. The current system uses 15 NIR separators, which are individually programmable and adjustable, giving the system the flexibility to deal with changing input materials. Additionally, further sorting equipment can be easily added to the plant if necessary (BDE et al., 2018).

4 CONSTRUCTION AND DEMOLITION WASTE REVERSE CYCLE

Construction and demolition waste (C&DW) is the largest waste stream in the EU in terms of mass. In 2017, 374 million tonnes (excluding excavated soil) were generated. The amounts generated annually are relatively stable, and recovery rates are high. However, much of the recovered material is not used for the production of secondary raw material. Instead, it is used for backfilling operations and low-value recovery (e.g. as recycled aggregates in road construction). The 2008 Waste framework sets a 70% recovery target for construction and demolition waste by 2020. Most EU countries exceeded this target already in 2016. However, there is still significant potential to make the reverse cycle of construction and demolition waste even more circular and keep the materials in the loop as long as possible (EEA, 2020).

4.1 TREATMENT STEPS AND ACTORS

There are four main types of construction and demolition waste: soil excavation (topsoil, gravel, loose rocks), building debris (concrete, reinforced concrete, brick), road debris (asphalt, concrete pavement, sand), and construction waste (wood, metal, plastic, cable, glass, paper/cardboard). In this report, we focus on the recycling of building and road debris also called mineral debris because it is the largest fraction in the construction and demolition waste stream. The processing steps for building and road debris are very similar and are described in this chapter. In the description, we follow the reverse cycle steps laid out in Figure 1.

4.1.1 COLLECTION

The primary origin of mineral debris is the demolition of buildings and other infrastructure. Before demolition, the buildings need to be gutted to remove as much non-mineral material as possible, such as radiators, wallpapers, or wood panels. Then, the building is demolished. A first sorting of the waste is executed on-site by the excavators when loading the debris on trucks or containers. Depending on the size of the demolition site, the waste is transported to an external treatment facility, or it is treated on-site using mobile treatment plants. On-site treatment allows for direct reuse as recycled construction material at the same site. Additional sources of debris can be contractors and individuals who deliver their waste directly to the treatment plant as well as municipal collection points. At smaller construction sites, containers are provided by waste management companies, which are later picked up by the company in charge of recycling the waste material.

4.1.2 MATERIAL RECOVERY AND MATERIAL PURIFICATION

The first step at the treatment facility is the sifting of the debris. The larger debris parts are then dismantled using an impact crusher. The next treatment step is the removal of steel using an overband magnet. Iron is the primary contaminant in building debris as it is used, for example, as concrete reinforcement. Depending on the size of the target material, these steps of dismantling and removal of steel are repeated. Using a multidimensional sifting machine, the resulting pieces are sorted by grain size. To clean the resulting fraction, they are wind sifted to remove light material still contaminating the fractions like paper, wood, or plastics.

For further separation of impurities, different treatment steps might be used additionally, even though they are not as common. Among them are manual sorting by hand, float-sink separation to separate light materials (e.g. wood, paper, plastics) or washing to remove dispensable contaminants like soil. Since manual sorting is very expensive, it is often only used if a visual inspection of the truckload at the gate determines that there is a need for additional sorting.

4.1.3 PRODUCTION AND USE OF SECONDARY RAW MATERIAL

The recyclate coming from asphalt is used almost entirely in the production of new asphalt for road construction. The recyclate from building debris is used among other applications in base layers and frost protection layers in road construction, as well as backfill material. It can also be used as secondary raw material for concrete production. Concrete factories are especially interested in clean recyclate containing pre-dominantly concrete debris. Since the separation of different debris types is usually not carried out during the process, it means that the input material already has to be very clean and then treated separately from other batches.

4.1.4 Management

Construction and demolition waste is a highly localized business. It is heavy and voluminous material, which means that transportation costs to make up a significant part of the recycling cost. It is therefore an advantage if the distances between the demolition site, treatment plant, and construction site where the secondary raw material is used, are short. This also leads to the same companies having multiple smaller sides where the waste is treated instead of one larger one since this is the only way to cover a larger geographical region economically. Companies in the C&DW industry are often vertically integrated. They are active in the demolition of the infrastructure, as well as the treatment and distribution of recycled and non-recycled building materials.

4.2 Challenges

In this chapter, we highlight challenges related to the logistics and management of the construction and demolition waste reverse cycle. We indicate which steps of the reverse cycle are influenced by this challenge, followed by a short description. The examples given result from the analysis of our sample and data set and are not exhaustive.

4.2.1 Contamination of the material during the lifetime of the buildings

A risk with debris is contamination with hazardous substances, especially if it is coming from buildings. The contamination can enter the material during the lifetime of the building or the demolition process. Buildings have a very long life during which the material can be contaminated with many different hazardous substances. Even widely available liquids like petrol can severely contaminate the debris if it percolates into the concrete over a long time. This makes intensive testing of the infrastructure before demolition necessary. One possibility to obtain clean fractions from contaminated infrastructure is selective deconstruction, where the contaminated and clean parts of the building are demolished and collected separately. The second source of contamination can occur during the demolition process, for example when different materials like bricks contaminate a clean concrete fraction. A more critical issue is contamination with substances of concern, especially asbestos. It is essential to keep the different streams separate during demolition and storage, to avoid this kind of contamination. Careful planning of the demolition process is therefore necessary.

4.2.2 Dynamic supply and limited storage capacity

The reverse supply chain of demolition waste needs careful planning. The volumes that need to be transported in this waste stream are huge and heavy, making logistics costs an essential factor. If one part of the chain breaks down, the limited storage capacities are quickly used up. Additionally, the supply situation is continuously changing. On the other hand, there is a constant supply of material from various smaller construction and demolition sites. There are also larger sites that will lead to a spike in supply at a particular location. This material has to be processed and transported, but it also has to be sold quickly since storage capacity is limited. The material flows coming from larger demolition sites therefore need to be planned to avoid bottlenecks in transport, storage and processing.

4.3 Best practice

In this chapter, we highlight best practices related to the logistics and management of the construction and demolition waste reverse cycle. We indicate which steps of the reverse cycle are influenced by this best practice, followed by a short description. The examples given result from the analysis of our sample and data set and are not exhaustive.

4.3.1 Treatment of waste on-site using mobile equipment

For the treatment of high volumes of debris at large demolition sites, mobile treatment equipment can be used. This equipment offers the same basic treatment steps of crushing, sieving, and separating contaminants. The prepared secondary raw material can then be used directly at the site if a new infrastructure is built or it is transported directly to another location without first being sent to a treatment facility. Less transport is therefore required. Additionally, the material can be stored at the construction sites where there is often more room compared to the treatment site, which usually has only limited storage capacity.

4.3.2 Using secondary material in higher grade applications

If a clean recyclate from concrete debris is used as an additive in concrete production, its quality can be improved. In this way, even granulates that would otherwise have an inferior application can still be processed with high quality. The material is upgraded from the application in "sub-foundation" to "foundation" by adding cement to the crushed stone. This is a more sustainable application, better structural properties are assigned to the material, and space is freed up in the sub-foundation for the use of materials. It ultimately avoids the use of virgin materials higher up in the chain.

5 GLASS REVERSE CYCLE

The EU is the world's biggest producer of glass with a market share of around one-third of total world production. In 2018, a total amount of 35.4 million tonnes of glass was produced in the EU28 countries. The glass sector produces different types of glass. (i) The biggest fraction is container glass, which serves mainly as packaging material for food and beverages, but also flacons for perfumery, cosmetics, and pharmaceuticals. This stream accounts for 62% of the glass output in tonnage terms but about 54% in terms of value. Glass containers are produced in 162 manufacturing plants across Europe. (ii) The second group is flat glass mainly for the automotive industry, construction works, and windows. This accounts for about 30% in both tonnage and value. European flat glass is manufactured by seven companies in Europe, operating 50 plants in 12 countries. (iii) next to these big groups also domestic glass (tableware, cookware, and decorative items), special glass (heat-resistant glass, laboratory glassware extra thin glass for the electronics industry), and reinforced glass fibres are produced (Glass Alliance Europe, n.d.).

In 2017, 3.12 million tonnes of EU glass were exported out of the EU, with a value of 6.77 billion euro. A total volume of 4 million tonnes was imported into the EU, with a total value of 6 billion euro (Glass Alliance Europe, 2017).

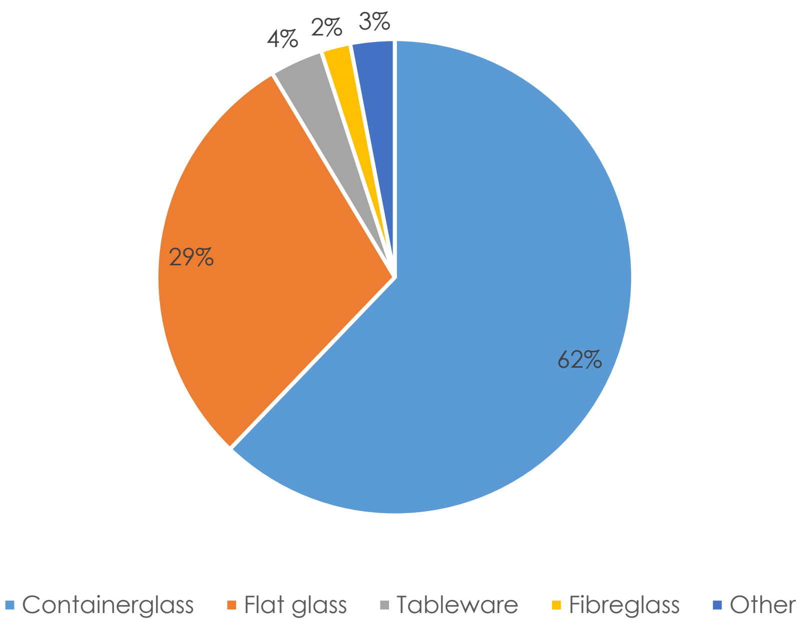

Figure 4: Market share of different glass types in EU 2018 (Glass Alliance Europe, 2019)

Due to these specific applications in numerous everyday products, the glass sector is interlinked with other sectors such as the food packaging industry, construction, automotive, appliances, and electronics. The EU glass industry is represented by large, EU-based companies. The production process is energy-intensive, and the manufacturers have to face high start-up costs and tied distribution channels. Production facilities are also capital intensive and require long investment cycles.

About 80% of the glass produced is traded within the EU. Data from industry show that the EU28 average recycling rate for glass packaging grew to a record rate of 76% in 2017. This makes glass the most recycled food and beverage packaging material. However, there is still a large spread in recycling rates across Europe. Countries such as Sweden, Belgium and Slovenia, which have efficient collection systems, perform best, and achieve recycling rates of more than 95%. Greece, Cyprus and Malta are the worst performers. Here, the recycling rates for container glass are sometimes even below 50%. This is particularly a consequence of the so-called collection gap in these countries, lack of government incentives, and the general economic framework. "Close the Glass Loop" is an industry platform to unite the glass collection and recycling value chain and to establish a material stewardship programme that will result in more bottle-to-bottle recycling. The European ambition is to reach a 90% average EU collection rate of used glass packaging by 2030, with a better quality of the recycled glass (FEVE, 2015).

For flat glass, the European recycling story is less straightforward. Most of the glazing from buildings could be dismantled and recycled in glass furnaces with no technical issues. Despite its recyclability, end-of-life building glass is almost never recycled into new glass products. Instead, it is very often crushed together with the other building materials and put into landfills or recovered together with other construction and demolition waste. This is facilitated by its inert characteristics. It currently has low market value because there is a lack of properly organised collection and recycling systems to generate what would be a valuable glass-making raw material. Some local solutions to enable recycling already exist. However, they remain experimental and very marginal (Glass for Europe, 2013). Also, broken windshields used to end up in landfills, but over the last decade, many companies have begun to recycle glass from the automotive sector (Thompson, 2016).

In 2012, End of Waste for glass cullet was established under Directive 2008/98/EC of the European Parliament and of the Council, determining when glass cullet ceases to be waste. The industry is regulated by the directives on emissions trading, industrial emissions, REACH, packaging and packaging waste, end-of-life vehicles, and restrictions on hazardous substances (European Commission, 2017).

5.1 TREATMENT STEPS AND ACTORS

The interviews were conducted with Flemish glass recyclers; therefore, the Belgian glass market is discussed in more detail next.

The Belgian glass sector consists of about ten glass production firms (flat glass, glass containers for pharmaceuticals and cosmetics and specialised commodities such as foam glass and glass wool insulation are produced) and 30 firms that specialise in processing the produced glass in various applications (Verbond van de Glasindustrie, 2019). Belgium (specifically Wallonia) is a major player in the European market for the production of new flat glass. It is a very concentrated market with some major European players. On the other hand, the market for the installation of windows is very fragmented with many small players, for example. There is also a competitive market for the collection of flat glass.

In 2019, the four glass sorting and recycling facilities in Belgium recycled more than half a million tonnes of hollow glass from Belgium and abroad (Geerts, 2019a). The collection of packaging glass for recycling in Belgium reached an impressive 96% in 2018 (FEVE, 2018). The Flemish glass recyclers are important players in the European market, also importing a lot (flat) glass cullet for further processing into secondary raw materials. Internal pre-consumer flat glass waste in Flanders amounts to approximately 43,000 tonnes. In addition, glass recyclers collect approximately 64,000 tonnes of Flemish waste flat glass, of which approximately two-thirds are pre-consumer flat glass and the remainder is post-consumer industrial glass and post-consumer glass from container parks. The Flemish container parks collect approximately 11,000 tonnes of flat glass waste selectively. The uncertainty about the unselectively collected quantity of plate glass, which is disposed of or used in low-grade applications, is high, but the estimation is 9,000-33,000 tonnes. About 1,000 tonnes of unselectively collected plate glass from container parks go to landfill or incineration. More and more flat glass is being used in buildings – through the use of triple glazing and more glass surfaces – this evolution has a delay in terms of an increase in waste flat glass. After all, flat glass has a long useful life in construction (approximately 35 years). Over the next two decades, a sharp increase in the amount of post-consumer flat glass is therefore expected (Maarten et al., 2013).

The glass waste stream predominantly consists of a single material, so all the treatment steps described in Figure 1 except primary treatment and material are required to process glass waste.

5.1.1 COLLECTION

Fost Plus is responsible for the promotion, coordination and financing of the selective collection, sorting, and recycling of household packaging waste in Belgium. Major waste companies, such as Renewi, Suez, and the inter-municipal waste collectors, organise the glass supply from waste to recycling in practice. Glass mainly comes in from the households after collection via glass collection bins or via door-to-door collection by the inter-municipal waste agencies. White and tinted glass is collected separately via the glass banks too. There used to be a distinction between green and brown tinted glass, but this separate collection was discontinued. White glass is recycled to white glass again, and tinted glass becomes green glass. There is no distinction between white and tinted glass in the door-to-door collection of glass. There is also a collection by the catering industry, but this makes up a relatively small share. Industrial flows (e.g.

from beer breweries) are also processed in the recycling plant that has to replace deposit bottles after 10-20 times of use. In contrast to individual bottles, the glass in itself is in principle infinitely reusable.

In the case of flat glass, the material comes from producers who put the glass on the market and have post-production waste. Often, these producers also collect the post-consumer glass when replacing windows in house renovation. Only the pre- and post-consumer glass is delivered; the profiles are already stripped. The flat glass material is preferably handed in as intact as possible. This has the advantage that the flow can be purified better, and the glass can be broken in a controlled way into certain sizes that are optimised for the recycling process. The flat glass of individual citizens is then collected through recycling centres or by specialised firms after the selective dismantling of old buildings. The car glass industry also has a direct collection of broken car windows.

The supply of the material to be recycled is fairly local in terms of input. For the interviewed companies, all supply is sourced in Belgium. There are some transfer stations to facilitate the supply by road to the recycling company. A car glass recycler is located in the proximity of car glass companies. Reverse logistics is already the standard in the car industry: when new windscreens are delivered, the emptied cargo is filled with the broken windows.

When arriving in the recycling plant, the quality of the input material is routinely checked by performing a straightforward visual inspection. There are clear acceptance criteria for the supplied material, and yearly audits are performed.

5.1.2 MATERIAL PURIFICATION

The first phase is manual processing. In the case of flat glass, the incoming material is broken down in a controlled way by shredders to reduce the particle size so it can fit into the sorting line. The incoming flow of glass is sorted according to its grain size and divided over different conveyor belts. A first manual sorting round is then carried out and larger contaminants are removed from the flow of glass. PET bottles, plastic bags, newspapers and magazines, ceramics, stone, porcelain, and other foreign domestic waste are carefully removed.

The second phase is a crushing process: A crusher is used to adjust the cullet size of the glass. A recent development is to dry the glass so that all food residues and organic matter can be removed more easily. Another advantage is that dry glass can be sieved more easily than wet glass, which is useful when the glass is separated into different size fractions. The next phase consists of removing all metals, ferrous as well as non-ferrous. Lids and caps are removed with magnets and eddy-currents. In-between the different phases of the process, lighter parts, such as paper and plastics, are separated from the glass in cyclones.

The final phase is the most complex: optical processing is applied to separate the glass into fractions based on the transmission of light. Different batteries of optical sorters remove ceramics, stone, and porcelain from the flow. This sorting uses digital cameras and compressed air valves. The cullet is subject to optical-mechanical colour separation, and the differently coloured cullet or contaminating materials are taken from the flow. This fully automated colour separation is merely a colour enhancement, not a full-colour separation of mixed-colour cullet. Collecting the different colours in separate fractions is still most efficient in terms of minimising residual flows and optimising the quality of the material. The process is constantly monitored online to ensure the high quality of the output material.

5.1.3 PRODUCTION SECONDARY RAW MATERIAL

After the recycling procedure for hollow glass, there is about 93% pure glass material (cullet), 2% ferrous and non-ferrous materials, 3% ceramics, stone and porcelain, and 2% of various waste. The purified cullet is sent to the glass factory and used for the production of new glass. The rest is contamination which is treated by other recycling facilities or incinerated. Lab tests are performed on the output material to ensure that European standards are met. There is also an annual audit for the End of Waste certificate. This certificate has become essential for glass manufacturers. For this purpose, the audit is carried out by an accredited audit organisation. The criteria are laid down in European Regulation 1179/2012 on the End of Waste certification of glass.

The quality requirements for (packaging) glass are strict. In addition to the standard quality evaluation by the recycler, glass manufacturers themselves also send samples for external inspection to specific analysis.

5.1.4 Use secondary raw material

The glass market is international in terms of sales of the recycled cullet. The interviewed Flemish companies stated that the largest volumes are exported to the Netherlands, Germany, and the United Kingdom, but certain quotas are even shipped to South America and the southern region of Europe.

In glass factories, the glass is molten and put in moulds. The recycled material must be very pure to have a completely molten glass stream. The presence of any contaminating materials, with higher melting points, form a quality and safety risk in the production of new glass.

5.1.5 Management

Fost Plus regulates the market of hollow glass by organising yearly tenders to sell the collected glass to the recycling firms. Depending on the market prices and the supply and demand, glass can also be sourced on the international glass market. Glass is mainly supplied by road, using tipping trailers. Discharge of the recycled material is carried out 50/50 by ship or truck, depending on the distance to be covered. The recycling firm acts as a buffer between the glass collection and production. There is a certain seasonality in the supply of glass during holidays and big sports events, although year-round supply is fairly steady and predictable.

5.2 Challenges

In this chapter, we highlight challenges related to the logistics and management of the glass reverse cycle. We indicate which steps of the reverse cycle are influenced by this challenge, followed by a short description. The examples given result from the analysis of our sample and data set and are not exhaustive.

5.2.1 Presence of film interlayer in flat glass

Flat glass (car windows, windows of office buildings) typically contains a film interlayer (PVB) to avoid breakage of this so-called safety glass. When flat glass is re-processed, the glass is first separated from the film by a huge crusher that breaks the glass so that the shards can be sieved out. The glass can be recycled. However, there is not a good operational solution available for the PVB film. There have been attempts to use the material in roofing or for the production of carpet underlay. Pyrolysis is also not ideal. In this process, the material is broken down again into the petroleum product, but this is not very profitable. Moreover, with the limited pyrolysis capacity, there is competition from plastics that would have a higher value in pyrolysis. PVB is a highly calorific material, but the energy balance of the incineration process is not easily controllable. This results in a high price to incinerate the material. The cement industry also accepts the material for considerable gate fees.

This results in the landfill of about 1 million tonnes of PVB per year in the EU. It is expected that this issue will gain importance over the next 10 to 15 years, as the flow of laminated glass is steadily increasing.

5.2.2 Contamination of the collected input material

In general, the quality of the hollow glass that is collected via glass bulbs is quite good. Because of the limited opening of the bulbs, it is hard to physically fit interfering materials. Certain streams that cannot be recycled are still collected systematically via bins. The selective sorting rule states that only packaging glass should be collected for recycling; however, people continue to wrongfully discharge kitchenware, porcelain, crystal, ovenproof dishes, and ceramics. Typical quantities of these contaminants can be handled by the recycling process scheme.

The quality of the collected flat glass is more an issue. More quality checks are therefore required when flat glass is recycled. The collection takes place in recycling parks where people can throw just about anything into the large, open containers of the flat glass like heat-resistant glass, e.g. from oven or stove windows or ceramics. These materials cannot be melted either and can be present in larger volumes. In particular, flat glass from dismantled buildings is also highly sensitive to the presence of stone. When unloading flat glass at the recycling plant, there is always an acceptor present for visual quality control. It is estimated that 80% of the heat-resistant glass is removed by the acceptor. There are also machines in the line that detect and remove the heat-resistant glass. However, there is a dangerous tendency with heat-resistant glass that is visually almost indistinguishable from regular glass.

The fine fraction of glass is also a challenge. From a certain size, the material can be sorted, but anything smaller than 3 mm cannot be optically organised. If everything is crushed to 1 mm, the contaminants (ceramics, stone, porcelain) will be processed with the glass. An additional disadvantage of working with highly fragmented material is the dusty character of the recycling process. This fine fraction typically goes to the glass wool industry.

5.2.3 COSTS OF PROCESSING OF RESIDUAL FLOWS AND LOW ENERGY PRICES

Glass recyclers buy collected glass volumes via tenders. A considerable amount of non-glass material can be present. Although the quality of the supplied material is described in contract specifications and checked, residual waste streams are systematically present. The recycling market, with the primary goal of processing glass, must remain competitive, including the costs of processing the residual flows. If the price of the recycled glass exceeds the achievable savings in natural resources and energy consumption for the glass producers, it reduces the chances of using recycled material. This can result in a higher demand for virgin material.

Taxes on landfilling and incineration force further innovation in the recycling industry by stimulating the maximal re-use of materials rather than disposal (e.g. landfilling). According to some companies, residual flows for which there is currently no technical recycling solution should not be taxed more heavily.

5.3 BEST PRACTICES

In this chapter, we highlight best practices related to the logistics and management of the glass reverse cycle. We indicate which steps of the reverse cycle are influenced by this best practice, followed by a short description. The examples given result from the analysis of our sample and data set and are not exhaustive.

5.3.1 THE GLASS INDUSTRY IS INHERENTLY SUSTAINABLE

Glass is an example of a resource that has unlimited recycling potential and can be recycled with virtually no loss of quality. Glass production processes are energy-intensive, and the industry aims to decrease its energy consumption. There is a high demand for shards from glass factories worldwide, mainly for energy-saving reasons: 10% shards deliver 2% energy savings. Accordingly, when using a 65% portion of glass cullet, the achieved reduction in energy consumption is 20%. Lower energy consumption also leads to reduced carbon dioxide (CO_2) emissions. Moreover, the production process of new glass is faster when the cullet is used than when virgin material is used (sand and soda). A green bottle can consist of 80% of recycled glass. These excellent recycling capacities can even further increase their popularity with consumers. This is different from the plastics market, where the use of recycled material is not standard practice, for example.

Glass recycling enables the hollow glass industry to dramatically reduce its environmental footprint by saving energy and raw materials, and it helps to maintain 125,000 stable and local jobs in the EU. Glass plants deliver more than half of their products within 300 km, and more than 70% of raw materials travel less than 300 km (FEVE, 2019). Recycled glass today is the most important ingredient in glass packaging for food and beverages.

5.3.2 SELECTIVE COLLECTION

Household glass is collected worldwide through the well-known bottle banks in collaboration with the national or regional systems and municipalities, depending on the geographical location. The anatomy of the collection banks is designed to optimise the quality of the collected material. Hollow container glass can be deposited, while larger contaminating materials or flat glass cannot physically fit in the banks. Several market research institutes predict high growth rates of glass collection of 7-8 % up to 2025. With a share of almost 50 %, Europe still dominates the market. However, in the leading countries such as Germany, France, Italy, Spain, and England, high growth rates are not expected. Prospects of strong market growth are particularly evident only in North America and in the emerging markets in Asia, South America, and Africa (Harder, 2018). A good example of this is South Africa, where over 41 % of glass is now recycled, and more than 4000 bottle banks have been installed for glass collection over the last decade.

A critical side note from the recyclers is that these bottle banks seem to be attracting litter. Innovations to avoid these include containers with camera control, sensor technology to report when the container is full so that it can be emptied more quickly. Also, the underground placement of banks is possible. However, this has the disadvantage that on the one hand glass breaks and therefore the shard can be sorted less on spec, and on the other hand possible contaminating flows (ceramics, porcelain) are also shattered, and therefore, more difficult to remove. As long as a certain ratio of above-ground to the underground collection is respected, there is no problem with quality. The sector is also investigating the reduction of breakage by using sliding plates or other mechanisms to improve the bin design.

Compared to the rest of the world, recycling rates in Europe are nonetheless very high, especially for hollow glass. Compared to Europe (EU28 average collection for recycling rate for glass packaging of 76% in 2017), the US glass-recycling (currently estimated to 33%) is remarkably small. The cause can be found in the processing, which is relatively inefficient compared to processing in Europe. US municipalities manage residential recycling primarily via single-stream kerbside collection, meaning that glass is mixed with aluminium and steel cans, various types of plastic, newsprint, junk mail, cardboard and other paper products. Selective (multi-stream) recycling, which is a far less common approach in the US, is simpler on the processing end as the selectively collected glass typically bypasses material recovery facilities and goes directly to cullet processors. Because of the difference in the quality of glass from the two streams, just 40% of glass from single-stream collection ends up recycled into new products, compared with about 90% of glass from selective collection.

Single stream collection is thus an inherently inefficient and expensive recycling method in terms of material recovery. But most municipalities in the US stick with single-stream because the collection costs are lower than those of multi-stream systems. These municipalities would need to introduce taxes or fees to meet the higher collection and handling costs and invest in consumer education to switch to multi-stream systems. Another significant difference between the US and European nations is country size. Distances in the US between a material recovery facility and a cullet supplier, or a cullet supplier and a buyer, tend to be greater. Transporting glass waste and cullet is costly because of the weight, and those costs can be a deal-breaker for some glassmakers, and prevent cullet suppliers from opening processing facilities.

Efforts to boost glass-recycling rates in the US have been state-driven and local affairs. For example, ten states have passed "bottle bills" that require consumers to pay deposits on beverage bottles. The idea is that consumers will more likely bring the bottles to recycling if they get back their deposits. The laws have the intended effect as 98% of bottles are recycled in those states, compared with the national average of roughly 33% (Jacoby, 2019).

5.3.3 INNOVATION IN RECYCLING TECHNOLOGY

Industrial glass recycling started in the late 1960s. Today, glass recycling takes place in the 4th generation of processing plants. Initially, purely mechanical processes were used, such as crushing and screening. Later, metal separation processes were added. Contaminants such as earthenware, stones, plastics, and organic materials were still sorted out manually. Optical glass sorting processes came onto the market in the late 1980s. Today, virtually all contaminants, such as heat-resistant glass ceramics or glasses containing lead oxide, can be sorted out with optical methods. Modern plants are now equipped with glass drying systems to fully exploit the sorting possibilities.

5.3.4 HIGH, UNIFORM QUALITY OF THE CULLET ACROSS EUROPE

There are no specific EN standards for the recycled glass, but there are ISO standards for the process with which the plants work. The processes are accredited and have resulted in a level playing field in the glass industry, making the quality very similar on a global scale. The glass that is processed in the recycling factory has obtained an end-of-waste status at EU level. This means that recycled glass ceases to be waste and obtains the status of secondary raw material in a well-specified legal framework.

The transparent quality in an international trade system has certainly encouraged glass recycling. However, this also comes with a risk. The main challenges include increased competition, downstream bargaining power, a lack of supply security, and non-EU country trade barriers.

6 PULP AND PAPER REVERSE CYCLE

The European paper industry produces more than 90 million tonnes of paper and cardboard and more than 36 million tonnes of pulp annually. About 750 companies are represented by the Confederation of European Paper Industries (CEPI), which operates 895 mills across Europe, accounting for 23% of the world production.

The pulp and paper manufacturing sector is energy and raw materials intensive. The industry has an excellent track record in resource efficiency and innovation. Thanks to its knowledge of wood fibre, the pulp and paper industry is at the forefront of developing innovative products alongside more traditional products. The paper and cardboard industry produces newsprint paper (about 7%), graphical paper (25%), case material (37%), other packaging material (17%), sanitary paper (9%), and other paper (CEPI, 2018).

Recycled paper is a major source of the paper industry's raw material, which is why the industry aims to maximise the European recycling rate. The recycling rate along the paper value chain reached 71.6% in 2018 - exceeding the voluntary target of 70% that was set by the industries' declaration in 2011. 92% of the raw materials used in the production and converting of paper and cardboard are sourced in Europe and certified as sustainable. The total amount of paper collected and sent to recycling in paper mills in 2015 was almost 56 million tonnes. 18.2% was exported for recycling in third countries in 2015. The recycling rate, defined as the ratio between used paper recycling (including net trade of paper for recycling), and paper and board consumption are now considered close to the maximum possible (EPRC, 2018).

6.1 TREATMENT STEPS AND ACTORS

The interviewed companies are located in Flanders but are part of major Belgian or European multinationals. In Belgium, six companies actively produce paper, and two more cardboard producers are members of Cobelpa, the federation of Belgian producers of pulp, paper, and cardboard (COBELPA, 2018).

The Belgian production of cardboard and paper accounted for more than 2.000 kilotons in 2017, of which 70% was graphical paper and 24% was intended for packaging. About 1.600 kilotons or 80% of the production was exported, against a total import of 3.500 kilotons. These numbers have been quite stable over the past decade (COBELPA, 2018). More than 1.200 kilotons of wastepaper are recycled in Belgium nowadays. And 60% of the paper fibres needed by Belgian paper mills come from wastepaper. This is five times more than 25 years ago.

The paper waste stream predominantly consists of a single material, so all the treatment steps described in Figure 1 except primary treatment and material are required to process paper waste.

6.1.1 COLLECTION

When it comes to paper collection, there are different systems in place in Europe. There are systems where paper and board are collected separately from other recyclable materials, i.e. in Belgium and Spain. There are even more sophisticated systems where there is a separation between graphic paper and packaging (Sweden, Switzerland). Almost any paper can be recycled, including used newspapers, cardboard, packaging, stationery, magazines, catalogues, greeting cards, and wrapping paper. It is important that paper is kept separate from other household waste, as the contaminated paper is not acceptable for recycling. There are an estimated 22% of paper products that cannot be collected or recycled, such as cigarette papers, wallpapers, and tissue papers. Some countries are not yet collecting paper and board. Here the risk is that it ends up as residual waste or in a landfill.

In Belgium, the total amount of collected wastepaper and cardboard amounts to about 1.700 kilotons each year (INDUFED, 2017). For the interviewed companies, the majority of the supply of input material comes from households, where the paper and cardboard are collected separately by intercommunal waste agencies. About a third of the material comes from specialised waste companies collecting waste at companies. A small portion of the input material is post-industrial waste from the paper industry itself. After collection, the wastepaper is sent to specialised recycling centres for sorting into different fractions according to quality. By sorting the paper into different fractions, the requirements of the papermaker that will use the recycled material can be considered. Depending on the quality, different applications are possible, such as packaging boxes or magazines. Standards describe the composition of the sorted material, which could consist of 40% of magazine paper. The fraction (or absence) of cardboard is also an important parameter. Any material that is not paper or cardboard is removed. The material is compressed to bales, wrapped in steel wires, and sent to the paper plants. In Flanders, sorted paper is supplied using trucks, and 70% of the wastepaper comes from within a 300 km action radius. However, when there is a local shortage of supply, the range can be extended to 700 km.

When the truck arrives at the paper mill, there is a visual check using a checklist. The moisture content of random samples is measured, and the type and quality of the paper are checked. The contact stipulates these properties.

6.1.2 MATERIAL PURIFICATION

The paper is mixed with water and becomes pulp. The wastepaper goes into the pulper and is screwed. The "paper tails" are removed with a screw, and large contaminating materials are removed, such as steel wires, sleeping bags, boots, and more. Then, step by step, the small contaminants are also removed by applying different methods to remove as many substances as possible (lacquer, staples, varnish, glue, plastic, and rope). This results in a "reject" stream consisting of small iron particles, polystyrene foam and a lot of other plastics. To produce certain types of paper, the pulp is deinked and bleached.

The residue stream from paper production called the non-pulpable fraction (e.g. plastic film, facial cream samples) can be valorised energetically locally to supply the steam and electricity that is required to produce paper. The ashes that are left after the burning process can be used in specific building and construction applications, by the end-of-waste regulation (e.g. replacement product for quicklime in stabilised soils, cement industry).

6.1.3 PRODUCTION SECONDARY RAW MATERIAL

The pulp is grated so that the cellulose fibres can adhere to each other better, and a homogenous fibre distribution is found on the sheet of paper. Before the pulp suspension goes to the paper machine, it is first stripped of all foreign particles and fibre clots. The fibre-water mixture now consists of more than 95% water. This mixture is then sieved, pressed, and dried. The drying of paper is a very energy-intensive process. The sheet of paper is continuously passed from one cylinder to another until its moisture content is about 6%.

The dried material is wrapped on large rolls, and these are cut down to the size required by the customer.

6.1.4 USE SECONDARY RAW MATERIAL

Paper is recycled at a rate of 71.9% in Europe (2018 data), which is the highest recycling rate for paper in the world. Paper-based packaging is even recycled at 84.6% (CEPI, 2018). Recycled paper is considered to be a valuable material that can be sourced locally (e.g. 70% of the recycled paper remains within the own group of the interviewed company) for the production of new paper or cardboard. About 30% goes to other factories but is still used as close as possible.

6.1.5 MANAGEMENT

The paper industry is driven by public tenders and is a relatively stable market in which contracts are negotiated. The sourcing of wastepaper and finding reliable suppliers are paramount to ensure a stable volume of the required input material.

6.2 CHALLENGES

In this chapter, we highlight challenges related to the logistics and management of the pulp and paper reverse cycle. We indicate which steps of the reverse cycle are influenced by this challenge, followed by a short description. The examples given result from the analysis of our sample and data set and are not exhaustive.

6.2.1 CONTINUOUS SUPPLY OF WASTEPAPER FOR A CONTINUOUS PROCESS

The interviewed companies process paper in a continuous process. It requires a constant supply and discharge of resources. The location of the companies in the densely populated region in Flanders makes it hard to create a strategic buffer capacity for the company. Contrary to what one might expect, wastepaper also has an "expiration date," as paper older than six months cannot be properly de-inked anymore. The just-in-time supply of wastepaper is a daily, practical challenge, in particular in terms of logistics, the number of truck transfers and delivery hours that comply with local regulations. The vision of one of the interviewed companies is to process the materials as locally as possible with minimal transportation to enable a sustainable, profitable paper industry.

The supply of paper is also confronted with challenges in the longer term. The graphic paper consumption in Europe continues to decrease due to digitalisation. This is counter-balanced by the growth in packaging and hygiene papers, which could be an opportunity for the industry. Switching to the production of a different type of paper product would require significant investments, however. At the same time, there is competition between using the paper for high-quality recycling purposes and using it as an energy source that could result in a distortion of the recycling market.

The sourcing of wastepaper and negotiating with suppliers remain key activities for a stable, continuous process.

6.2.2 PRICE FLUCTUATIONS ON AN INTERNATIONAL MARKET

The paper industry is driven by public tenders and is a relatively stable market, although the market prices of wastepaper have been fluctuating. In 2019, the prices of wastepaper collapsed further, mainly because China closed its borders for wastepaper, just as it did for plastics. Other Asian countries such as the Philippines, Malaysia, and Indonesia followed the Chinese example (Geerts, 2019b)

Only paper that meets very high standards can enter the Chinese market. But in a market that has been disrupted, it has become harder to sell wastepaper, even for regions that can deliver material of excellent quality. This has created an oversupply that has led to a drop in prices. This could even mean that the companies responsible for collecting and processing the wastepaper are no longer able to pay for the paper they collect. This puts pressure on the entire chain management of the paper industry, up to the level of the relation with the municipal authorities, who might even have to start paying for the service of collecting paper waste.

6.2.3 QUALITY OF THE COLLECTED MATERIAL

The quality of the collected material is essential to produce high-quality, recycled paper. Quality parameters include moisture content (wet paper is more difficult to handle in the supply chain), the proportion of non-pulpable material, and the yield. The presence of plastics is technically not a major problem, as the recycling process can handle non-pulpable material. However, the material has been paid for, it cannot be used for the production of new paper and costs are associated with its disposal. The yield describes how much of the input material can be effectively recycled for paper production and is determined by the age of the recycled paper, as the fibre can only be recycled for a limited number of times. This condition is very difficult to assess when sourcing wastepaper. Ordinary citizens also have no idea about the age of the fibre, so this is very difficult to impose when collecting the material. There is no easy way of checking this material characteristic. With the current recycling rate that we have in Europe, fibre is used 3.5 times on average. The presence of cardboard is also an important factor determining the yield. For the production process of paper, cardboard is a disruptive element as it causes stains in the recycled paper, which is a quality loss that is not acceptable for graphic paper. In fact, the presence of cardboard in paper waste is a bigger problem than the presence of plastic for the production of new paper. This is not an issue for recycling paper for cardboard production.

6.3 Best Practices

In this chapter, we highlight best practices related to the logistics and management of the pulp and paper reverse cycle. We indicate which steps of the reverse cycle are influenced by this best practice, followed by a short description. The examples given result from the analysis of our sample and data set and are not exhaustive.

6.3.1 Standardised quality of outgoing material

CEPI (Confederation of European paper industries) standards determine the quality per different type of paper in for characteristics like strength, moisture content, colour and water permeability. This standard also contains a reference to the ISO standard on how to analyse these values. The advantage of standards is that they provide a clear guideline and stand for quality. The standards are considered broadly on an international scale. However, there might be a small disadvantage if a company does much better than the standard. If it sets higher requirements and benchmarks itself voluntarily with the rest of the market, although it cannot distinguish itself through the standards. However, in the end, the customer will notice the difference in quality, and in the long run, there will still be an economic gain by doing better than the standard.

There are further certificates that can be obtained to differentiate the quality of the product of the process, such as a cradle to cradle certificate.

6.3.2 Green list of waste materials

Paper is on the green list of waste materials (Appendix III of the EU Regulation on Shipment of Waste). This green list includes all types of waste that do not pose any likely risk to the environment when shipped for recovery. Examples of such waste include scrap metal, wastepaper and untreated wood. Generally, these may be shipped from one OECD member state to another without a separate notification procedure.

The EU environmental, energy, and transport policies have a major influence on the future of the sector. A good regulatory framework is essential to supporting sustainable growth, investor certainty and a level playing field.

6.3.3 Energy recuperation for an energy-demanding process

With the general tendency of rising energy prices in Europe, this energy-intensive sector is at a global competitive disadvantage. However, thanks to the innovation of the industry, in particular on the improved process efficiency, the paper and pulp industry has become more energy self-sufficient and less CO_2-intensive by generating more than half of its primary energy from biomass. The energy recovery of the paper plants can even provide heat for the surrounding companies through heat networks.

Continuous technological improvements can further reduce environmental impacts and optimise the use of resources such as raw materials, water, and energy. New processes can offer innovative ways to develop new products and applications based on cellulose fibre that generates more added value. Breakthrough technologies, such as those reducing heat use in paper production through reduced water consumption, are needed to achieve the sector's objectives for the 2050 Roadmap towards a low-carbon bio-economy. These voluntary objectives include an 80% CO_2 reduction and a 50% value growth by 2050. The paper industry is turning the EU low-carbon bio-economy into an industrial reality (European Commission, 2016).

7 Summary and conclusion

7.1 Summary challenges

Table 1: Summary of challenges for reverse cycle logistics

Waste stream	Challenge	Collection	Primary treatment	Material recovery	Material purification	SRM production	SRM use	Management
WEEE	WEEE does not enter the correct reverse cycle	●						
	WEEE is damaged during the transport		●	●				
	More products contain batteries		●	●				
	Dismantling is dominated by large universal shredding facilities			●	●			●
	Metal is the main target material in WEEE recycling			●	●			●
	Time lag of return of end-of-life products				●		●	
	Producers are hesitant to use plastics secondary raw material						●	●
PPW	Keep it clean from the start	●						●
	Low recyclability of packaging			●	●			●
C& DW	Contamination of the material during the lifetime of the buildings	●			●		●	
	Dynamic supply and limited storage	●			●			●
Glass	Presence of film interlayer in flat glass				●			
	Contamination of the collected input material	●			●	●		
	Costs of processing of residual flows and low energy prices				●			
Pulp& paper	Continuous supply of wastepaper for a continuous process	●						●
	Price fluctuations on an international market	●			●	●		●
	Quality of the collected material	●			●	●	●	●

As part of our analysis, we identified several challenges for every reverse cycle (see Table 1). All of these challenges warrant collaboration as they can either only be solved by a joint effort of the whole reverse supply chain or affect multiple actors in the supply chain.

The first significant challenge that affects all reverse cycles are contaminations of the waste stream. In post-consumer streams targeting a specific material like glass, paper, or plastics packaging, the contamination is mostly due to foreign substances. These foreign substances either come from wrongly disposed waste like ceramics in the glass bin or from paper labels in the glass and plastics packaging waste stream. For complex packaging and products, another source of impurities is the mix of materials from which the products are made. These materials are added to the products to improve their functionality but require more complex recycling processes. To produce a high-quality secondary raw material, these substances need to be separated carefully. Finally, there is the risk of contamination with hazardous substances in WEEE and construction and demolition waste, which makes careful testing and handling of these waste streams necessary.

Another major challenge that is especially affecting the plastics reverse cycles is uncertainties, specifically concerning the legislation. Recyclers are hesitant to invest in new equipment because they do not know how the law about the allowed content of specific hazardous substances will change in the coming years. Any changes in the legislation could result in their current equipment not being sufficient anymore. At the same time, manufactures are hesitant to use high-quality secondary raw material because they do not trust the recyclers to deliver recycled plastics free of hazardous substances over a longer time period. This environment of legal uncertainty and mistrust by the manufacturers is not a sound basis for the further improvement of the plastics recycling processes.

Additionally, there is a lack of design for recycling. Currently, the manufacturers of polymer products do not cooperate with recycling companies; therefore, they design products in a way that is not beneficial for recycling. The products are difficult to disassemble and contain many different materials. Bringing together all actors in the reverse cycle to speak about design for recycling would lead to higher recycling rates and increased sustainability for products using plastic materials. For products that have a long life, the environmental footprint of the recycling activities might only be small compared to the footprint of the rest of their lifetime. For packaging material that is, in most cases, only used once and then discarded, design for recycling can significantly benefit its sustainability by making sure that the products stay in the loop.

7.2 Summary best practices

Table 2: Summary of best practices for reverse cycle logistics

Waste stream	Best practice	Collection	Primary treatment	Material recovery	Material purification	SRM production	SRM use	Management
WEEE	Making the WEEE disposal more convenient for the consumer	●						
	Reducing the input variety of the waste stream		●	●				●
	Standardised waste fractions in scrap			●	●	●		
	Use of equipment specifically designed for the waste stream			●	●			●
	Vertical integration and collaboration along the supply chain			●	●	●		●
PPW	Using the internet to improve bin collection	●						●
	PET bottle deposit system	●			●	●	●	●
	Closed-loop recycling of packaging waste				●	●	●	●
	Future-proof design of the sorting plant			●	●			●
C& DW	Treatment of waste on-site using mobile equipment	●		●	●	●		
	Using secondary material in higher grade					●	●	
Glass	The glass industry is inherently sustainable	●				●	●	
	Selective collection	●			●			
	Innovation in recycling technology	●			●	●		
	High, uniform quality of the cullet across Europe	●			●	●		
Pulp& paper	Standardised quality of outgoing material						●	●
	Green list of waste materials							●
	Energy recuperation for an energy-demanding process							●

We identified several best practices related to the logistics and supply chain that show how some of the current challenges can be overcome (see Table 2).

One best practice that we identified in different forms in all reverse cycles is a selective treatment of smaller sub-streams of a waste stream. This leads to smaller variations of the material mix. The treatment process (e.g. the dismantling) can therefore be adjusted carefully to the reduced number of materials in the waste stream. Additionally, it makes the material recovery and elimination of contamination much easier because there are fewer materials with similar mechanical properties. The most extreme example is the deposit system for PET bottles that exclusively collects one material, making the identification of the contaminants very simple because everything that is not PET is a pollutant. Also, the separate treatment of fridges is a good example because it reduces the number of plastics present in the waste stream, allowing for a much easier separation using, for example, flotation sorting.

Our best practices underline that often a joint effort of multiple actors in the supply chain is necessary to overcome the challenges. For example, the company Werner&Mertz closely cooperates with the German EPR scheme for plastics packaging and the material recovery and material purification companies to develop their new processes. Only after years of close cooperation were they able to filter out the right materials from the waste stream to produce a closed-loop plastics packaging solution for cosmetics and cleaning products. Neither the right plastics fraction nor the right equipment existed before they started to request this material. This also highlights how important it is that the manufacturing companies demand high-quality, recycled materials to further push the innovation process in the recycling industry.

For different materials, such as metals, construction material, glass, or paper, there are standardisations either for the materials used or the fraction resulting from the recycling process. These standards are an elite basis for communication among the different actors. They are also a support for the recyclers because they know which quality levels are demanded on the market, and which, therefore, they need to aim for during their recycling process. This kind of standardisation exists only partially for plastics. There are, however, different initiatives like the European Plastics Alliance which work on defining standards for the plastics industry.

The main takeaway from our analysis is that, in order to produce large volumes of high-quality secondary raw materials, it is essential to better link the individual treatment activities in the reverse cycles. Only if the different actors collaborate, and all the actors know what the requirements of the next treatment step are, can they produce high-quality secondary raw material fulfilling the specification of the manufacturer. However, there needs to be one actor responsible for the management of the supply chain. This management goes beyond the usual activities of EPR schemes, which mostly aim to fulfil the legislation. This management activity must instead start by talking to the customer interested in buying secondary raw material and then ensuring that every actor in the reverse cycle is aware of the quality they need to provide to fulfil the requirements of the customer. Only then can secondary raw material use become the new normal in product design – ultimately enabling a circular economy.

Within the CREAToR project, we are designing a comprehensive logistics concept that comprises the whole recycling process from collection to use of the secondary raw material. As part of the next tasks within the work package, we will investigate different sources of raw material and possibilities for the use of the secondary raw material. By exploring these possibilities, as well as testing and comparing different supply chain designs, we can give recommendations for the implementation of the CREAToR technology. In this way, we make sure that the processes yield high quality secondary raw materials in an adequate volume and price.

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