Towards a more circular economy for WEEE plastics - Part A: Development of innovative recycling strategies

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11 ABSTRACT:

12 This two paper series describes a method to develop and evaluate innovative recycling
13 strategies for WEEE plastics. Part A presents a SWOT analysis of a new dismantling based
14 recycling process of plastic components and the integration in an existing post-shredder
15 separation recycling facility. Subsequently, recycling strategies are developed and the
16 economic potential is evaluated. Part B investigates the technical feasibility of the recycling
17 strategies.

18 As a case study the dismantling of LCD TV plastic back cover housings is taken. First, the
19 advantages and disadvantages of the new process and the main external factors based on the
20 market for recycled plastics and the waste material input are discussed on industrial level.
21 Subsequently, five recycling strategies are developed: Strategy (1) produces recycled
22 granulates with the dismantling process for direct re-application in electronic products, strategy
23 (2) recycles plastics for the use as carrier materials for flame retardant masterbatches, strategy
24 (3) blends the recycled plastic with post-shredder recyclates for material upgrading, strategy
25 (4) recycles the plastics with the post-shredder process and strategy (5) thermally treats plastics.
26 Finally, the economic evaluation shows that the special engineering plastics used for LCD TV
27 back covers have very high virgin prices up to 5 € per kg. The implementation of the new
28 process indicates a significant potential for value recovery based on plastics that would
29 otherwise be incinerated or downcycled.

1. Introduction

1.1. *Waste Electrical and Electronic Equipment (WEEE) plastics*

Waste Electrical and Electronic Equipment (WEEE) is one of the fastest growing waste streams with approximately 44,7 million metric tonnes that were generated worldwide in 2016 (Baldé et al., 2017). Until today, WEEE recycling is challenged by a large mix of different materials, often containing hazardous substances such as lead, cadmium or some types of brominated (Br) Flame Retardants (FRs) that are today restricted (European Commission, 2003; Peeters et al., 2014). In contrast, WEEE recycling encompasses many opportunities to reduce environmental impacts, as well as generating economic value (Unger et al., 2017; Vanegas et al., 2017). It is estimated that the potential raw material value of WEEE plastics alone was 15 043 million euros in 2016 (Baldé et al., 2017). On average WEEE contains approximately 15-30 % of plastics in weight, where the plastic concentration changes strongly depending on the equipment category (Buekens and Yang, 2014; Menad et al., 1998; Nnorom and Osibanjo, 2008; Schlummer et al., 2006). Several processes and companies are involved in the WEEE value chain, which can be categorized in collection, pre-processing and end-processing (Chancerel et al., 2009). Main processes include size reduction by shredding and subsequent separation of the different materials, such as ferrous and non-ferrous metals, plastics, glass, wood and precious metals. The plastics fraction is treated by magnetic and Eddy-current separation to remove steel and aluminium, respectively (Buekens and Yang, 2014; Cui and Forssberg, 2003; Menad et al., 2013). Afterwards, different plastics are separated based on different physical or chemical properties. Examples for WEEE plastic separation processes are sink-float separation, froth flotation or electrostatic separation (Chagnes et al., 2016, Lungu, 2004; Peeters et al., 2014). In addition, spectroscopic sorting, such as Near InfraRed (NIR) and optical colour recognition sorters, allow to separate plastics by chemical structure and colour, respectively (Masoumi et al., 2012; Ragaert et al., 2017). These techniques are commonly used

for packaging waste plastics, however, plastics from WEEE are mostly black or grey, which limits the application of many techniques due to a strong absorption of the colouring pigments. After sorting, purification with classifiers and shifters, washing and drying may be used to remove dust, wood, films and other contaminations. In a final compounding step remaining impurities are removed by melt filtration and properties can be improved using additives (Buekens and Yang, 2014; Plastic Recyclers Europe, 2019; Wagner et al., 2018). However, WEEE plastics are still confronted with low recycling rates (Buekens and Yang, 2014; EERA, 2017). Today post-shredder approaches only target the most common plastics such as ABS, HIPS and PP, which are available in relatively large volumes. As WEEE plastics further consist of a large mix of often very special engineering plastics, new recycling strategies need to be developed to expand the recycling possibilities and produce a reliable supply of high quality recycled plastics.

1.1. *Innovative dismantling based recycling of plastic components*

One innovative approach to supplement the state of the art recycling of WEEE plastics is dismantling based recycling, which is characterized by a product based view on the End-of-Life (EoL) treatment. In contrast to post-shredder separation recycling, components of WEEE products are dismantled for improved material recycling, for the purpose of depollution if required by legislation or to harvest reusable components (Peeters et al., 2016). Several examples exist where partial dismantling is conducted for the purpose of depollution. Fridges requires the removal of the robust compressor, which could damage the shredder, and the removal of cooling fluids is needed for decontamination (Ardente et al., 2015). In addition, many electronic products, such as laptops or tables require dismantling to remove batteries that may cause fires in the shredding process. A separate treatment of cathode ray tube TV housings is common in Europe to safely treat the lead glass and potentially toxic phosphorescent layer (Salhofer et al., 2016). While years ago these TVs were considered a burden for recyclers,

today the dismantling of the plastic housings to harvest PWBs and components rich in copper allow the recyclers to run profitable dismantling operations. In addition, the dismantling of cables from WEEE is commonly performed for improved copper recovery. In previous research, it has been demonstrated that also the dismantling of Printed Wiring Boards (PWB) from LCD TVs before shredding can significantly improve the overall recycling efficiency for precious metals (Peeters et al., 2016, 2014; Vanegas et al., 2017).

Dismantling operations for plastic recycling are known for car bumpers to create closed-loop systems for the automotive industry (Coevert and Wiedemann, 2017). In addition, previous research has shown that the dismantling of plastic components before shredding results in a high quality of post-consumer plastics compared to post-shredder recycling. This performance can be explained by a higher purity as well as the focus on a dedicated plastic component reduces plastic grades with different properties that are applied in these components (Wagner et al., 2018). Moreover, several waste electronics that are separated for depollution, contain large plastics components or that are partly dismantled for PWB recovery or depollution are considered promising for dismantling based plastic recycling strategies. Examples are, inner linings and baskets of fridges, laptop and tablet housings or screen housings. There is an economic trade-off between the materials' values resulting from dismantling and the involved costs. On the one hand, dismantling and subsequent purifying can result in purer material fractions than post-shredder separation. This in turn can substantially increase the economic value of the separated output. On the other hand, the cost of the dismantling step needs to be compensated by the additional value recovered by increased value recovery (Duflou et al., 2008). The dismantling of End of Life (EoL) products, therefore, needs to be subject to an economic analysis to determine the optimal selective dismantling strategy, as the full dismantling is rarely the ideal solution (Duflou et al., 2008). Furthermore, it is necessary to properly integrate new dismantling based recycling approaches for plastic components in the

prevailing recycling operations and to assess possible new opportunities and challenges that arise in this context.

Therefore, this paper performs a SWOT analysis and develops novel recycling strategies for WEEE plastics. As a case study a dismantling based recycling process for plastic back cover housings of LCD TVs is taken due to available data and knowledge from several years of research. The SWOT analysis describes the targeted waste input, the market of recycled plastics and internal factors that consider the implementation of a new recycling process in a state of the art post-shredder recycling facility. Subsequently, a set of tailored recycling strategies is defined in order to maximise the economic and environmental viability of a dismantling based plastic recycling process and their potential to recover the economic value is evaluated. In part B of this two paper series, a dedicated way of processing for selected plastics is presented to test the technical feasibility of the defined recycling strategies.

2. Research Methodology

A Strengths Weaknesses Opportunities Threats (SWOT) analysis is a strategic planning instrument developed for business management to identify the external opportunities and threats and internal strengths and weaknesses of an organization and its environments. The SWOTs are most commonly displayed in form of a matrix that can be used to define strategies in order to make use of external opportunities or confront threats with the internal strengths and weaknesses (Chermack and Kasshanna, 2007). In prior research SWOT analyses have been applied to various research questions. Examples from recycling include industrial development of EoL vehicles (Zhang and Chen, 2013), municipal solid waste management in India (Srivastava et al., 2005), assessment of energy and climate policies (Fertel et al., 2013), analysis of environmental management practices in mining (Nikolaou and Evangelinos, 2010) and construction waste management decision making (Yuan, 2013).

External factors are defined using the five influencing factors of a business environment, namely economic, political/legal, social, environmental and technical factors (Rouse et al., 2008). The external factors describe the input material (plastic back cover housings from LCD TVs) and the market for the obtained plastic recyclates (reapplication in electrical or electronic equipment in Europe), while the internal factors describe the strengths and weaknesses of the dismantling-based recycling process in the context of a state of the art, post-shredder recycling facility. This context is necessary as WEEE is most commonly treated by post-shredder recycling processes and the complexity of the waste stream is expected to require a combination of different recycling approaches. Therefore, novel dismantling process will aim to add value to the existing recycling operations and be part of such a recycling facility. The internal and external factors are based on knowledge achieved during years of research which lead to the development of the process in close cooperation with industrial partners.

The dismantling based recycling process investigated in this SWOT analysis consists of a dismantling step, where the back covers of LCD TVs are removed. Subsequently, the plastic type and presence of FRs of every back cover is identified via a spectroscopic contact measurement by Laser Induced Breakdown Spectroscopy (LIBS) or a combination of Fourier Transform InfraRed spectroscopy (FTIR) and X-Ray Fluorescence (XRF). After the identification the back covers are sorted based on the identified plastic and FR type to one of the multiple outputs. The single material streams are further shredded and metal inserts, foams, PWB pieces and other impurities are removed in a two-step sink-float separation process. The density cuts are selected based on the density distribution of the targeted plastic (Peeters et al., 2014). Further fine shredding, washing and drying produces small plastic flakes of approximately 5 mm that can be directly introduced in a compounding process with melt filtration. This step allows the incorporation of additives to stabilize the recycled plastics and improve their properties as well as to remove remaining impurities from the molten polymer

with a metal mesh. The compounding process produces the final recycled plastic granulate, which is used in later processing (e.g. in injection moulding) to again produce plastic components.

3. Results of SWOT analysis

The SWOT analysis for the integration of the dismantling based recycling process for plastic housings from LCD TVs in a commercial post-shredder recycling facility for WEEE plastics is shown in Table 1.

3.1. Strengths

S1 High quality and supply of targeted plastics. The focus on high quality plastics that are used in LCD TV back covers combined with a high purity due to a good separation processes allows to recover high quality recycled plastics (Wagner et al., 2018). Often high gloss materials that contain P and Br FRs are used for this application, which allows an added value due to the recovery of flammability properties. Previous research has forecasted the LCD TV plastic composition to come to EoL treatment in Belgium (Peeters et al., 2015). Approximately 1000 tonnes of plastics from LCD TVs are expected annually until 2025 in Belgium alone, thus, showing sufficient and reliable supply for this process.

S2 Spectroscopic sorting with contact measurement. A significant advantage of the dismantling based recycling process lies in the sorting step. While post-shredder sorting requires high measurement speeds in the range of milliseconds, the sorting of larger plastic components allows measuring times in the range of seconds. The average mass of LCD TV back cover housings is approximately 1-3 kg (Peeters et al., 2015). Therefore the identification of the plastic and FR type can be more reliable by dedicating more time to the measurement or implementing contact measurements without sacrificing the throughput of the process. In

addition, a broader range of spectroscopic techniques can be applied (FTIR, Raman, LIBS, XRF, XRT, SSSP) can be used to determine the plastic and FR type.

S3 Increased flexibility by multi-output sorting. The sorting of the back covers can be a multi-output process where after the determination of the plastic type, the back covers can be directed towards multiple outputs. This allows the formation of flexible output streams where pure plastic fractions can be produced or plastic types can be mixed together if desired for material upgrading and volume increase. Multi-output sorting has the advantage that the components only need to pass through the sorting step once and no long chain of (binary) separation equipment is needed.

S4 Boundary conditions due to mercury depollution and PWB recovery. In dismantling-based recycling the purer recovery of materials competes against the low operational cost of post-shredder recycling (Langerak, 1997). Therefore, it is necessary to evaluate the disassembly time of EOL products to determine if they are suited for such approaches and the degree to which they need to be dismantled (Duflou et al., 2008). The presence of mercury containing backlight lamps in older generations of LCD TVs, cooling liquids in fridges or enclosed batteries in several electronic products require a separate treatment for depollution. The separation from other WEEE in combination with added economic value that can be recovered by dismantling of main PWBs results in favourable boundary conditions for a dismantling based recycling approach (European Commission, 2012; Peeters et al., 2013b).

3.2. Weaknesses

W1 Low target volumes. The focus on dedicated components in EoL products results in a low volume waste stream compared to post-shredder recycling. The amount of plastics from LCD TVs coming to EoL in Belgium alone are expected to increase to 1000 tonnes in 2025 (Peeters

et al., 2015). The treatment of other WEEE such as monitors, laptops or tablets in the described process would require additional technological development of the process.

W2 Mix of materials. The target of specific plastic components results in a mix of materials that is present. Around 12 % of plastics from WEEE contain FRs, that are added to improve the flammability properties of the material and are mostly bromine (Br) or Phosphor (P) based (Imai et al., 2003). A sampling trail in 2015 in Belgium for LCD TV back cover plastics resulted in a share of approximately 41 % of plastics containing P FRs, 14 % containing Br FRs and in 45 % no FRs could be detected (Wagner et al., 2018). Some Br FR types are restricted and need therefore to be removed during the recycling process (European Commission, 2011; Kemmlein et al., 2009; Peeters et al., 2014). Further, the compatibility of the different plastics needs to be considered in order to mix plastic streams if volumes are too low for a pure recovery (Tall, 2000; Vazquez and Barbosa, 2016). This is relevant as the mixing of incompatible plastics could result in a poor final quality.

W3 Higher complexity in recycling system. Manual dismantling can be very time consuming and requires the development of tailor made automated dismantling systems (Langerak, 1997; Peeters et al., 2012). In addition to the creation of new infrastructure also an increased complexity in logistics is expected. Storage of dismantled plastic housings to accumulate relevant amounts necessary for further processing might be required. As part of the treatment steps such as shredding, sink-float separation, washing, drying and compounding are commonly available at recycling facilities. Therefore, the dismantling based recycling strategies for plastic components need to be implemented in the existing post-shredder recycling infrastructure to become economically viable when only operated at limited capacity.

W4 Additional quality testing. The integration of dismantling based recycling in a post-shredder separation facility will require additional quality testing as new materials will be produced by

the recycling facility. In addition, the partial treatment of dismantled plastic components in post-shredder equipment poses the risk of additional contamination, if the equipment is not properly cleaned before every material change. Especially the mixing with other incompatible plastics can cause severe quality losses. Therefore, higher control measures will be required to guarantee a controlled mixing of different plastics.

3.3. Opportunities

O1 New markets for recycled plastics. The demand for plastics is growing every year with a current demand of 50 million tonnes in the EU in 2016, while the demand for recycled plastics is only 6 % (European Commission, 2018; Plastics Europe, 2018). The recycling of plastics with a high quality, reliability and sufficient volume could tackle the main reasons for this low demand (European Commission, 2018). Consequently, recycled plastics could be used in applications with high quality requirements such as visible components, which make up a large share in electronics that are today hardly targeted.

O2 Higher value and increased product portfolio. A high market value could be the result of a high quality and stable supply of recycled plastics. Additional value can be added by the recovery of additives and their functionality, such as FRs that are present in the plastics (Peeters et al., 2013a). Previous studies have shown that the mechanical recycling of plastics containing FR is possible for both P and Br plastics when targeting the right FRs with the suitable process (Peeters et al., 2014, 2012; Tange and Drohmann, 2004). Additional properties, such as high gloss or colour, could also increase the value as it avoids the use of additives or other surface treatment techniques. New plastics types that can be recycled as well as blending strategies allow to increase the product portfolio of recycle producers.

O3 Higher recycling targets and favourable political environment. The European Commission's strategy for plastics in a circular economy creates a favourable environment that

could drive the recycling of plastics by providing the necessary support to develop and implement novel dismantling based recycling processes. In addition, the ban of waste plastic imports to China may result in larger amounts of WEEE plastics that need to be treated in Europe (European Commission, 2018; Freytas-Tamura, 2018). The European Commission (European Commission, 2012) set recycling targets of 70 % for LCD TVs. The recycling of plastics that are today incinerated or landfilled needs to be addressed in order to reach this target (Plastics Europe, 2018).

O4 Enabling closed-loop recycling of plastic. Closed-loop recycling is a sustainable concept in which the recycled materials are kept in loop with no loss in properties and therefore an equal value. For plastics recycling, one example of a closed-loop recycling system is the recycling system for PET bottles into new bottles (Hopewell et al., 2009). Unfortunately, the recycling of most plastics still involves downgrading of properties and the application in lower value products (European Commission, 2018). The reapplication of the material in the same components or components with similar quality requirements could support the formation of new, long-term relationships between producers and recyclers. In addition, dedicated product based recycling processes can enable eco-design approaches that improve the recyclability of products and improve the performance of the entire product life cycle (Peeters et al., 2017).

O5 Lower incineration and landfill costs and improved environmental performance. In some European countries landfill bans are in place requiring the plastics to be incinerated or recycled (Plastics Europe, 2018). The incineration or landfilling of plastics that are not recycled often results in a cost for the recyclers, as the recovered energy does not cover the costs for operation and undergone treatment. Such costs strongly depend on the country and existing tax system and whether the plastics are considered hazardous or non-hazardous waste (e.g. plastics containing BR FRs) (European Commission, 2012; European Environment Agency, 2019). These avoided costs support the economic performance of mechanical recycling, which also

results in a significantly better environmental performance (Dodbiba et al., 2008; Wäger and Hischier, 2015).

3.4. Threats

T1 Economic issues of recycled plastics. Discussions with original equipment manufacturers and recycling companies indicated that one of the main drivers for the application of recycled plastics today is the lower price compared to virgin plastics. Accordingly, the virgin price, which is influenced by the oil price and subject to fluctuations, will influence the market price of recyclates (Hopewell et al., 2009). While this imposes a threat for low oil prices, high oil prices would be an opportunity for recycled plastics. The market value together with the cost of processing will determine the economic viability of the recycling operation (Hopewell et al., 2009).

T2 Compliance to changing legislation. One of the main challenges in recycling operations is the compliance to chemical restrictions such as RoHS and REACH (European Commission, 2003). In the recycling value chain the risk of contamination needs to be controlled by knowledge about the sources of contaminants, continuous quality control and measurements and according treatment decisions. While in a linear economy, restricted substances can be phased out by using substitute chemicals in the production, in a circular economy strategies need to be developed to identify the restricted substances when they come to End-of-Life. At this point the main challenge for recyclers is to generate relevant information about the presence of these substances, as it is not economically feasible to measure all restricted substances during the recycling process. Changing regulations can therefore create a threat if the recycling is not sufficiently considered (Römpf and Calster, 2018).

T3 Quality requirements for the application in components. For the application of recycled plastics in new components, a set of quality requirements needs to be fulfilled. Mechanical,

chemical or thermal properties, the material behaviour during processing, the ageing behaviour and the aesthetical appearance of the plastic surface are some examples. The requirements depend on the final application and are often defined by internal quality standards of the producers, mostly considering virgin plastics. Therefore, aspects such as a reduced colour freedom of recycled plastics are often not covered as producers aim for a direct exchange from virgin plastic to recycled plastics with no changes to the process, infrastructure or way of working. The final quality of recycled plastics is the result of a long chain of processes, including multiple companies across the value chain. Depending on their previous application and the adopted process, the recycled plastics may be partly degraded, contain impurities or low molecular compounds (Vilaplana and Karlsson, 2008). While actions can be taken during the recycling process and compounding to reduce deterioration and improve material properties (Vilaplana and Karlsson, 2008), this is not always technically or economically viable.

T4 Variation of input material and low collection rates. Fluctuations in waste input quality or quantity will influence the output of the recycling process, which results in the risk that no constant volumes or quality of recycled plastic can be produced. For dismantling-based recycling processes that target specific EoL products, knowledge about the expected lifetimes and resulting volumes that reach EoL every year are required. Also, possible changes in the plastics composition need to be taken into account. Methodologies presented in prior research allow the forecasting of this relevant data (Peeters et al., 2015). However, often only limited information about the materials applied in different electronic products is available. In addition, WEEE is subject to low collection rates with 35 % as an European average that significantly reduces the potential for value recovery (Baldé et al., 2017).

4. Discussion

4.1. Definition of recycling strategies for WEEE plastics

Based on the SWOT analysis five recycling strategies are developed, which are summarized in Table 2 along with the recycling category according to ASTM D5033, which categorizes recycling into primary – recycling without quality losses, secondary – downcycling into lower qualities, tertiary – recovery of chemical constituents and quaternary – recovery of energy (Hopewell et al., 2009). The strategies are described in detail with brackets in the text indicating which O or S is used and which T or W is confronted. The integration of the dismantling based recycling strategies for plastic components in the post-shredder process are displayed in Figure 1 as numbered connections between the process steps.

4.1.1. Dismantling based recycling of plastics for direct reapplication (1)

Dismantling-based recycling of plastics for direct reapplication (1) produces recycled plastics with added value quality criteria such as flame retardancy, mechanical properties, good aesthetical appearance to be applied in a component with equivalent properties (primary recycling). The plastic component (e.g. LCD TV back cover) is treated in the dedicated dismantling based process to produce recycled granulates without the addition of virgin additives. High quality plastic recyclates can be produced (S1) by targeting high quality plastics that are present in LCD TVs combined with a pure recovery. This is achieved as the risk of contamination is reduced in a dismantling based recycling process compared to post-shredder recycling where significantly more materials are mixed and processed. New markets for recycled plastics can be opened (O1) as long as the quality allows a direct replacement of virgin plastics in existing high quality components, no further market development will be necessary. In addition, improved aesthetical properties allow the application in visible plastic components (O2), which will significantly increase the application potential (Vlugter, 2017). In addition, an increased product portfolio can be achieved by recycling plastics that can fulfil flammability requirements without the addition of virgin additives (O2). Plastics that currently are incinerated can be targeted to increase recycling rates (O3) and avoid incineration and landfill

costs (O5). The focus on dedicated products or components (e.g. LCD TV back cover housings) supports the development of closed-loop systems (O4), where the recycled material is re-applied in the same component or components with similar requirements (Peeters et al., 2014; Vanegas et al., 2012; Wagner et al., 2018). Such systems would support a recycling-friendly material and product design, taking the EoL treatment into account. It requires a separate collection and allows component producers to regain their material. However, logistics are considered the main bottleneck for these take back approaches.

The high quality and recovery of flammability properties can make its price competitive with virgin plastics (T1). The cost of the process is additionally supported by the pre-sorting of LCD TVs, as they need to be separated from other WEEE for depollution in a dedicated process. In addition, dismantling of the back covers enables a purer recovery of PWBs and therefore added value by a purer precious metal recycling (Peeters et al., 2013b). Together with the high potential value of the plastics, very supportive boundary conditions are present to apply a selective dismantling strategy (S4). The identification of the plastic and FR type of every component via a contact measurement (S2) allows a good control on the input material, which strengthens the reliability of the output quality as well as the control of possible restricted chemicals (T2). For plastics from LCD TVs, the main possible contaminations to be controlled are mercury, cadmium and various Br FRs that can be present in the plastic (Buekens and Yang, 2014; Peeters et al., 2014). Br FRs can be detected by the LIBS measurement in the sorting process and separated from non-Br containing plastics. Mercury comes from the back lights and can therefore be avoided by dismantling based recycling of plastic housings. Possible cadmium application in plastic materials are special yellow, red and orange colour pigments (ECHA, 2013, 2012), which should not yield a risk for the mostly black back covers. Multiple outputs allow the sorting of several plastic streams and by accumulation of separated housings (S3) before further processing, both a change in input material and small or varying amounts

of plastics can be addressed (T4). The strategy requires intensive collaboration between recycler and client, which can in the long run lead to strong industrial partnerships. However, possible consequential costs also due to increased quality testing (W4) and more logistical activities and infrastructure (W3) need to be taken into account.

4.1.2.Dismantling based recycling of plastics for masterbatch carriers (2)

Dismantling based recycling of plastics for masterbatch carriers (2) aims for the recovery of valuable additives (e.g. FRs) present in the plastics by using the recycled plastic as a carrier matrix in a MasterBatch (MB). A MB is a polymer with a very high concentration of additives that is mixed with plastic granulates during production to integrate the additives in the final plastic component. MBs most commonly use virgin plastic and additives for carrier materials, which reduces the recycled content of a final plastic component as defined in EN 15343 by mass of recycled plastic in the total mass of product (W1). In addition, the recycled MBs can make it very easy for producers to use some recycled content in their products without changing to their process or main materials. Relatively low volumes of plastic waste containing high concentrations of valuable additives (O2) could be recycled and the final concentration of additives can be increased with virgin additives to produce an MB. This would allow to maintain the functionality of the recycled plastic (O4) and create new recycled materials (O1) that would otherwise be incinerated or landfilled (O3). In addition, the relatively limited amount of polymers needed to produce MBs compared to normal virgin granulate production, fits with the processing of smaller batches as is realistic for a dismantling based recycling process (W1). The flexibility of the multi-output dismantling process (S3) allows the recovery of additional material streams without a large extra cost, additionally a high value of additives, such as FRs can help the economic aspects (T1). However, also possible additional compounding activities or the purchase of virgin additives might result in additional costs that need to be considered. As MBs are used in relatively low concentrations in final products,

fulfilling the quality requirements of the final components will largely depend on the main polymer (T3). For the application for Br FRs a very reliable, RoHS and REACH compliant source is necessary. While the strategy to recover FR promises the most economic benefits, it could be applied to plastics rich in other additives (e.g. glass fibres, fillers, antioxidants,...). Losses or changes on functionality of the additives as well as possible differences in the processing properties and the possible filling degree need to be evaluated case by case (W4).

4.1.3. Blending with post-shredder plastic recyclates (3)

Blending with post-shredder plastic recyclates (3) uses the high quality of plastics recycled with the dismantling based recycling process and blends it in a controlled manner with post-shredder recycled plastics for material upgrading or to buffer quality flaws (O3). Mixing strategies are very common for virgin plastics in order to fine-tune properties and sell materials tailored for every application. The implementation of mixing strategies for recycled plastics allows to create a broader and more targeted product portfolio (O2). Mixing can be done before or during compounding and increases the overall quantity of recycled plastics. Thus, avoiding incineration by targeting plastics that are today not recycled due to low volumes or no market request (W1). If no new material grades are targeted this strategy can be used without the development of new markets for the recycled plastics (O1) as the material will be applied with the commercial stream. In addition, changes of the input material (T4) can be buffered and a higher control and stability of the output (O2) can be achieved. However, also for this strategy the compliance to legislation and the avoidance of restricted substances to enter the recycling streams need to be safeguarded (T2). In order to generate relevant amounts (W3) of recycled plastic it might be necessary to accumulate and store input material. Possible centralization to process LCD TV back covers from several recycling sites will, however, result in an additional logistical challenge and cost. A treatment of other EoL products with similar plastics present, such as monitors or laptops, will require further development of the dismantling systems. Also

accumulation of material until critical masses for further processing are reached will need storage space and therefore increase the processing cost. The compatibility of the plastics needs to be considered as blending incompatible plastics will lead to a loss in quality. In addition, blending always results in an increased complexity of substances that are contained in the final recycled plastics and long-term effects need to be estimated case by case. Additional testing will be necessary to assess the final properties and control the quality, which can be influenced by changing compositions of the two plastic types. Another possibility of a blending strategy is to make use of the multi-output sorting of the process (S3) and combine plastic types in the sorting step. This will increase the volume of the plastic stream (W1) and the materials can be further processed together if they are compatible.

4.1.4. Refeeding into the post-shredder recycling process (4)

Refeeding into the post-shredder recycling process (4) will allow to recycle materials using the established post-shredder recycling facility. This strategy can be used for plastics with insufficient volumes (W1) or if the added value does not justify the treatment by the dismantling based recycling process. It is only applicable to plastics that are already recycled today by post-shredder recycling (W3, T1). While also this strategy can be seen as a form of blending, it aims for the dilution of the plastics in a larger waste stream without influences on the quality (W4).

4.1.5. Thermal treatment (5)

In case no mechanical waste treatment strategy can be applied due to the presence of restricted substances (T2), insufficient input quality (T3, T4) or economic boundaries because of low volumes (T1) the thermal treatment or chemical recycling can be viable options. The thermal treatment in this paper is understood as the recovery of energy in cement kilns or disposal by controlled combustion, which can be necessary for the Br FRs to decompose as required (Tange

and Drohmann, 2005; Weber and Kuch, 2003). A possible alternative for the future could be the application of the Creasolv® process that has been shown to be able to remove Br FRs, while maintaining the quality of the polystyrene and copolymers including ABS and PC/ABS (Freegard et al., 2006; Schlummer et al., 2016).

4.2. Economic potential and evaluation of the developed recycling strategies

It is estimated that 399000 tonnes of LCD TVs will reach the End-of-Life in Europe in 2020 (Cucchiella et al., 2015; Salhofer et al., 2011) containing approximately 14 wt% of plastic back covers (Peeters et al., 2015). This targeted waste stream of plastic back covers from LCD TVs constitutes approximately 2,25 wt% of all WEEE plastics. Plastics used in these components are considered top quality grades of Acrylonitrile Butadiene Styrene terpolymers (ABS) and their blends with PolyMethylMehtAcrylate (PMMA) or PolyCarbonate (PC), as well as High Impact PolyStyrene (HIPS) and its blend with PolyPhenyleneEther (PPE) (Wagner et al., 2018). In Figure 2, the resulting masses expected to come to EoL in Europe are indicated as bubble sizes together with virgin prices of the targeted plastics. These special engineering blends have market prices up to 4 times higher compared to standard packaging polymers such as polyethylene, polypropylene and polyethylene terephthalate (1,2-1,3 €/kg). A significant price increase between FR containing plastics as well as blends is visible compared to non-FR copolymers ABS and HIPS. The total economic potential for all back cover plastics is an estimated 160 million € per year, not taking processing costs or losses during recycling into account. The economic potential was calculated as the average of virgin market prices multiplied by the volume of the plastic. Virgin prices were taken from the CES Edupak database, plasticnews.com and two plastic market data suppliers. Price information strongly depends on supply volumes, spot or contract purchases and market changes and therefore, significant price variations are expected. WEEE collection rates in Europe are approximately 35 % and will significantly influence the potential for value recovery (Baldé et al., 2017). The

dismantling of the back cover further enables the dismantling of the main PWB which can lead to an improved recovery with an estimated economic benefit of 420 € per tonne LCD TV (Peeters et al., 2013b), but this is not considered in this analysis. Today only ABS and HIPS without FRs are recycled by means of post-shredder recycling and the other plastics are incinerated with an estimated cost of 150 EUR per tonne. Hence, the recycling of these plastics only target a total economic potential of 30 mio €. The prices of plastics recyclates can be significantly lower than the prices of the virgin plastics, largely depending on their quality, supply volumes and reliability. Estimates of the potential of the 5 strategies to recover the value of the virgin price are indicated in Figure 2. The dotted lines between the different materials are only included for visibility of the strategies and do not represent any connection or tendencies between the different materials.

Dismantling based recycling of plastics for direct reapplication (1) recovers value added quality features such as flame retardancy, mechanical and aesthetical properties without downgrading and the addition of virgin material. It is expected to recover the most potential material value as the recycled plastic can directly replace virgin. 10 % in value loss compared to the virgin price is used for the calculation. The main causes for a reduced price are expected to be plastic or flame retardant degradation or due to mixes of different FRs that could reduce their functionality.

Dismantling based recycling of plastics for masterbatch carriers (2) can recover part of the value of the FRs or high value additives in the described plastics as the plastics are recycled and filled with additional virgin FR to form master batches that can be mixed in injection moulding with virgin or recycled materials to form flame retardant components. The value is estimated to be between the value of flame retarded and non-flame retarded plastic and to calculate the estimated potential value 90 % of the average value of the FR and non FR

containing virgin plastic is used. As strategy 1 can recover more value this strategy is the preferred solution for plastics with high value additives that are present in low volumes.

Blending with post-shredder plastic recyclates (3) uses the high quality of dismantling-based recycled plastics for material upgrading or buffering of quality flaws by controlled mixing with post-shredder recycled plastics. It is estimated to perform better than the post-shredder recycling Strategy 4 due to an improved quality of the material. As no flammability properties are recovered, the potential value of this strategy is oriented on the value of recycled HIPS, ABS and PC/ABS without FRs. The potential value was calculated with 70 % of the virgin price of the three plastics without FRs (e.g. HIPS/PPE with P FR recycled by this strategy could only achieve 70 % of the virgin value of HIPS without FR and without PPE). This strategy is therefore mainly beneficial to recover plastics that are not recycled today.

Refeeding into the post-shredder recycling process (4) produces a baseline quality without added value of FRs or special blend properties. However, for plastics such as ABS and HIPS that are recycled today in a post-shredder process, the added material value of a dismantling based approach cannot be justified. Therefore, the potential value of plastics recycled by this strategy is estimated to be 50 % of the virgin price of ABS or HIPS.

The *Thermal treatment (5)* of plastics is considered a cost for the recyclers should only be targeted for plastics that cannot be recovered by the other 4 strategies. Chemical recycling strategies that allow decontamination of restricted substances should be considered.

The costs of the dismantling based recycling process largely depend on the related investment costs for additional infrastructure and the operational costs, which is typically dominated by the labour costs of the dismantling and sorting process. Based on previous research by Jef Peeters et al. (Peeters et al., 2014), typical manual dismantling and sorting times including sample preparation and loading are estimated to be 2 min and 1 min, respectively. Assuming a purely manual dismantling and sorting scenario for a baseline, a labour cost of 25 €/h, 80%

dismantling productivity and an average back cover weight of 2,18 kg are assumed. The dismantling step would result in 478 €/tonne. The manual sorting with a handheld scanner would cost between 191 and 490 €/tonne, depending on whether all plastic types are valorized or whether in the worst case only the main stream of 39 % of PC/ABS is targeted. Further operational costs for subsequent treatment steps are expected to be 100 €/tonne for the density treatment, 150 €/tonne for the washing and drying, 350 €/tonne for the shredding and compounding and 50 €/tonne for semi-regular RoHS compliance testing. The operational costs in total were calculated to be between 1,3 and 1,6 €/kg. Partial automation of the dismantling and sorting process are expected to significantly reduce these costs. It is important to note that the economic evaluation needs to be considered in a larger context, as dismantling cost can also be allocated to the recovery of other materials, such as precious metals from the PWBs.

5. Conclusions

The described dismantling based recycling approach is defined by a product focus and the complexity of plastics found in the target component with relatively low volumes compared to other commercial operations raise economic and technical challenges. The developed set of recycling strategies was derived from a SWOT analysis and allows to support an improved mechanical recycling of the housing plastics that are characterized by a high economic value, up to 4 times higher than for packaging plastics. The dedicated treatment of special engineering plastics by *Dismantling based recycling of plastics for direct reapplication (1)* shows the highest potential to recover value added properties such as flammability and directly replace virgin plastics. For plastics present in low amounts strategies that aim for a controlled final mixing with other recycled or virgin plastics to improve the quality are a good alternative such as the (2) *Dismantling based recycling of plastics for masterbatch carriers* and (3) *Blending with post-shredder plastic recyclates*. Mixing of various plastic grades with the focus on high volumes by (4) *Refeeding into the post-shredder recycling process* is suitable for plastics of

relatively low value. The (5) *Thermal treatment* is expected to result in a cost for the recycler and is only suitable for plastics that cannot be recovered otherwise. Similar as for LCD TVs, for many other product categories significant economic and environmental benefits are expected by the implementation of the presented recycling strategies. Overall, the new recycling process offers clear advantages due to an increased flexibility and additional treatment options. High value special engineering plastics can be recycled that are otherwise incinerated or downcycled. However, present post-shredder separation recycling operations that target continuous and high throughput approaches need to be considered. Therefore, the technical feasibility of the strategies is analysed in part B of this two paper series.

There is a need for future research on the quality and supply chain management that allows to put the proposed recycling strategies in practice. New concepts considering the entire multi-actor supply chain are required in order to deliver a reliable supply of high quality recycled plastics.

6. Abbreviations

ABS-Acrylonitrile Butadiene Styrene

Br- Bromine/Brominated

EoL-End of Life

FTIR-Fourier Transform InfraRed

FR- Flame Retardant

HIPS-High Impact PolyStyrene

LCD TV-Liquid Crystal Display TeleVision

LIBS-Laser Induced Breakdown Spectrometry

MB- MasterBatch

P-Phosphor/Phosphorous

PC-PolyCarbonate

570 PMMA-PolyMehtylMethAcrylate
571 PPE-PolyPhenyleneEther
572 PWB-Printed Wiring Board
573 SWOT- Strength Weaknesses Opportunities Strengths
574 WEEE-Waste Electrical and Electronic Equipment
575 XRF-X-Ray Fluorescence

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Figure 1. Visualization of the dismantling based recycling integration options in a post-shredder recycling process.

Figure 2. Virgin price of targeted plastics and indicated potential for value recovery of the defined strategies.

Table 1. SWOT analysis of the dismantling based recycling process for LCD TV back cover housings

Strengths		Weaknesses	
S1	Targeting high quality plastics	W1	Low target volumes
S2	High quality spectroscopic sorting with contact measurement	W2	Mix of materials
S3	Increased flexibility by multi-output sorting	W3	Higher complexity in recycling systems
S4	Boundary conditions due to mercury depollution and PWB recovery	W4	Additional quality testing
Opportunities		Threats	
O1	New markets for recycled plastics	T1	Economic issues of recycled plastics
O2	Higher value and extended product portfolio	T2	Compliance to changing legislation
O3	Higher recycling targets and favourable political environment	T3	Quality requirements for the application in components
O4	Enabling closed loop recycling of plastics	T4	Variation of input material and low collection rates
O5	Lower incineration and landfill costs and improved environmental performance		

773 **Table 2. Overview of developed recycling strategies.**

	Recycling strategies:	Recycling category
1	Dismantling based recycling of plastics for direct reapplication	Primary
2	Dismantling based recycling of plastics as masterbatch carriers	Primary/Secondary
3	Blending with post-shredder plastic recyclates	Secondary
4	Refeeding in post-shredder recycling process	Secondary
5	Thermal treatment	Tertiary

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