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Improving Resource Efficiency through Recycling Modelling: A Case Study for LCD TVs

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Abstract

Nearly 20% of the global emissions and energy consumption originate from material extraction. In the last decade recycling has emerged as an ecologically sound solution to face material scarcity and to lower the environmental impact caused by material extraction and refining. Mainly due to the high labour costs, in industrialized countries automated material separation processes are nowadays commonly adopted for recycling complex products such as e-waste. In consequence, proper understanding on the performance of these automated separation processes and the overall efficiency of multi-stage recycling schemes is required for adequate investment planning. This article presents a set of modelling techniques and metrics to assist small and medium sized pre-treatment recycling companies, in the initial design phase of multi-stage recycling schemes, while minimizing the required input data. To illustrate this, the recycling of LCD TVs is analysed in detail as a case study.

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Keywords: Recycling; Automated Sorting; WEEE; LCD TVs.

1. Introduction

1.1. Relevance of recycling

Due to the growing concerns regarding our finite material reserves, traditional views on waste management have changed; more and more waste streams are regarded as valuable material sources [1]. Waste prevention and recycling play a primordial role in the European strategy towards a more resource efficient future [2]. Several laws and directives, such as the European Waste Electrical and Electronic Equipment (WEEE) Directive, regulate the End of Life (EoL) treatment of products and set minimum targets for collection and recycling. Recycling has the potential to reduce the Environmental Impact (EI) of mining and primary material production. For instance, manufacturing cans from virgin aluminium requires four times more energy than from scrap aluminium [3]. However, important to note that energy savings strongly depend on the material, the EoL source utilized and the applied recycling processes [4]. Moreover, recycling creates business opportunities through the recovery of valuable materials; it is estimated that between 1.2 and 1.5 million people are employed in the waste and recycling sector across the EU [5].

Unfortunately, increasing product complexity poses major challenges for recycling; Dahmus and Gutowski show that recycling rates are significantly affected by the level of material complexity of products [6]. One of the waste streams with the highest material complexity is WEEE, which contains more than 1000 different substances, of which many are hazardous and others have considerable market value [7, 8]. WEEE is also one of the fastest growing waste streams, with an estimated increase of roughly 11% between 2008 and 2014 in Europe [2].

Due to boundary conditions, which include legislation, high labour costs and markets for recyclates, in industrialized countries the EoL treatment of complex products like WEEE is mainly based on mechanical size reduction processes with a high throughput followed by automated sorting at pre-processing, and high-tech refining processes at end-processing [9]. These recycling schemes encompasses high recovery rates for specific fractions, such as iron and aluminium, but underperforms for other materials such as PMs [10], critical and rare earth elements [11], and specific plastics such as

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plastics containing Flame Retardants (FR) [12]. The main reasons for this poor performance are the technical limitations of mechanical size reduction and automated sorting processes, which are characterized by imperfect material liberation and separation, resulting in the inevitable loss of materials [13]. To cope with increasing product complexity and to improve recycling efficiency a better understanding of automated recycling systems is instrumental.

1.2. Recycling process modelling

The objective of automated recycling modelling is to determine the material distribution in the output streams of a separation process from a known input material composition, aiming to maximize the recovery of valuable materials. In a recent study Wolf et al. classify prior research on recycling systems in two groups [14]: 1. Models of recycling technologies from a mineral processing perspective, which describe the physical behaviour of comminution and sorting processes to predict their individual performance as a function of process parameters. 2. Models to evaluate recycling systems mainly from economic and environmental perspectives. Many of these models include detailed physical separation modelling.

One of the main challenges for recycling modelling is that the necessary data is not readily available in industry and often difficult to collect [14-16] [17]. Extensive data collection represents a burdensome task, and the required calculations can be computationally demanding, which present implementation challenges specially for the over 95% of companies involved in the recycling sector in Europe that are SMEs [5]. A trade-off needs to be made between the level of detail of the results derived from the model and the required input data.

The authors have found that, in practice, most pre-processing recycling lines are designed based on experience with operational recycling systems and often require substantial fine tuning during operation. This finding is in line with recent research that indicates that the most common modelling approach used by pre-processors, which are mostly SMEs, is basic numerical calculation based on flow sheets [14]. The aim of this article is to present a set of modelling techniques and metrics to assist small and medium sized recycling companies in the initial design phase of multi-stage systems, and thus on investment planning, while minimizing the required input data. Furthermore, a step by step procedure to implement the proposed methods is presented and demonstrated by means of a topical case study: Liquid Crystal Displays (LCD) TVs.

2. Materials and methods

2.1. Materials

In this article, LCD TVs, of which 569 000 tonnes of waste per year are forecasted in EU 25 by 2018 (equals 1.2 kg/cap/yr) [18] are used as a case study to demonstrate the proposed approach. Flat screens constitute one of the fastest growing waste streams. Recycling processes for this waste stream are still under development. Worldwide about 1.2 billion Flat screen TVs were sold until 2013 [19]. 87 % of these TVs are LCDs [19]; from which 72% utilize Cold Cathode Fluorescent Lamps (CCFLs) as backlight, that contain hazardous mercury. The other 28% uses Light Emitting Diodes (LEDs), which are mercury-free and more energy-efficient [9]. Furthermore, LCD TVs contain a high amount of engineering plastics and PMs, which have significant economic value.

2.2. Method

In order to assist recyclers to design recycling lines at an early stage the procedure depicted in Figure 1 is proposed.

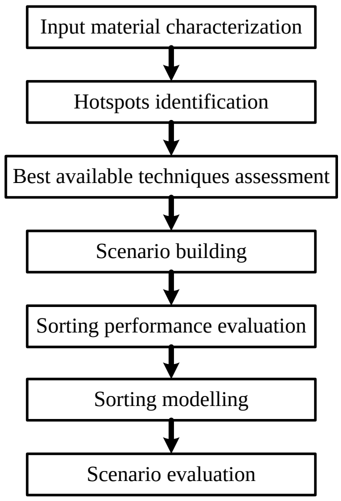

Figure 1. Proposed procedure to assist the design of recycling lines

2.3. Input material characterization

The first step is to estimate, as accurately as possible, the material composition of the input waste stream. The amount of the different materials can be estimated based on disassembly experiments and laboratory analysis. Material composition needs to be described in a manner that is unambiguously understood by all involved parties. In this research, the CAS number is used as a standardized naming system [20-22], the materials are furthermore organized in a hierarchical way, forming a parent-child relationship. This structure allows describing materials at different levels of abstraction. The lowest level of abstraction is the chemical constitution of a material and all higher levels are based on physical properties of the materials. It is worth noting that material characterization techniques still face major limitations to identify certain materials and additives, as it is the case for plastics [23]. Thus, multiple identification techniques for cross-validation of results may be needed for some materials.

2.4. Hotspots identification

Once the material characterization is performed, material prioritization from both an economic and environmental perspective is carried out. The purpose of this step is to determine the upper bound of the financial and environmental benefits that are attainable, and to identify the most promising components and materials. In this step, the virgin material value is utilized for the economic valorisation, and the EI of material production from the Ecoinvent database [24] is used for the ecological evaluation.

2.5. Best available techniques assessment

A broad range of technologies exists to achieve the separation of different materials from a waste stream based on physical properties such as density, color and magnetic properties.

In general the pre-processing recycling system consists of 2 main groups of unit operations:

- Pre-treatment operations involving: product sorting, dismantling of EoL equipment and segregation of hazardous components.
- Liberation operations: size reduction and smashing
- Sorting operations involving: size separation, electromagnetic separation, eddy current separation, density separation, hand picking, optical separation, electrostatic separation, and other techniques such as selective dissolution by means of solvents and thermal separators.

In this study, the best available recycling techniques are assessed by expert judgment on their technical feasibility, environmental performance and economic aspects.

2.6. Scenario building

By adequately combining technologies that use different discriminating properties, a mixed material stream can be sorted into different material fractions with the required purity characteristics. Based on the evaluation of separation technologies and the material composition, several promising scenarios are built. These scenarios are constructed by a panel of experts. To facilitate the construction of the scenarios, the treatment technologies are classified based on the target material that the separation technologies are able to sort. Informative cards with the different technologies and properties are distributed among the expert panel members and multiple treatment sequences are jointly designed and evaluated on their technical feasibility. A number of promising scenarios are the output of this step.

2.7. Sorting performance evaluation

Purity and yield metrics are commonly used to evaluate separation efficiency. These metrics originate from the mineral processing industry, where separation processes are used to extract valuable materials from unusable material. Purity or grade is the concentration of the targeted material in the designated output stream. Yield is the fraction of the targeted material correctly separated into the designated output stream [25, 26].

In this article, purity and yield are calculated using the separation Bayesian model, originally proposed by Gutowski and Dahmus [27]. The basic idea is that having a binary material mixture of material *t*, the target material; and *nt*, the non-target material, the concentration of *t* in the input *I*, represented as $C_{t,I}$ is the probability of *t*, and the concentration of *nt* is 1- $C_{t,I}$. Given a sorting process A that separates *t* and the compliment A^c which separates *nt*, the following conditional probabilities are defined:

$$p(A|t) = r \quad (1)$$

$$p(A^c|t) = 1 - r \quad (2)$$

$$p(A|nt) = 1 - q \quad (3)$$

$$p(A^c|nt) = q \quad (4)$$

In the context of material recycling, probability *r* represents the chance that the target material *t* is correctly separated in the primary fraction, and probability *q* that the non-target material *nt* ends into the secondary material fraction. These separation efficiency parameters are obtained through experimental trials or by means of process modelling; the following equations are used to estimate *r* and *q*.

$$r = \frac{m_{t,P}}{m_I \times C_{t,I}} \quad (5)$$

$$q = \frac{m_{nt,S}}{m_I \times C_{nt,I}} \quad (6)$$

Using the estimated separation parameters *r* and *q*, it is possible to calculate the mass of target and non-target materials in the primary and secondary separated fractions via:

$$m_{t,P} = m_i \times C_{t,I} \times r \quad (7)$$

$$m_{nt,P} = m_I \times C_{nt,I} \times (1-q) \quad (8)$$

$$m_{nt,S} = m_I \times C_{nt,I} \times q \quad (9)$$

$$m_{t,S} = m_I \times C_{t,I} \times (1-r) \quad (10)$$

Where:
P= Primary separated fraction
S= Secondary separated fraction
$C_{t,I}$= concentration of target material in the input
$C_{nt,I}$ =concentration non-target materials in the input
m_I= input material mass
$m_{t,P}$= mass of target material in primary fraction P
$m_{nt,P}$= mass of non-target material in secondary fraction P
$m_{t,S}$= mass of target material in primary fraction S
$m_{nt,S}$= mass of non-target material in secondary fraction S

Purity and Yield of the target material in the primary fraction is calculated using:

$$Purity_{t,P} = \frac{m_{t,P}}{m_{t,P} + m_{nt,P}} \quad (11)$$

$$Yield_{t,P} = \frac{m_{t,P}}{m_I \times C_{t,i}} \quad (12)$$

Note that purity and yield are specific to the analysed separation method and material input. The efficacy of this model for predicting separation performance depends on the accuracy of the probabilistic description of the separation processes. Based on this model for two materials, the separation parameter r_M is defined to model the separation efficiency of multi-material streams. This parameter represents the probability that material M is separated into the output streams, which can be the primary or secondary.

2.8. Sorting modelling

Multi-step separation processes are modelled using the network model proposed by Wolf et al [17]. In this approach, parameter $r_{M,i,P}$ represents the recovery rate of material *M* in separation step i into the primary material stream P. The output streams can be the primary or secondary material stream. Thus, the mass of each material is calculated by:

$$m_{M,i,P} = m_{M,I} * C_{M,I} * r_{M,i,P} \quad (12)$$

In this approach, the material flows within the system are determined by the separation performance of the individual separation steps and the input material flow. This allows to model multi-step separation processes by placing different steps in a sequence of which the individual separation efficiency is described by $r_{M,i,P}$ and $q_{M,i,P}$. Each process has a target material and a primary and secondary output streams. Thus, a complete set of separation efficiency equations can be generated, which is able to describe a complete multi-material, multi-step separation process. Main assumptions are that the system operates in steady state, and with fixed operating parameters [17]. The Bayesian model does not capture the separation variability based on variation in particles size and shape [25].

2.9. Scenario evaluation

Currently, the WEEE directive sets mass based targets to assess the minimum efficiency required for EoL treatments, so mass separation efficiency suffices to fulfil legal requirements. However, starting from mass based recovery efficiency, economic and environmental metrics to assess the overall performance of the recycling system can be calculated. In this study, financial and environmental aspects are analysed.

For the economic evaluation, material revenue per tonne is used. Processing costs are not accounted for because those are facility specific; and thus, represent sensitive information to be published. The main cost contributors are the initial investment in equipment, owning or leasing workspace, maintenance of equipment, labour, utilities, and proper disposal of problematic fractions. Regarding the value of recyclates, it is worth mentioning that the estimation of secondary material value represents a challenge, since there is often is no direct relationship between purity of secondary materials and their value, especially for complex materials like plastics. Peeters et al. has pointed out that higher purity recyclates sometimes do not have higher economic value because markets for these recyclates are inexistent [23]. The commonly applied strategy is to specify minimum purity levels on the fractions to be traded rather than a stepped price-purity relationship. The material values utilized in this article come from literature and were validated by industrial partners.

In order to assess the environmental gains of material recycling, the quantity of target material effectively recovered and the benefits of avoiding the need for extracting new resources must be quantified. However, it is not always straightforward to assess how secondary materials will be reapplied, as the options for valid destinations are influenced by several factors, such as: quality of secondary materials, regional legislation, and economic factors [28]. In this study, the percentage of the recovered monetary value is utilized to estimate the environmental gain in case the material that will be replaced by the recyclates is unknown. This approach is in line with the substitution allocation method for Life Cycle Assessment (LCA), as specified in the International Reference Life Cycle Data System ILCD handbook [29]. The EI in mPt is calculated by means of LCA tools, utilizing the Ecoinvent 2.2 Life Cycle Inventory data.

3. Results and discussion

3.1. Input material characterization

LCDs contain a complex mix of materials, thus proper material characterization represents a challenge [30]. In this study, the average material composition depicted in Figure 1 is estimated by means of the analysis of 110 EoL LCD TVs from the Belgian waste in 2012. These TVs were manually disassembled, and for each component both weight and material type were registered. Previous studies have pointed out that plastic data are mismarked in a significant number of components [31]. Therefore, both plastic and FRs type of the main disassembled components were identified by combining sliding-spark spectroscopy and Fourier Transform Infrared analysis. In addition, the different types of PWBs were collected and classified, and the amount of gold, silver, palladium and copper of these components was determined by means of laboratory analysis. Based on the performed material characterization, the average PM content of the PWBs of LCD TVs is 90 ppm Au, 590 ppm Ag, 10 ppm Pd and the copper concentration is 18 wt%.

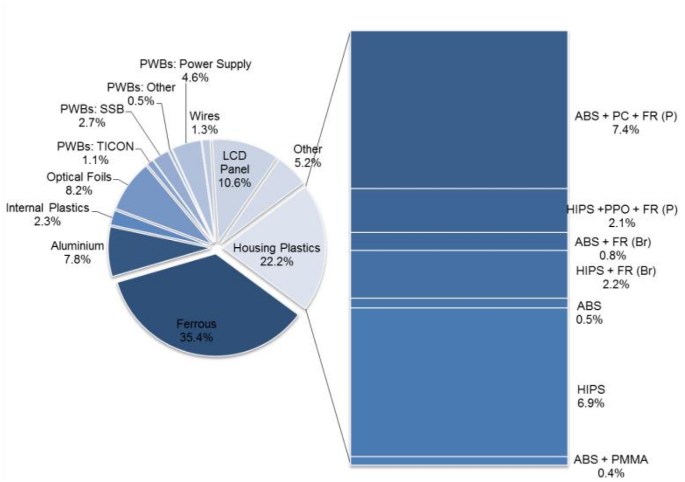

Figure 1. Average material content of LCD TVs

3.2. Hotspots identification

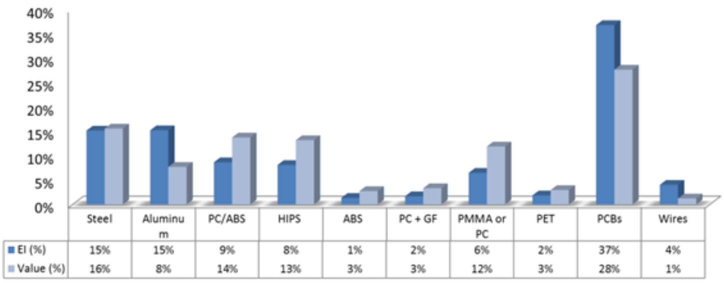

Figure 2. Economic and environmental relevance of materials

For this analysis the LCD module was not included, as there are not readily available technologies to recycle it. Based on the economic and ecological evaluation of materials presented in Figure 2, PWBs represent about 1/3 of both economic value and EI, steel and aluminium together represent about 1/3 of the EI and 1/4 of the economic value. Regarding plastics, PC/ABS and HIPS, which are mainly present in the TV housing, contribute each with 9 % and 8% of EI respectively, and 14% and 13% of the economic value.

3.3. Best available separation technologies

The recycling techniques applicable for the recycling treatment of LCD TVs were evaluated with respect to their technical feasibility, environmental performance, and economic aspects. Technical, environmental and economic performances of the techniques were scored by expert judgment. The expert consultation was based on qualitative and quantitative figures taken from case reports supplied by plant managers, manufacturers and other literature sources.

3.4. Scenario building

During the performed research, a number of promising scenarios resulted from this exercise. However, in this article two scenarios are presented; (1) the baseline scenario where only a magnet separator for steel and an eddy current for aluminium separation is performed following shredding, as it has been found operational in several recycling facilities (2) a scenario which involves manual picking of PWBs, targeting the environmental and economic relevant PM rich fraction as shown in Figure 2. This scenario evaluates one operator hand picking PWBs after the magnetic separation, in a recycling line operating at 2 tonnes per hour.

3.5. Sorting performance evaluation

For the selected separation technologies, practical experiments were set up to determine the separation efficiency in terms of yield and purity. Separated fractions were manually classified, and the separation efficiency for the different materials was calculated. The sorted pieces of complex components, like PWBs, were sent to specialized laboratories to determine the PM content of the separated fractions. In this manner, data tables were created with separation efficiencies for the different materials present in the input stream.

3.6. Sorting modelling

With the separation efficiencies calculated through practical experiments and the average material input, the mass recovered in each separation step is calculated using (12) and represented in the network model depicted in Figure 3. This model was implemented in a spreadsheet which facilitates verification by managers and technical staff at recycling facilities. In this model, different processes can be switched on or off to evaluate the overall effect on the system.

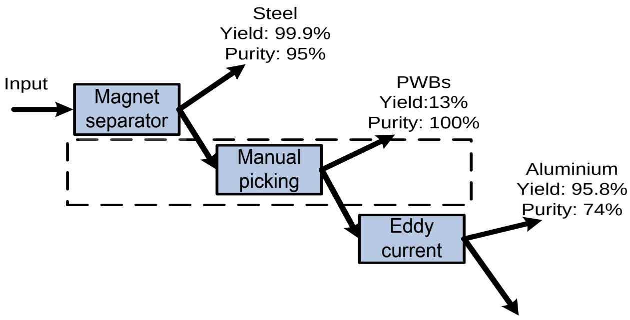

Figure. 3. Network representation of analysed scenarios

3.7. Scenario evaluation

Table 1 depicts the evaluation of the two scenarios for recycling LCD TVs. To calculate the overall material recovery, the efficiencies for PMs recycling of PWBs in a metallurgical plant are calculated based on the estimations of Bigum et al [32]. Manual picking of PWBs increases material revenue by €28.4 per tonne or 13 %, whether this value is profitable depends on the associated labour costs. The proposed approach can assist investment planning decisions accounting both economic and environmental aspects. From an environmental point of view, manual picking increases the avoided EI about 10 %. Interestingly, the PM content of the post-shredder separated PWBs decreases about 74% for Au and 42% for Ag compared to the PM content of an intact high grade PWB of LCD TVs. This reduction is due to the high intensity shredding process needed for the mercury extraction. As a result, less than 10% of the PMs of the PWBs is valorised. To determine an optimal treatment for LCD TVs, a more in-depth analysis is being prepared by the authors, which also includes models for manual dismantling operations.

Table 1. Economic and Environmental assessment of the proposed scenarios

	Ferro based	**Aluminium**	**Housing Plastics**	**Internal Plastics**	**PWBs**	**Wires**	**LCD module**	**Other**	**Total (kg)**	**Material Revenue (€)**	**Avoided EI (mPts)**
INPUT Mass (kg)	**353.6**	**78.5**	**202.7**	**105.6**	**89**	**12.6**	**105.8**	**52.2**	**1000**		
Magnet	99.95%		0.2%	0.1%	30.5%	14.1%		0.2%			
Extracted (kg)	**353.4**		**0.5**	**0.1**	**27.1**	**1.8**		**0.1**	**383.0**	**104.2**	**57648**
Remain (kg)	**0.2**	**78.5**	**202.2**	**105.5**	**61.9**	**10.8**	**105.8**	**52.1**	**622.4**		
Manual Picking PWBs					20.9%						
Extracted (kg)					13.0				12.96	**28.6**	**13828**
Remain (kg)	**0.2**	**78.5**	**202.2**	**105.5**	**48.9**	**10.8**	**105.8**	**52.1**	609.4		
Eddy Current		95.8%	0.4%	0.2%	74.1%	7.9%	1.7%	0.4%			
Extracted (kg)		75	0.8	0.2	36.3	0.9	1.8	0.2	115.4	**115.39**	**83730**
Remain (kg)	**0**	**3.3**	**201.4**	**105.2**	**12.7**	**10.0**	**104.0**	**51.9**	**488.6**		
Total Scenario 1										**219.6**	**141378**
Total Scenario 2										**248**	**155205**

4 Conclusions and further work

Many operational pre-processing recycling plants are designed empirically, based on experience with past system performances. Due to the increasing material complexity of WEEE a better understanding of recycling processes is required. One of the main challenges small and medium sized recycling companies currently face to optimize recycling processes by means of modelling techniques is data availability. The presented article presents a set of metrics and modelling techniques along with an implementation procedure for decision makers to evaluate multiple investment configurations when only limited data on recycling processes is available. Its primary advantages are: the possibility to incorporate different separation technologies, different configurations and requires simple information about individual process performance.

During the research it was noted that material characterization techniques still face major limitations to identify certain materials and additives, as it is the case for plastics. Further work includes the incorporation of modelling techniques that allow forecasting the volumes of EoL products, and also modelling of dismantling operations to be able to assess optimal combinations of manual and automated treatment. The authors reckon that modelling and optimization of pre-processing steps represent challenging problems that need more research and that a system approach where the interdependences between processes are accounted must be taken.

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