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Recycling of electronic displays: Analysis of pre-processing and potential ecodesign improvements

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ABSTRACT

This article analyses the current and future end-of-life management of electronic displays (flat screen televisions and monitors), and identifies and discusses possible ecodesign recommendations to improve it. Based on an investigation of the treatment of displays in two typical European recycling plants, key aspects and criticalities of the recycling methods (sorting, dismantling and pre-processing) are identified. Disaggregated data concerning on-site measurements of the time needed to manually dismantle different displays are presented. The article also discusses the potential evolution of end-of-life scenarios for electronic displays and suggests possible recommendations for recyclers, producers and policy-makers to promote resource efficiency in the recycling of such waste products. Data on time for dismantling the displays can be used to build measurers for voluntary and mandatory policies, to stimulate design innovations for products improvement, and to assess possible alternative treatments of the waste during the pre-processing at the recycling plants. Some quantitative product measures (based on the time thresholds for dismantling some key components) are also discussed, including an assessment of their economic viability. These measures can potentially be enforced through mandatory and voluntary European product policies, and could also be extended to other product groups.

1. Introduction

Electric and electronic equipment (EEE) contain a wide range of substances, some of which are valuable, and some which are toxic or otherwise hazardous (Hagelüken, 2006). Components containing harmful substances (which would impair recycling efforts) or valuable substances (which retain their high value only when treated separately) should be easily identifiable in order to ensure that they are extracted and recycled (Wimmer and Züst, 2003).

Waste Electric and Electronic Equipment (WEEE) need to enter the appropriate mix of recovery processes, including sorting, dismantling and pre-processing (e.g. shredding) and end-processing (e.g. using pyrometallurgy, hydrometallurgy and electro-metallurgy) (Mathieux et al., 2008; Chancerel et al., 2009; Schluep et al., 2009). Selective dismantling is often recognised as an indispensable part of the recycling process because it allows for the selective extraction of hazardous components (Cui and Forssberg, 2003), a higher quality of valuable recyclable materials (e.g. engineering plastics) (Aizawa et al., 2008), and, as opposed to shredding, it allows for the re-use of parts (Kondo et al., 2003).

Mixing product parts of different compositions during the collection/pre-processing stages negatively influences the recycled yields (due to dilution or the technical constraints of some recycling processes) (Hagelüken, 2006). Chancerel et al. (2009) observed that unselective fine shredding can lead to the loss of valuable substances, including various rare and precious metals, contained in electronic components (especially printed circuit boards—PCBs). These losses occur due to the dispersion, after shredding, of mass-relevant fractions of valuable metals (e.g. plastics and ferrous metals). A comparison of recycling treatments of televisions (TVs) by Peeters et al. (2013) concluded that less than 10% of precious metals are recovered when mechanical treatments are used, while the manual dismantling of waste products allows for the recovery of more than 90% of such metals. Similarly, Meskers et al. (2009) concluded that up to 92% of the silver and 97% of the gold contained in the PCBs of EEE can be recovered in an economically viable way when these components are selectively extracted and sorted from other waste streams.

The content of precious metals in WEEE is relevant both for economic (Hagelüken, 2006; Peeters et al., 2013) and environmental

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reasons, as the manufacturing of these materials can have relevant lifecycle impacts (Ardente and Mathieux, 2012).

The recycling yields of scarce and precious metals from WEEE can be improved by an appropriate design of the product that facilitates the dismantling and sorting of components according to their material composition (Chancerel et al., 2011). WEEE should also be pre-processed in order to remove large iron and aluminium parts without causing the simultaneous loss of precious metals (Hagelüken, 2006).

As the dismantling process accounts for a large part of the costs of recycling, it is imperative to minimise the amount of work required for this stage (Willems et al., 2006). Furthermore, it has been estimated that large-scale dismantling can only be profitable and optimal when the time taken to dismantle a product is substantially reduced, in particular with regard to medium- and large-sized EEE and in products that are rich in valuable substances (Willems et al., 2006).

The need to improve the recovery of resources from the recycling of waste products and, in particular, WEEE, has been pointed out in various European policy initiatives (EC, 2011a; EC, 2011b). Policies promoting resource efficiency can be subdivided into two groups: policies that address waste treatment (end-of-pipe) (e.g. the Waste Directive (EU, 2008) and the WEEE Directive (EU, 2012)), and policies that focus on promoting cleaner production (e.g. the Ecodesign Directive (EU, 2009a) and the Ecolabel Regulation (EU, 2009b)). The first group sets the framework for the proper treatment of waste, while the second group focuses on requirements with which products should comply when being commercialised. In both groups, dismantlability has been highlighted as a key feature for the recyclability of products. For example, article 4 of the European WEEE Directive (EU, 2012) states that ecodesign requirements facilitating the dismantling of WEEE should be laid down in the product design in order to optimise the re-use and recovery of materials. The Ecodesign Directive (EU, 2009a) states the need to improve the dismantlability or products, for example by using various strategies such as the reduction of the number of materials and components used, or the reduction of the time and the complexity of tools needed to disassemble a product.

A recent study by Dalhammar et al. (2014) reviewed several studies on resource efficiency and its inclusion in policies. The study formulated various recommendations, including the need to establish pilot projects and research to examine the potential of cost-effectively recycling materials (with a special focus on critical materials), the need to establish research into new materials and better designs, and the need to develop new and well-designed product requirements through the timely introduction of new standards.

It is therefore necessary to carry out an analysis of the end-of-life (EoL) of EEE, with a special focus on dismantling processes, in order to improve a product's design so as to enhance its recyclability and to optimise the overall resource efficiency of EoL treatments. This can be promoted through policy measures that support good design practices (Mathieux et al., 2008), in synergy with other measures to improve the collection and recycling of waste (Bouvier and Wagner, 2011).

Resource efficiency of EEE can be promoted with the enforcement of some "push" and "pull" policy measures on "design for dismantling" (Dalhammar et al., 2014). In particular, the manufacturer could be "pushed" to achieve minimum performance levels (e.g. via the enforcement of Ecodesign measures for energy-related products), before introducing new products to the market. These measures would allow for the removal of products that are very difficult to dismantle (EU, 2009a). In addition, pro-active manufacturers could be encouraged ("pulled") to design high-performance products, e.g. via the introduction of specific criteria for environmental labelling (such as the EU Ecolabel (EU, 2009b)).

2. Aim of the article

The considerations discussed in the introduction concern all WEEE, particularly waste electronic displays (flat screen TVs and monitors) (Hagelüken, 2006; Ardente and Mathieux, 2012; Peeters et al., 2013).

With an estimated 30 million devices in the EU reaching their EoL by 2015, flat panel displays is a particularly significant waste category (Fakhredin and Huisman, 2013). In recent years, there has been much scientific interest in improving the design of this product category for recycling purposes (Dodbiba et al., 2008; Ardente et al., 2013; Peeters et al., 2014). Recycling with dismantling has been judged to be one of the most efficient strategies in treating waste displays (Shih et al., 2006).

Some policies already address design for the recycling of electronic displays. For example, the need for easy disassembly/dismantling[1] of electronic displays and for the extraction of some key components has been highlighted in some criteria for voluntary environmental product labelling, as in the European Ecolabel[2], the 'Blaue Engel'[3], and the 'Nordic Ecolabelling'[4] initiatives. However, these criteria are general and difficult to verify. A more specific and detailed criterion on design for dismantling electronic displays has been published by the Institute of Electrical and Electronics Engineers (IEEE)[5], although its application by manufacturers is only voluntary.

Additional measures could be enforced via mandatory policies, such as the European Ecodesign Directive (EU, 2009a). Annex I of this Directive states that the assessment of the ease of reuse and recycling of energy-related products (ErP) should consider the time necessary for disassembly and the ease of access to components containing valuable and recyclable materials, and hazardous substances. Measures based on 'time for dismantling' thresholds have not yet been enforced in European policies, although their application has been discussed in the scientific community (Ardente and Mathieux, 2014a) and in the policy debate (ECEEE, 2012).

This article presents a novel approach to identify workable and quantitative measures for the 'design for dismantling' of product based on an analysis of the pre-processing of electronic displays at recycling facilities. The approach starts from the 'on-site' analysis of two recycling plants (Section 3.1) to identify criticalities of the pre-processing stage in extracting key components from the displays. Potential future changes of the current recycling treatment methods are also assessed (Section 3.2). The time taken to dismantle displays is measured using 'on-site' disaggregated data (per size

[1] The terms 'dismantling' and 'disassembly' of a product (or its parts) are generally used as synonyms when referring to recycling processes. However, there is a slight difference between the two terms: the former mainly refers to the careful removal/extraction of the part (e.g. for substitution or repair), while the latter refers to the removal/extraction of the part in a way that could potentially destroy the functional integrity of the product.

[2] "The manufacturer shall demonstrate that the television can be easily dismantled by professionally trained recyclers using the tools usually available to them, for the purpose of: undertaking repairs and replacements of worn-out parts; upgrading older or obsolete parts, and separating parts and materials, ultimately for recycling" (EC, 2009).

[3] "The appliance shall be so designed and as to allow an easy and quick disassembly for the purpose of separating resource-containing components and materials" (der Blaue Engel, 2012).

[4] "The manufacturer shall demonstrate that the product can be easily dismantled [. . .] for the purpose of separating parts and materials, ultimately for re-cycling. [. . .] To facilitate the dismantling: fixtures within the products shall allow for this disassembly, e.g. screws, snap-fixes, especially of parts containing hazardous substances" (Nordic Ecolabelling, 2013).

[5] The time for dismantling the television for recycling shall be "at most 10 min for products weighting less than 50 lb (18.7 kg); and at most 10 min plus 1 min per each additional 5 lb (1.87 kg) of total product weight, for products weighting 50 lb or more" (IEEE, 2012).

and mass of the displays) and discussed (Section 4). Finally, the analysis derives possible recommendations for recyclers, producers and policy-makers to promote the resource efficiency of such waste recycling. In particular, the article identifies some quantitative ecodesign measures to support the resource efficiency of products (which would increase the quantity and quality of relevant recycled materials) (Section 5.1). The economic viability of proposed measures is described in Section 5.2.

3. Analysis of end-of-life treatments of electronic displays

The following sections analyse current EoL treatment methods for electronic displays, and the possible future evolution of recycling treatment methods.

3.1. Analysis of current EoL scenarios

Two Italian WEEE recycling plants were investigated between 2012 and 2013. It was observed that the recycling of waste electronic displays mainly consists of the complete manual dismantling and sorting of the displays. This EoL scenario is assumed to be representative of EU recycling treatments, as confirmed by studies in the scientific literature (Kopacek, 2008; Cyran et al., 2010; Buchert et al., 2012; Peeters et al., 2013) and by recyclers. In particular, the European Electronics Recyclers Association confirmed the manual dismantling of electronic displays as an essential step in the pre-processing of displays in Europe[6]. In addition, according to Cyran et al. (2010), Europe is currently missing of automated commercial-scale processes which can recycle electronic displays safely, economically and at high volume, as requested by European waste treatment standards.

The main goal of the two recycling plants investigated is to treat the WEEE in the most economical way, while complying with the environmental requirements of the European WEEE Directive (EU, 2012), and, in particular, to separate the following key components from other waste flows:

- Mercury-containing components (backlighting lamps);
- external electric cables;
- printed circuit boards (PCBs) with a surface greater than 10 cm^2;
- electrolyte capacitors (height > 25 mm, diameter > 25 mm or proportionately similar volume);
- liquid crystal displays (LCDs) together with their casing (where appropriate) of a surface greater than 100 cm^2, and all those backlit with gas discharge lamps.

The following explains in detail why the treatments of the abovementioned components and their related criticalities.

The extraction of backlighting lamps is probably the most critical phase in the recycling of the displays. Each fluorescent lamp can contain up to 3.5 mg of mercury (EU, 2013), as confirmed by experimental analyses conducted by the European Electronics Recyclers Association (EERA) in European recycling facilities (Krukenberg, 2010). Lamps should be carefully extracted and safely stored for further recovery treatments. Lamps are also generally one of the most deeply embedded components in the electronic displays, so they can only be safely extracted at the end of the dismantling process. The extraction of lamps is a delicate process as there is a risk of accidentally breaking the lamps. The EERA also verified that approximately 20–30% of the waste display boards in recycling plants already contained one or more broken backlights (Krukenberg, 2010). It is therefore recommended that displays be recycled in dedicated treatment facilities so as to avoid the possible release of mercury, which can cause health risks, pollute the environment and contaminate other recyclable materials.

The extraction of external cables does not cause specific problems for recycling plants, but represents a relevant process due to the valuable content of potentially recoverable copper.

The disassembly of PCBs is another difficult task in the recycling of WEEE (Yang et al., 2009). The extraction of PCBs is relevant because they can contain a number of hazardous substances (including arsenic, antimony, beryllium, brominated flame retardants, cadmium and lead (EC, 2008)), and several precious and valuable metals (including gold, silver and platinum group metals (Chancerel et al., 2009)). PCBs can also contain some critical raw materials, as defined by European Commission (EC, 2010). As PCBs are generally fastened to various different frames in the electronic display, the product must be almost completely disassembled in order to manually extract them. During the recycling of electronic displays, PCBs are carefully dismantled and sorted according to their 'richness' (i.e. their potential content of precious metals). This manual sorting increases the resource efficiency (in terms of the quantity and quality of recoverable materials) and economic revenues of the recycling process. During this sorting process, capacitors that are greater than 2.5 cm are also extracted.

The LCD is one of the last components to be extracted. It is generally framed together with plastic optical components (mainly a polymethyl methacrylate–PMMA–board and various plastic foils), some PCBs and film connectors. The LCD contains the thin-film-transistor (TFT) panel, which is relevant for its indium content (Chou et al., 2009). According to recent studies in the literature, more than 80% of indium in the world is produced for indium tin oxide (ITO) coatings used in LCDs (Park et al., 2009). Indium is currently considered a critical raw material worldwide (Buchert et al., 2009; EC, 2010).

In the two recycling plants investigated, TFT panels are stored after extraction and are not further processed. In fact, there is currently no established system in Europe for the recycling of indium from WEEE (Buchert et al., 2012). The storing of TFT panels is only a temporary solution, which is still possible because of the limited amount of waste materials. However, as the amount of waste electronic displays accumulates, TFT panels will have to be further recycled or, as a last option, deposited in the landfill. As highlighted by Ayres et al. (2014), even though the content of indium in electronic displays is small, TFT waste is a potentially relevant future supply source; the non-recyclability of this waste product can call into question also the sustainability of the 'flat screen' technologies (Ayres et al., 2014). Some pilot studies have shown that the recovery of indium from TFT panels can be technically and economically feasible (Li et al., 2009; Takahashi et al., 2009; Virolainen et al., 2011). A company recently claimed that it could recycle indium from TFT panels, although some problems (e.g. the low market value of indium, the need to concentrate indium in the pre-processing stage) render indium 'valorisation' by smelter/refinery technology still impossible (Art, 2014). The trend of increasing market prices for indium may be a future driving force for the development of technologies for indium recovery (Ayres and Talens Peiró, 2013). Furthermore, the growing amount of TFT waste may contribute to reaching the 'critical mass" necessary to make the indium recovery process economically viable.

However, high recycling rates of indium can be achieved only when TFT panels are carefully extracted and before any mechanical treatments such as shredding (Li et al., 2009; Lee et al., 2013; Yang et al., 2013). Indium in electronic displays is generally also used together with other substances such as arsenic, phosphorous and tin. Indium arsenide (InAs) and indium phosphate (InP) semiconductors, and ITO are potentially hazardous and can cause lung disease and cancer (NTP, 2001; Chou et al., 2009; Lim and

[6] Information from private communications collected in June 2012.

Schoenung, 2010). Therefore, TFT panels must be manually separated from other waste flows to allow for indium recovery and to avoid the potential contamination of other recyclable fractions.

The extraction of the previous key components also requires the dismantling, extraction and sorting of other intermediate parts, such as:

- external (front and back) covers: mainly constituted by acrylonitrile butadiene styrene (ABS) and polycarbonate–ABS blend (PC-ABS),
- support (when present): ferrous parts,
- internal frames: ferrous and aluminium parts,
- internal cables: copper and PVC,
- light guide: PMMA,
- plastic optical foils: various plastics such as polyester, polyvinylidene chloride and PET (Lee and Cooper, 2008),
- other components (when present): fans, speakers, fasteners, etc., made of various materials.

During the 'on-site' analysis of the dismantling of displays, it was observed that ferrous parts are identified (with a magnet) and sorted from other metals. Plastics are generally stored together for sorting after being shredded. The only exception to this is the PMMA board, which is highly recyclable and valuable thanks to its high purity, relatively large mass (ranging from a few hundred grams in small displays to several kilograms in large displays) and high market price. The PMMA board is therefore stored separately and sold to plastics industries for monomer recycling (Kikuchi et al., 2014).

A schematic description of how electronic displays are recycled in the recycling plants investigated is given in Fig. 1(A).

3.2. Possible future EoL waste treatment scenarios

From communications by recycling plants and from studies in the literature, it emerges that the electronic display recycling sector is continuously developing, mainly due to the technological changes within this product group. In particular, fluorescent lamps are being progressively replaced by alternative and energy-efficient 'mercury-free' systems (mainly light-emitting diodes—LEDs) in newer electronic display designs (Buchert et al., 2012). The absence of mercury, together with the lower costs and safety risks, will contribute to the future diffusion of shredding-based processing for displays, although this could lead to higher losses of resource and the downcycling of other recyclable materials (Fig. 1B).

The full manually dismantle of displays will probably not be feasible in the coming decade due to high costs and the expected dramatic growth in waste electronic displays. This could lead to the displacement of the recycling of electronic displays to countries with low manpower costs, which would also mean a displacement of resources. Alternatively, other recycling treatments will have to be developed, mainly based on mechanical shredding and sorting.

Some automated recycling technologies (based on the shredding and mechanical sorting of recyclable fractions) are under development and being tested (McDonnell and Williams, 2010). The shredding process is designed to break components into small pieces which can then be sorted into concentrated fractions. However, "100% recovery can never be achieved in combination with 100% grade", and research is underway to try to measure "the effect of product design on the liberation behaviour and quality of recyclates from complex consumer products" (Van Schaik and Reuters, 2014).

Shredding-based treatments require a suitable mercury abatement system to prevent the dispersion of mercury and the contamination of the other recyclable parts. Without suitable processes to remove mercury after shredding, the shredded material would be classified as hazardous (McDonnell and Williams, 2010). Systems to decontaminate shredded waste of mercury have also been analysed in pilot testing plants (Cyran et al., 2010). Innovative automated treatments of electronic displays in a closed controlled environment have also been developed by some European recyclers (Stena Metall Group, 2010). These treatment processes might be more economically efficient than the current EoL scenario (and reduce the safety risks of exposition to mercury). However, quantitative disaggregated data on the recycling efficiency of the shredding of electronic displays are still not publicly available.

On the other hand, as discussed in Section 1, the shredding-based treatment of electronic displays would lead to higher losses of precious and rare materials, with consequent reduced environmental benefits (Peeters et al., 2013; Yang et al., 2013). Shredding-based scenarios fail to fully address key policy objectives such as reducing the "wasteful consumption of natural resources", avoiding "the loss of valuable resources", reducing "the disposal of waste and [contributing] to the efficient use of resources and the retrieval of valuable secondary raw materials" (as mentioned in the introduction of WEEE Directive (EU, 2012)). This is particularly the case for LED-backlit displays, due to the high content of several relevant materials in LEDs (including indium, gallium and rare earths) (Buchert et al., 2012). Rare earths from LEDs are generally not currently recycled (Ayres et al., 2014): the most important obstacle being their collection, as they are used in very tiny amounts. Moreover, there is evidence of the potential hazards of LED-backlighting systems, as they include various substances such as arsenic, lead gallium, indium, and antimony, which can affect human health and ecological toxicity (Lim et al., 2011). Therefore, the shredding of LED-backlit displays could have the same effect as that of displays containing mercury-based backlighting systems, i.e. they could lead to the hazardous contamination of recyclable fractions.

The current EU WEEE legislation does not yet foresee specific treatments for LED-based products, mainly because the massive use of LED in EEE only began in recent years and there is still little evidence regarding their potential toxicity and their proper EoL treatment. It is possible that future changes in WEEE policy will restrict the recycling treatments of LED.

It must be noted that the recycling of relevant materials in the various parts of electronic displays is very difficult and generally not feasible when such materials are dispersed in shredded waste.

Future EoL scenarios for the recycling of EEE could also include automatic disassembly (Bley et al., 2004). Recently, some companies have installed automated systems for LCD disassembly (Electrical Waste, 2013; ALR, 2014), but there is currently little information about their processing steps and recycling efficiency. As highlighted by Ryan et al. (2011) and Elo and Sundin (2014), automated disassembly systems for the pre-processing of displays have yet to cater for the treatment of different types of waste. According to Elo and Sundin (2014), the most effective approach for disassembling/dismantling LCD systems would involve hybrid systems that combine manual and automated processes. Research is also being carried out on the implementation of active disassembly, whereby innovative reversible fasteners can be simultaneously activated by an external trigger (Peeters et al., 2011). Automatic disassembly applications are mainly at the pilot/testing stage for some specific components (Duan et al., 2011; Zeng et al., 2012), and have still not been developed for commercial displays (Cyran et al., 2010). Furthermore, product development is currently going against automated disassembly, as products are becoming more complex, more heterogeneous and sleeker, and are using more proprietary joints (Sundin et al., 2012).

This article proposes a resource-efficient and economically viable waste treatment method which couples shredding-based technologies with selective manual pre-treatment processes for

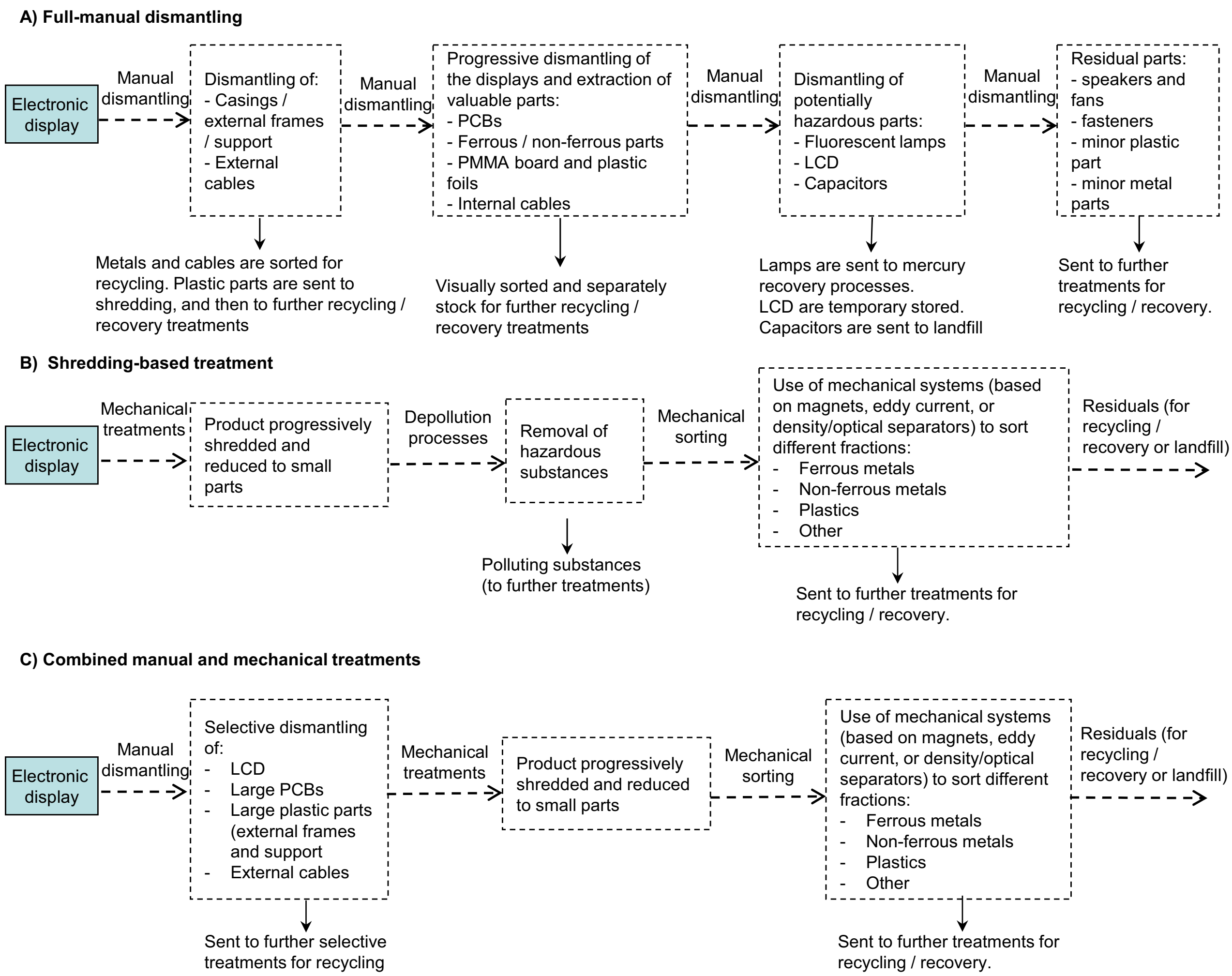

Fig. 1. Possible recycling treatment of electronic displays. Part A) Full-manual dismantling; Part B) Shredding-based treatment; Part C) Combined manual and mechanical treatment.

de-polluting the waste product and extracting some key (economically and environmentally relevant) components (Mathieux et al., 2008; Yu et al., 2010; IEC, 2012; Ardente and Mathieux, 2014a). An example of the combined 'manual-mechanical' recycling scenario, to be potentially developed and optimised in the future, is illustrated in Fig. 1(C).

However, in order for it to be viable, this scenario requires that the dismantling of key components is not very time consuming and is economically viable. Furthermore, quantitative data on the disassembly time is also needed in order to identify and implement product 'design for disassembly' solutions (Fan et al., 2013).

The analysis of the EoL of electronic displays therefore proceeded to a detailed investigation of the time taken to dismantle products. Results are illustrated in the following sections.

4. Detailed analysis of the dismantling process of electronic displays

'On-site' data on the time taken to dismantle electronic displays have been measured and analysed for one of the recycling plants investigated in this study.

The scientific literature was surveyed to identify relevant studies on the dismantling of electronic displays (Section 4.1), and a method for measuring the time taken to dismantle displays was subsequently developed (Section 4.2).

4.1. State-of-the-art of studies on the time taken to dismantle electronic displays

One of the first studies on LCD dismantling, presented by Kopacek (2008), compared the time taken to dismantle LCDs using different techniques: manually, by water-jet cutting, by laser cutting and by circular-saw cutting. This study found that manual dismantling is the preferred choice as it involves the least cost per item and results in higher quantities and quality of the recovered materials. Kopacek (2008) also estimated that a dismantling time of the backlighting systems of less than 1.4 min would make manual dismantling preferable to other systems, even with high labour costs.

A paper by Kim et al. (2009) analysed the manual and automated dismantling of displays. In their study they carried out the non-destructive disassembly of 43-cm (17-inch) LCD monitors. According to the authors, manual disassembly times ranged from 3.6 to 8.7 min. Kim et al. (2009) also provided a breakdown of the disassembly times of some components, based on which we estimated that the extraction of PCBs (including the controller, sound card and inverter) and of the LCD panel required on average 6.2 min. Kernbaum et al. (2009) compared these disassembly time measurements with the destructive dismantling of some monitors, concluding that extracting all relevant components (i.e. frame, housing, LCD, foils, lamps, light guide and PCBs), required approximately 1 min.

Cyran et al. (2010) analysed the dismantling of several displays, including 12 monitors (with masses of 2.1 kg to 6.4 kg, and 33-cm to 48-cm displays) and 11 televisions (with masses of 8.4 kg to 24 kg, and 51-cm to 102-cm displays). The analysis focused on the dismantling of display components in preparation for further treatment, and the evaluation of potential risks to workers (due to the release of mercury from broken lamps). The average time for dismantling monitors was 9 min, and 12 min for dismantling televisions (no further disaggregated figures were provided). Cyran et al. (2010) also measured the percentages of devices with broken lamps (15% of televisions and 23% of monitors), while highlighting that it was not possible to establish whether or not the backlight was broken prior to the disassembly or during the disassembly process itself.

A study by Salhofer et al. (2011) analysed the dismantling trials of 47 LCD monitors and 41 LCD televisions. A routine dismantling procedure was developed for the measurement of the dismantling times. Salhofer et al. (2011) estimated that the full dismantling of a monitor takes from 10 to 35 min (18 min on average), while the dismantling of televisions varies from 14 to 40 min (24 min on average)[7]. The authors calculated that, at the time of the study, the revenues from the recycling of materials in the displays did not cover the costs of their full dismantling. However, considering that more than 84% of the revenue derived from the separation of PCBs, the selective dismantling of these components could decrease the costs of dismantling and make the process economically feasible (Salhofer et al., 2011). Unfortunately, the authors did not provide disaggregated figures about the time taken to dismantle PCBs or other parts.

The disassembly of 17 LCD monitors (between 20 and 40 in. in size) was analysed by Ryan et al. (2011), who estimated that the average time taken to fully disassemble the waste product into its individual components was 14 min. However, this was largely influenced by various factors, such as the screw position, heat shielding, quantity of screws, presence of adhesive tape and the size of the screen. The authors did not provide disaggregated figures about the disassembly times and about the detail of their dismantling process compared to the standard treatment at recycling facilities.

The research project HÅPLA (Sustainable Recycling of Flat Panel Displays) analysed and compared existing recycling treatment methods for electronic displays (Swerea, 2012). The study observed that electronic displays represent very complex waste material to be recycled. According to this study, the dismantling of electronic displays is usually very time consuming and is therefore very costly. While the large-scale shredding of electronic displays requires less time and is less expensive, this process leads to valuable or scarce materials being dispersed and lost in other fractions from which they are difficult, if not impossible, to recover (especially from the ferrous or plastic fractions) (Swerea, 2012). Swerea (2012) also estimated that the manual dismantling of displays leads to the recovery of almost 99% of the total display mass, whereas mechanical separation with shredding only recovers 70–75%. Manual dismantling also allows for the recovery of some components with critical materials (e.g. capacitors with tantalum, and PCBs containing relevant materials). The HÅPLA project analysed the dismantling of 41 computer monitors (up to 56 cm (22 in.), and between 2 kg to 6 kg) (Letcher, 2011a), 19 LCD TVs (produced since 2006) and 7 newly designed LCD TVs (produced since 2010) of over 61 cm (24 in.) (Letcher, 2011b). Letcher (2011a) found that the time for dismantling monitors decreased on average from 502 s (for the older devices) to 402 (for the newer ones), i.e. by around 20% (Letcher, 2011a). Concerning TVs, the time taken to dismantle newer devices is generally 25% less than the time for older ones. However, further detailed and disaggregated figures of the dismantled sample of the HÅPLA study have not been published. Letcher (2011b) also reports that an 81-cm (32-inch) television produced in 2007 was fully dismantled in 1300 s, while a 140-cm (55-inch) television from 2010 was dismantled in 990 s. This proves that the proper design for the dismantling of displays (e.g. with a more rational layout, the use of less fasteners, metal parts and PCBs) can greatly simplify the recycling processes. The project concluded with few generic 'Design for Disassembly' guidelines (e.g. 'use standardised screws'; 'use snap fits').

A recent study by Vanegas and Peeters (2013) analysed the time taken to dismantle LCD TVs with an average age of 6 years, of different brands and sizes. The dismantling took place in a specific testing area, where dismantlers were provided with a set of common dismantling tools. After the collection of information on the waste product (i.e. type, brand, mass, screen size, colour, and year of production), displays were dismantled as follows: PCBs (separated according to their higher or lower content of precious metals), cables, optical foils, LCD panels, back covers (separated according to the type of plastic), small fractions and residual material. The dismantlers, although experienced, were previously trained on how to perform the dismantling process. The average time taken for the full manual dismantling of televisions was 508 s (ranging from 222 to 1461 s) (Vanegas and Peeters, 2013). This time measurement increases to 634 s when the "effectiveness" of workers is considered (e.g. taking into account the effect of fatigue). The time necessary to extract both PCBs and the LCD panels amounted to about 390 s.

Finally a recent study by Juchneski et al. (2013) analysed the manual dismantling of 27 different flat-screen TVs. The study found that TVs backlit by LED or fluorescent lamp systems have a similar structure and characterised by a similar disassembly. Based on characterisation tests of the waste, Juchneski et al. (2013) concluded the materials used in the displays can be largely recycled when the disassembly is carefully carried out without contamination between parts. However, the study did not provide detail about the time to dismantle the displays.

According to this analysis of the literature, various authors highlighted the relevance of the "ease of dismantling" electronic components and the need for information about the time taken to dismantle the devices (or their components). However, few detailed figures have been published (mostly based on average and aggregated values related to the waste sample). Some disaggregated data have been published, but these relate to example products that were dismantled in laboratories or special testing areas, or based on dismantling procedures that were specifically developed for the analysis. Many studies focused on full disassembly and only considered non-destructive processes: this does not reflect the reality of treatment facilities, which combine dismantling and shredding processes and use destructive tools (e.g. hammer) for the dismantling process. No detailed information was available about on-site measurements of the time taken to dismantle products in a recycling plant under normal working conditions. Finally, specific product measures have been not the focus of the data already published on the time taken to dismantle products. In all the previously discussed studies, in fact, the recommendations remained general and qualitative and no study aimed at identifying specific quantified ecodesign objectives. This seems particularly surprising when considering that the engineering design community has been arguing for a couple of years that, to be efficient, general guidelines and handbook need to be coupled with quantitative metrics (see e.g. Holt and Barnes, 2010; Dombrowski et al., 2014).

[7] The monitors and the televisions in the sample were 38 cm (15 in.) to 107 cm (42 in.) in size; the majority of monitors were 43 cm (17 in.), while the majority of televisions were 81 cm (32 in.) (Salhofer et al., 2011).

In order to fill this gap identified in the literature, measurements of the time taken to dismantle electronic displays have been collected and analysed, as described in the following sections.

4.2. Method for the analysis of the time taken to dismantle electronic displays

A method for the analysis of the time taken to dismantle electronic displays has been established, based on the following:

- Screening of the dismantling process at a recycling plant (to identify the dismantling procedure(s) adopted in the recycling plants, the dismantled parts and the dismantling steps).
- Preparation of a detailed data-sheet for data collection. This lists the main components of each display and the various dismantling steps. The data-sheet has been specifically designed to help the analysts to record the dismantling steps and time taken.
- Data collection with 'on-site' measurements taken at the recycling plant.
- Elaboration of the data.

The 'on-site' measurements were taken during a normal working day in an Italian recycling plant in May 2013. The dismantling process was carried out by two experienced workers with the set of tools they use on a daily basis (electric screwdriver, wire cutter, wrenches, pliers, hammers). The workers were not familiar with the dismantling sequence of the displays, but proceeded based on their observations and experience[8].

The condition of the electronic displays used in the investigated sample was judged to be representative of the Italian WEEE collection system. However, a few waste products were excluded from the analysis as they were too damaged or were already missing some main parts.

The measurements of the time taken to dismantle the electronic displays were recorded by two couples of analysts (in order to avoid potential mistakes in the measurements and recordings).

The 'on-site' measurements included the preliminary collection of information about the waste products (brand, model, screen size, total mass and pictures). The age of the displays was not recorded as it was not specified on the product labels or because labels were often missing or damaged. According to the recyclers, the displays were about 5–7 years old.

Analysts recorded (in the data-sheet) the dismantling steps and the related times taken to carry them out (measured using chronometers). The measured dismantling time represents the time taken to separate hazardous components and valuable recyclable fractions according to the recycling procedures as described in Section 3.1.

Measurements began once the electronic displays were positioned on the disassembly table. The measurements were performed taking care not to affect the dismantling activities of workers, in order to get a realistic and representative picture of the dismantling treatments in the recycling plant. Videos of the dismantling process were also recorded in order to support the data elaboration phase.

The dismantling steps carried out by the workers were analysed. These dismantling steps included the handling of tools, the removal of fasteners and the separation of recyclable components. During the dismantling process, recyclers also sorted extracted components. The dismantling process proceeded as far as the extraction of the lamps, TFT panels and PCBs, as detailed in Fig. 1A. As discussed in Section 3, these are the key components of the displays to be dismantled and the subject of the measurements taken at the recycling plant. The material fractions that were separated were: fluorescent lamps (hazardous waste collected in special containers); ferrous metals; non-ferrous metals; PCBs sorted in different containers according to their 'richness'; TFT panels; PMMA boards; other plastic optical components (plastic foils); other plastics (unsorted); and other components (speakers, fans).

The time taken to completely dismantle the displays was measured. The separate dismantling steps were subsequently analysed to calculate the dismantling time for the key components (as discussed in Section 4.4).

4.3. Results of the measurements of the dismantling time

The dismantling of a complete day's batch of waste displays (25 monitors and 42 televisions) was investigated. Only waste displays with fluorescent lamp backlighting systems were considered. The few Plasma Display Panel (PDP) televisions dismantled during the day were excluded. PDP televisions are currently marginal in the market (less than 3% of the total number of devices sold in 2012) and are likely to disappear from the market in the coming years (Gray, 2013). Therefore, we considered PDPs to be beyond the scope of the analysis.

Table 1 illustrates the time measurements taken for the dismantling of the displays.

The results of Table 1 are in line with the dismantling times observed in the literature (Section 4.1). The values measured in the present study were, however, less dispersed than those illustrated by, for example, Salhofer et al. (2011). Compared to data from Cyran et al. (2010), the time measurements in Table 1 are generally lower, while our results are closer to figures illustrated by Letcher (2011a), Letcher (2011b), and Vanegas and Peeters (2013). However, a more detailed comparison is not possible because data in the literature are generally not sufficiently disaggregated. It must also be considered that the results given in Table 1 refer to 'on-site' measurements that are in line with the "real" dismantling procedures at the recycling plant. Our measurements do not consider, therefore, training steps for dismantlers and have not been corrected to take into account factors such as the effectiveness and fatigue of workers, as in Vanegas and Peeters (2013).

The time taken to dismantle the displays was plotted against the size of the screen and the mass of the devices (Fig. 2). It was observed that:

- there is no substantial difference in the times taken to dismantle televisions and monitors. However, this is based on sampled monitors that were smaller than 60 cm and weighed less than 6 kg;
- the dismantling time increases with the size and mass of the waste product;
- displays of the same size (or the same mass) can have very different dismantling times. For example, the time taken to dismantle displays of around 38 cm (15 in.) varies from 200 to 600 s.

During the measurements of the dismantling times it was observed that the use of screws as fasteners generally simplifies the disassembly process. However, greater numbers of screws, especially of different dimensions, increase the time taken to dismantle the product due to the need to change dismantling tools. Furthermore, according to the recyclers, the higher amounts of time taken to dismantle products can be related to:

- the use of several types of fastening systems (e.g. several screws of different sizes);

[8] The lack of knowledge of the dismantling sequence represents an element of uncertainty in the measurement process. As confirmed by the scientific literature, the dismantling time depends on the dismantling sequence adopted (Li et al., 2013).

Table 1
Set of waste displays dismantled at the recycling plant.

Type	Mass [kg]	Size (diagonal) [cm]	Time for dismantling [s]	Type	Mass [kg]	Size (diagonal) [cm]	Time for dismantling [s]
Monitor	4	35.8	369	Monitor	2	43.6	354
Monitor	6	37.8	477	Monitor	3	47.0	986
Monitor	6	37.8	384	TV	6	47.2	582
TV	8	37.8	431	Monitor	4	48.0	256
Monitor	6	37.8	344	Monitor	6	48.0	519
Monitor	3	37.8	411	TV	5	48.4	393
TV	5	37.8	510	Monitor	5	48.7	515
TV	2	37.8	299	Monitor	4	50.6	397
Monitor	3.9	37.8	415	TV	12	50.7	624
Monitor	3.5	37.8	385	TV	4	50.7	361
Monitor	4	37.8	262	TV	9	51.1	452
TV	7	38.0	492	TV	4	51.5	510
TV	2	38.0	214	TV	5.9	55.9	450
Monitor	3	38.1	295	TV	8	66.0	523
Monitor	5	38.1	578	TV	10.5	66.0	780
Monitor	4	38.1	502	TV	13	66.0	855
TV	4	38.2	457	TV	10	66.5	598
Monitor	4.7	38.2	482	TV	13	69.0	768
Monitor	3.2	38.2	418	TV	15	80.1	859
TV	3.9	38.2	460	TV	5	80.1	410
Monitor	4	38.2	560	TV	10	80.4	807
TV	4	38.6	578	TV	16	81.3	760
TV	2.5	39.6	308	TV	10	82.8	550
TV	2.5	39.6	282	TV	10	82.8	522
TV	2	40.0	260	TV	11	82.9	1010
TV	2.5	40.6	294	TV	20	94.0	882
TV	6	41.1	440	TV	21	94.5	1158
TV	6	43.0	525	TV	29	95.4	1151
TV	6	43.0	427	TV	11	95.4	852
Monitor	4	43.0	482	TV	27	107.0	996
TV	3.9	43.3	450	TV	24	134.7	986
Monitor	6	43.4	434				
Monitor	6	43.4	986				
Monitor	5	43.4	505				
Monitor	3.5	43.4	377				
TV	3.5	43.4	358				

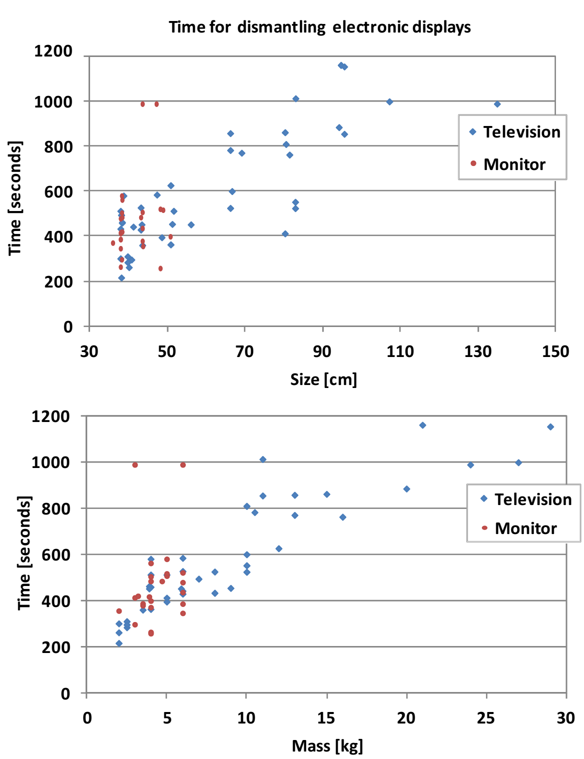

Fig. 2. Time for dismantling electronic displays.

- large amounts of different PCBs attached to the plastic cases or the external frames of the displays;
- the use of fastening systems that are very difficult to remove (e.g. PCBs glued to the frames).

In some cases the displays appeared to be not optimised for the dismantling. For example, Fig. 2 shows two monitors (with diagonal sizes of 43 and 47 cm) which required a very high dismantling time (around 1000 s).

4.4. Elaboration of the data to calculate the time taken to dismantle of key components

As discussed in Section 3, fluorescent lamps, PCBs, TFT panels and PMMA boards are currently the key components that are extracted and sorted during the recycling of electronic displays, as they contain hazardous substances, scarce and precious metals, and valuable plastics. A design that facilitates the easy extraction of these components could help to divert them from other waste flows and ensure that they undergo optimised recovery treatment processes, which would improve the amount and quality of recycled materials (Ardente and Mathieux, 2014a).

Previous data on the dismantling of electronic displays have been processed to derive the time taken to extract key components. In particular, the dismantling process of each electronic display has been analysed to identify the steps that were necessary for the extraction of the key components. This data elaboration was based on the information compiled in the datasheets during the dismantling processes, and it was supported by videos registered during the data collection phase.

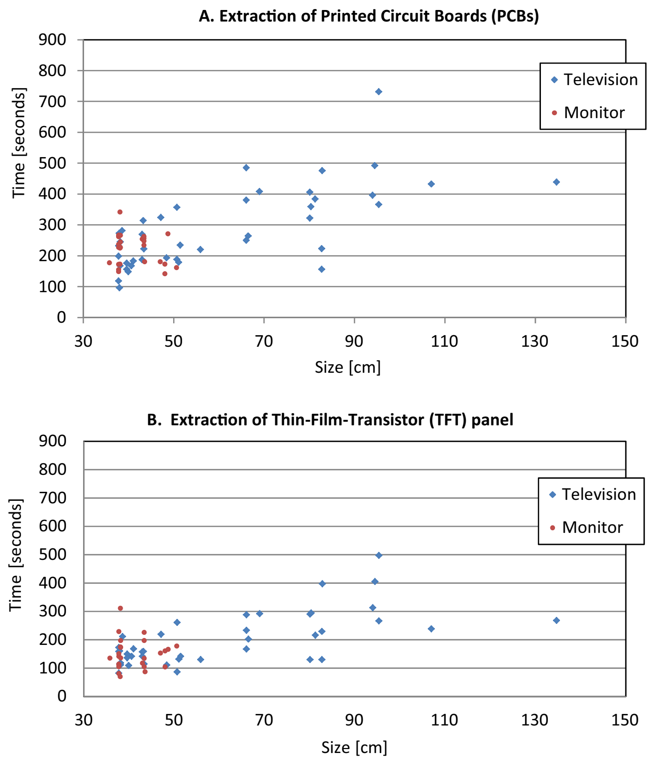

Fig. 3. Time for extracting: (A) printed circuit boards and (B) thin-film transistor panels.

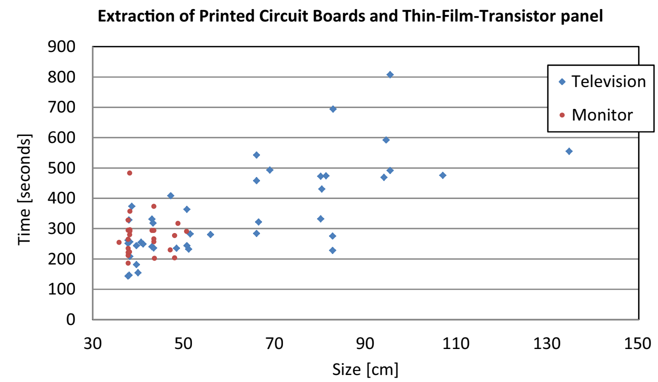

Fig. 4. Time for dismantling printed circuit boards and thin-film transistor panels.

Concerning the backlighting system, in Section 3.2 we highlighted the current technological shift towards LED-backlit systems. Fluorescent lamps have therefore not been considered in this additional analysis of the dismantling times.

It has also been observed that the extraction of PMMA boards occurs jointly with the extraction of the TFT panels, with the same dismantling steps.

Therefore, the analysis focused only on the extraction of PCBs and TFT panels (Fig. 3).

The process for extracting PCBs generally comprises of the following sequence:

- dismantling of support and back covers;
- dismantling of internal chassis and framework (supporting the inner PCB);
- dismantling and extraction of PCB and power supply;
- dismantling of front cover and extraction of side PCB and film conductors.

The process for extracting TFT panels generally comprises of the following sequence:

- dismantling of support and back covers;
- dismantling of internal chassis and frames;
- dismantling of front cover;
- dismantling and extraction of the TFT panel.

It has been observed that more time is generally required to extract the PCBs and TFT panels of larger displays. However, a lot of variability has been observed in time measurements for displays of similar sizes. For example, the time taken to dismantle the PCBs contained in an 81–84-cm (32–33-in.) electronic display varies from 150 s to over 700 s.

The time taken to extract key parts has also been plotted against the masses of the displays. Results are similar to those presented in Fig. 3. In this case, displays with similar masses can also be characterised by very different results, with some extreme cases where the time taken to extract key parts from monitors is analogous to that of televisions that are ten times heavier.

Finally, the overall time taken to dismantle PCBs and TFT panels has been calculated. This overall time measurement doesn't correspond to the sum of the times taken to dismantle these components separately, due to common steps in the dismantling sequence (e.g. the dismantling of the back cover and of the internal frames). Results are illustrated in Fig. 4.

5. Discussion of potential eco-design measures that could facilitate the dismantling of electronic displays

The disassembly of WEEE improves the value of the materials recovered by subsequent processes through the removal of contaminants and separation of valuable components (Williams, 2006). Design for disassembly has been recognised as one of the key strategies for material efficiency (Allwood et al., 2011). Whether or not to promote selective disassembly prior to shredding is an important strategic decision that should be assessed with regard to potential environmental benefits, governmental sustainability goals, process capabilities, and/or economics (Williams, 2006).

The manual dismantling of electronic displays (prior to further mechanical processes) proved to be resource-efficient and to deliver relevant environmental benefits from a lifecycle perspective (Kopacek, 2008; Peeters et al., 2013; Ardente and Mathieux, 2014a). Although manufacturers have already improved the design for dismantling in the past decade (Section 4.1), the great amount of time involved in dismantling devices could render manual treatments no more competitive than full-shredding treatments in the future. Furthermore, the full manual dismantling of displays would be difficult to maintain with an exponential growth of waste flows of displays.

In order to promote the transition to a combined manual-mechanical recycling scenario (Fig. 1C), products should be designed in such a way that key components (e.g. PCBs and TFT panels) could be extracted within a short period of time. As some of these components are generally deeply embedded in the product, a better design of the whole product for disassembly would be necessary. Considering that manufacturers have been addressing design for dismantling for many years (see e.g. (Ferrendier et al., 2002; Fujisaki, 2005; Bakker et al., 2012), they could implement this further on a voluntary basis, using the target dismantling time as a design objective.

Policy measures could be seen as good incentives to improve the design of products. Data presented in the dismantling analysis of Section 4 can be used to build possible thresholds for such policy measures. These measures could represent a significant progress in

Table 2
Percentage of displays below some thresholds of the time for extracting PCBs and TFT panels.

Diagonal size [cm]	Time [s]	Displays [%]
<64	220	18
	240	35
	260	51
	280	63
	300	78
≥64	320	17
	380	28
	440	33
	500	72
	560	83

current criteria for design for dismantling (Section 2). In addition to recycling, the design for dismantling of key components could be also synergic to the design for their reparability and substitutability, improving the product's durability (Ardente and Mathieux, 2014b).

The relationship between the time taken to extract key components and the display's size[9] (with no differentiation between televisions and monitors) must be taken into account when setting potential thresholds. Therefore, the sample investigated in Section 4 is subdivided into two sets of displays according to whether they are larger or smaller than 64 cm (25 in.). The percentage of displays for which the time taken to dismantle PCBs and TFT panels falls below certain values (Table 2) is then calculated. For example, the time taken to extract PCBs and TFT panels in 51% of the analysed displays that are smaller than 64 cm is less than 260 s.

5.1. Technical and economic viability of measures for dismantlability

This section briefly discusses the technical and economic viability of the potential measures to enhance the dismantlability of electronic displays.

It is highlighted that the design for dismantling measures will not hamper the development of mechanical recycling systems; on the contrary, the lack of such measures could represent an insurmountable obstacle for the dismantling-based facilities.

Manufacturers should not find it difficult to comply with such measures. Design-for-dismantling strategies should be relatively simple and cheap to apply in the early stages of product development (for example, at the "design for the assembly" stage of the product) (Crowther, 1999; Luttropp and Lagerstedt, 2006; Go et al., 2010; Mule, 2012). Uniform instructions for assembly and disassembly can also help optimise assembly operations (Wimmer and Züst, 2003).

With regard to the economic assessment of potential measures for dismantlability, Cui and Zhang (2008) highlighted that the major economic driver behind the recycling of electronic waste is the recovery of precious metals, followed by the recovery other metals such as copper and zinc. As highlighted by Ryan et al. (2011), a fundamental criterion for successful recycling is that there is an economic gain to be had from the disassembly process. To achieve this, it must be possible to isolate the valuable materials from the overall assembly in a timely and efficient manner, so as to keep labour overheads as low as possible (Ryan et al., 2011).

The manual dismantling of key components leads to higher recovery yields of several relevant materials (e.g. gold, silver, palladium, copper and indium), compared to a scenario whereby the displays are shredded without any manual pre-treatment. In particular, the recovery yields of precious metals are significantly higher (in the range of 95–99%) if PCBs are manually extracted for recycling compared to yields when the PCBs are mechanically sorted after shredding (12–60%) (Chancerel et al., 2009; Meskers et al., 2009).

A simplified economic assessment of the dismantling process has been carried out as follows: (a) estimation of the additional recycling yields for some materials (copper, precious metals and indium contained in electronic components) obtained with manual pre-processing, in comparison to a shredding-based scenario (values derived from the scientific literature); (b) calculation of additional revenues that can be gained thanks to manual disassembly (multiplying the additional recycled yields by the average market value of recycled materials); c) comparison of these additional revenues with the additional costs involved in the dismantling process (dismantling time multiplied by the average hourly labour cost).

Assuming an average content precious metals in PCBs (Ardente and Mathieux, 2012), it has been calculated that the manual extraction of PCBs, compared to shredding-based treatment, would allow for the additional recycling of 46.2 g of copper, 0.44 g of silver, 0.15 g of gold and 0.03 g of palladium from a small (51-cm) display; and 80.7 g of copper, 0.77 g of silver, 0.25 g of gold and 0.05 g of palladium for a large (94-cm) display. Based on the current market values of metals, estimations of the revenue to be gained from such recycling activities range between €3.5 and €4.3 (for a small display) and between €6.1 and €7.6 (for a large display)[10].

The average content of indium in a display is assumed to be 234 mg/m^2, which corresponds to 58.5 mg/kg of display (Boeni et al., 2012). Once displays are dismantled, TFT panels can be sent for selective processing; for example, the indium content could be separated by acid leaching or vaporisation, which has a recovery yield of about 85% (Götze and Rotter, 2012). Indium can be then purified by solvent extraction, electrowinning or smelting. Purification processes can recover almost 99% of indium (Götze and Rotter, 2012). Overall, it is estimated that about 80% of the indium contained in displays can potentially be recycled. The recyclable indium content of, for example, 51-cm or 94-cm displays, has an approximate economic value of €0.13 and €0.23, respectively[11].

Assuming a labour cost for a dismantler of about €150/day (Salhofer et al., 2011), it has been estimated that the extraction of PCBs and TFT panels is economically viable when:

- the time for extraction is less than 650 s (for a 51-cm display),
- the time for extraction is less than 1280 s (for a 94-cm display).

As the dismantling time of the investigated sample of displays was below these thresholds, it is economically viable to manually dismantle the displays, as is the current practice. However, modern displays should be specifically designed to improve the dismantlability of their key components.

Data presented about costs and potential revenues associated to the dismantling could be also useful for recyclers to assess different recycling scenarios with different target components to be extracted during the pre-processing.

[9] A relationship is also observed between the extraction time and the mass of the display. However, the size of displays (visible screen area) is preferred for potential future measures, as size has already been introduced as a criterion in some European policies for televisions [EC, 2009]. The size of the displays is also assumed to be a proxy for the complexity of the device and of its dismantling time.

[10] Prices of primary copper, silver, gold and palladium are derived from websites of "Infomine" (http://www.infomine.com, accessed November 2013) and "Metalprices" (www.metalprices.com, accessed November 2013). The cost of recycling is assumed to range from 20% to 30% of the cost of primary metals.

[11] The price of indium is taken from website of "metalpages" (http://www.metalpages.com/metalprices/indium/. Accessed October 2013).

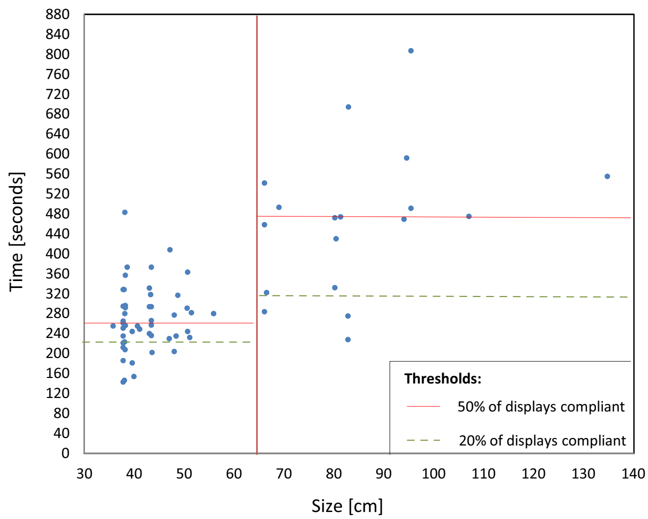

Fig. 5. Thresholds for potential measures of the dismantlability of electronic displays.

5.2. Examples of measures for the design for dismantling of electronic displays

This section briefly introduces some examples of measures to improve the dismantlability of displays based on the time thresholds for extracting PCBs and TFT panels. According to the previous analysis, it is assumed that a label of excellence (e.g. the European Ecolabel) should be awarded to the share of products that show the best performance, while mandatory policies (e.g. the European Ecodesign Directive) should remove poorly performing products from the market. In particular, it is assumed that thresholds for a voluntary policy should be set in such a way that around 20% of products in the market would be compliant, while thresholds for mandatory policy should be set in order that around 50% of products in the market are compliant.

Based on figures in Table 2, some examples of potential measures for the design for dismantling of electronic displays have been set (Fig. 5):

- Measure for a mandatory policy: For electronic displays that are smaller than 64 cm, the time for the extraction of PCBs (greater than 10 cm^2) and TFT panels shall not exceed 260 s. For electronic displays that are between 64 cm and 140 cm, the time for the extraction of PCBs (greater than 10 cm^2) and TFT panels shall not exceed 470 s.
- Measure for a voluntary policy: For electronic displays that are smaller than 64 cm, the labelling should be awarded to devices for which the time taken to extract PCBs (greater than 10 cm^2) and TFT panels is less than 220 s. For electronic displays that are between 64 cm and 140 cm, the labelling should be awarded to devices for which the time taken to extract PCBs (greater than 10 cm^2) and TFT panels is less than 320 s.

The benefits of implementing such product measures in policies include:

- The mandatory measure could remove products from the market that are not easily dismantled. This would prevent problems in the recycling plants;
- the voluntary measure could ensure the development of products that can be easily dismantled, thereby also contributing to increasing the profitability of recycling plants;
- increased profitability of manual pre-treatment in the recycling of displays would help reduce the amounts of displays to be treated via full shredding. Consequently, higher quantities of relevant materials could be more efficiently recycled;
- the time needed for the extraction of key components represents also a good proxy to assess the 'easiness to disassembly' of the product. The setting of thresholds about time for dismantling could stimulate design teams to systematically address 'dismantlability' during the design process, hence encouraging future innovations in the area of product architecture and fastenings (e.g. disassembly-oriented fasteners, as reported by Duflou et al., 2008).

Measures for the "design for dismantling" of products and associated thresholds could also be used by various stakeholders (e.g. EU Member States, manufacturers, WEEE collection and recovery sectors) to define appropriate "differentiated fees" (as proposed by the WEEE Directive (EU, 2012)) based on how easily products and their valuable raw material contents could be recycled.

Displays that are greater than 140 cm (55 in.) are not covered in the previous proposals, due to a substantial lack of data at the recycling plants about the dismantling of such products. While the amount of very large displays currently sold in the European market is still small, only a small fraction of the total WEEE market (Gray, 2013), these figures could change in the medium-long term, should very large displays become more common among consumers (as is currently the case in North America). Therefore, the continuous monitoring of the dismantling processes at recycling plants is recommended.

Also, technological changes in displays (e.g. the shift to LED backlighting systems) must be monitored in order to prevent possible future problems arising at the recycling plants. However, on-site primary data on dismantling will be available only after several years, when the first LED-backlit displays will reach their EoL. Until then, it would be beneficial if information about the dismantling of new products were disclosed by manufacturers.

Finally, in order to enforce regulations regarding the time taken to dismantle products, standardised methods to measure the dismantling times will be required, as argued by Mathieux et al. (2014). Verification of such measurements is crucial to effectively implementing dismantling measures.

6. Conclusions

This article presents a novel approach to identify practicable ecodesign measures to support the disassemblability of WEEE. The approach has been tailored to electronic displays (flat screen televisions and computer monitors).

As observed in two recycling plants in Italy, and confirmed by communications from associations of recyclers and by scientific studies in the literature, the recycling of displays in Europe currently involves mainly the manual disassembly of the waste product. The choice of treatment is mainly driven by legislation (WEEE Directive 2012/19/EU) and by the limited amount of waste flow reaching the recycling plants. In addition, manual dismantling has economic benefits due to the revenues obtained for precious and scarce metals recovered from the electronic components.

Some shredding-based recycling plants are currently under development, but these are still hampered by technical problems (mainly the removal of mercury from the backlighting system, which can contaminate other recyclable fractions). Some companies also claim to have developed the first examples of automated dismantling systems, but data about the processes involved and their efficiency are not yet available.

According to our analysis, the recycling of displays will probably change significantly over the coming years because of technological changes of the displays (e.g. adoption of mercury-free backlighting systems), a massive increase of the number of displays entering the waste stream at their end-of-life, and higher labour costs (due, for example, to more complex displays which require more time to be dismantled). All of these aspects could drive recyclers of electronic displays to adopt shredding-based recycling technologies in the future. On the other hand, shredding-based treatments of electronics in general, and of displays in particular, were found to be less resource-efficient due to higher material losses (Chancerel et al., 2009; Peeters et al., 2013; Ardente and Mathieux, 2014a). In addition, shredding-based recycling treatments are currently not compatible with the recycling of other relevant and hazardous materials (such as indium in the displays, or rare earths and arsenic in LEDs), and the potential design for reuse of some components.

The article therefore identifies potential quantitative measurements that would help improve the pre-processing of waste displays, with a particular focus on the time taken to dismantle some key components. The analysis carried out at two recycling plants found that some key components of the display (such as the PCBs, lamps and TFT panels) are highly relevant in terms of: (a) their content of hazardous or scarce materials; and (b) economic revenue for the recyclers. The time taken to dismantle the displays was measured on-site, and the disaggregated results are presented. For example, it has been estimated that the time necessary to dismantle the PCBs in 40-cm to 70-cm displays varies from 100 to over 500 s.

Data on dismantling time have been used to assess the costs and potential revenues of pre-processing waste displays. For example, it emerged that manual dismantling is economically viable when the extraction of the key components takes less than 650 and 1280 s (for displays smaller or greater than 64 cm, respectively).

To support the adoption of manual dismantling in pre-processing activities, future displays will have to be designed to be easily dismantled. The presented data have been used to identify some "design for dismantling" measures based on thresholds of the time needed to extract key components. These measures could be enforced via a mix of voluntary product policies (e.g. the EU Ecolabel) and mandatory product policies (such as mandatory ecodesign implementing measures). The implementation of such measures could have multiple benefits, including improved economic profitability of recycling plants, reduced costs for consumers (e.g. through differentiated fees when products are put on the market). The analysis of times for dismantling and the setting of potential policy measures could also stimulate industrial innovations in designs for dismantling. Manufacturers could start to implement on a voluntary basis such quantified objectives in their design processes and could be encouraged to develop innovations in the area of product architecture and fastenings.

Additional research is recommended concerning the dismantling of large (greater than 140-cm) displays and displays with new technologies (e.g. LED-backlighting).

Finally, although this analysis focused on electronic displays, the approach followed and the conclusions on the relevance of manual dismantling and related policy measures are sufficiently general and might be feasible for other WEEE product categories. This should be assessed in future research projects, using a similar method to systematically analyse the recycling treatments applied to the product group and comparing the costs and revenues of automated and manual pre-processing.

Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

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