Journal of Cleaner Production 19 (2011) 1066–1071

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Characterising components of liquid crystal displays to facilitate disassembly

A. Ryan[1], L. O' Donoghue*, H. Lewis

Manufacturing & Operations Engineering Department, University of Limerick, Castletroy, Limerick, Ireland

A R T I C L E I N F O

Article history:
Received 18 May 2010
Received in revised form
7 January 2011
Accepted 17 January 2011
Available online 26 January 2011

Keywords:
Recycling
Liquid crystal displays
Disassembly

A B S T R A C T

Liquid Crystal Display (LCD) technology has evolved and developed over the past decades to replace Cathode Ray Tube (CRT) display technology as the market leader. This is evident, with global market figures for liquid crystal displays surpassing $75 Billion in 2008.

Current End-of-Life (EoL) disposal for LCD screens is typically landfill or incineration, this form of disposal restricts the ability to recover potentially reusable materials from waste LCD screens e.g. steel, aluminium, copper etc. Thus to conserve raw materials and to protect the environment it is essential to replace the traditional flow of products from manufacturer to landfill with a recycle and recover approach.

While the recycling methods for CRTs are well established, however those of LCDs are as yet in their infancy. However to reduce consumption of natural resources and reduce quantities of waste going to landfill, recycling process must be encouraged and developed.

This paper aims to address the challenges facing EoL treatment of LCD units by analysing LCD build types, structures and component material to establish traits which may make EoL treatment less of a challenge. Analysing this data will lay the foundation to developing a balanced recovery system meeting the needs of economic viability and environmental conservation in future work.

1. Introduction

The environmentally benign manufacturing, use and End-of-Life (EoL) treatment of LCD products are a challenge for all manufacturers, users and recyclers dealing with this strongly growing technology (Franke et al., 2006). LCD sales are forecasted to surpass $80 Billion in 2012 (Voorhees, 2009), (Fig. 1), this equates to a significant environmental issue when these products reach their EoL as current methods of disposal include landfill or incineration. The justification for selecting LCD panels for this study over Plasma Display Panels (PDP) for example is apparent from Fig. 1. In this graph is it evident that sales of LCDs in 2012 are predicted to be almost 6.5 times higher than those of PDPs making the need to develop a successful disassembly process for LCD panels critical. In future work the authors will focus on the issue of PDP panels.

To reduce the potential impact on the environment when electrical products reach their EoL, the European Union has introduced a number of directives, the most significant being the Waste Electrical and Electronic Equipment Directive (WEEE), whose main objectives are:

- Reducing the waste arising from EoL electrical and electronic equipment.
- Improving and maximising recycling, reuse and other forms of recovery of waste from EoL electric and electronic equipment.
- Minimising the impact on the environment from their treatment and disposal (Parliament, 2003).This research is focused on these central objectives and will characterise the components of an LCD to facilitate disassembly thereby significantly reducing the environmental impact at the products EoL.

The predicted growth in LCD production will certainly place an increased demand on the quantity of raw materials being consumed. Section 3 of this article illustrates the various different material types involved in the manufacture of LCD panel – from this analysis it is possible to approximate the quantity of materials needed to satisfy LCD demand.

A successful disassembly system which improves the recycling and reuse of materials from waste LCD screens would ensure that raw materials are conserved. It is therefore essential to replace the traditional flow of products from manufacturer to landfill with a recycle and recover approach (Kopacek and Kopacek, 1999).

However there are significant obstacles to developing this alternative product flow, one of which is unlike conventional manufacturing processes, recycling or disassembly operations are

* Corresponding author. Tel.: +353 61 202910.
E-mail addresses: alan.ryan@ul.ie (A. Ryan), lisaodonoghue@ul.ie (L. O' Donoghue).
[1] Tel.: +353 61 234864; fax: +353 61 202913.

0959-6526/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jclepro.2011.01.009

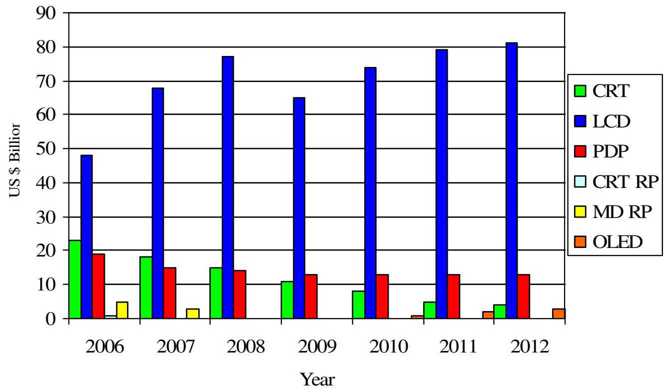

Fig. 1. Predicted future LCD sales (Voorhees, 2009).

characterised by a high variety of products and an uncertain product condition after usage (Parlikad et al., 2006).

This uncertainty influences the steps required to disassemble the product. When recycling or disassembling products the ladder of Lansink (Lansink, 1980) (Fig. 2) has long been recognised as the ecologically inspired hierarchy of preference for the end-of-life treatment of products. The optimal scenario for the treatment of EoL product is to aim for the highest levels in this hierarchy, namely product reuse and disassembly with optimal reuse of parts and components (Duflou et al., 2006), however this is not always a realistic objective.

It should be noted that where the responsibility for the treatment of discarded products is assigned to organisations operating to market principles (reduce costs/maximise profits), this typically leads to systematic shredding of discarded products after minimal de-toxification according to government regulations (Duflou et al., 2006).

This point illustrates that the recyclers key concern is to maximise profits by isolating the valuable materials from the waste product as efficiently as possible within environmental regulations. Thus any system developed for recycling of Liquid Crystal Display screens must be flexible to cater for a high variety of products, efficient in processing these products and deliver usable materials inline with environmental regulations.

This paper will focus on identifying the overall structure of the LCD and classifying the material types present. It will illustrate the presence of any hazardous materials and outline the potential obstacles to disassembly these may present. Performing a detailed analysis of the LCD structure will ensure that the LCD disassembly can be designed to achieve a balance between the quality of the recovered material and the economic cost required to extract the material.

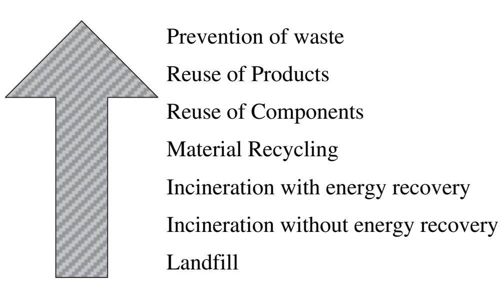

Fig. 2. Lansink's ladder (Lansink, 1980).

2. LCD disassembly investigations

2.1. LCD structure

In total 17 LCD units were disassembled, Table 1, this number was chosen as it was the number used by a similar study performed by Franke et al. (2006). A report issued by iSuppli – in June 2010 (Patel, 2010) indicated that for Quarter 2 2010 Samsung (18% of US market share), Sony (11.3%) and Philips (7.8%) were among the most popular LCD suppliers while 38% of the market (3.8 million units) was made up of unnamed other suppliers. Therefore to reflect the market Philips, Sony and Samsung LCDs together with a number of less recognised manufactures were selected for disassembly.

By selecting a wide variety of manufacturers and screen sizes is will be possible to determine both the internal structure of a generic LCD and also quantify the types of material associated with LCD manufacture. It will be possible to determine if there is significant variation between the internal structures from manufacturer to manufacture as major differences in LCD structure between manufactures will obviously impact on the efficiency of a disassembly process. Establishing the types of material and LCD structure will be used to develop a system of LCD disassembly targeting key materials.

Each unit was disassembled from the back by unscrewing the various screws, fasteners etc, layers were identified, the material type was recorded and weighed. The time taken to disassemble the units was also recorded. The average time taken to fully disassembly an LCD into its individual components was 14 min – factors such as screw position, heat shielding, quantity of screws, presence of adhesive tape and indeed the size of the screen influence the disassembly time. These factors were explored in a paper previously composed by the authors (Ryan et al., 2010).

From this analysis of LCD screens it was established that the general structure of the LCD unit remains unchanged from supplier to supplier, however positional location of PCBs, screws, cables, speakers etc can differ radically from one LCD manufacturer to the next & even within manufacturer families.

It was established that the LCD unit has the following structure (from front to back)

- Top cover
- Lightbox assembly
- PCB Mounting Frame
- LCD control layer – PCBs, speakers, cables
- Back cover

The lightbox assembly itself consists of a metal frame, LCD glass panel, plastic frame, a number of plastic diffuser sheets, Perspex sheet, cold cathode fluorescent (CCFL) tubes, reflective foil and the lightbox support frame. This is graphically illustrated in the exploded view in Fig. 3.

Table 1
LCDs selected for disassembly.

Screen No	Manufacturer	Size	Screen No	Manufacturer	Size
A	Sony Bravia	32″	J	Matsui	32″
B	Maxim	32″	K	Samsung	32″
C	Philips	32″	L	Advent	32″
D	Sony Bravia	40″	M	Sony	32″
E	Panasonic	32″	N	Maxima	32″
F	Philips	23″	O	Samsung	32″
G	Bush	27″	P	Bush	32″
H	Philips	27″	Q	Beko	20″
I	Sony	32″			

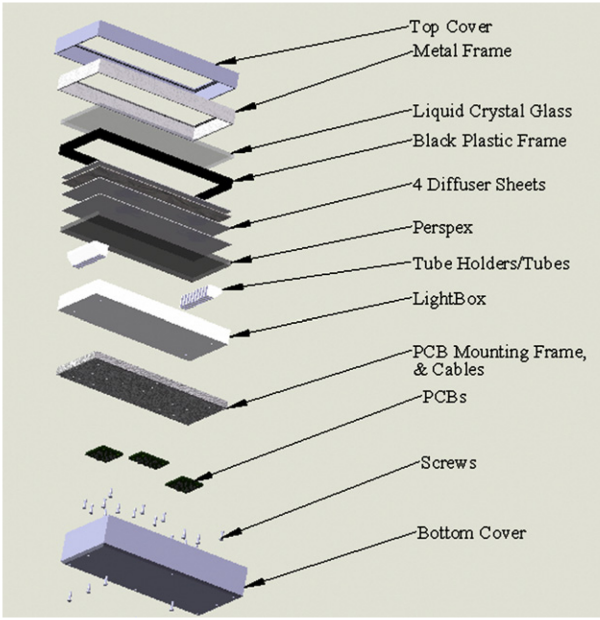

Fig. 3. LCD unit exploded view.

Fig. 4 illustrates the flow of the disassembly process for each of the LCD screens outlined in Table 1. For the analysis undertaken is was established that the overall generic structure of the LCD remained similar from screen to screen – however issues such as screw type, screw position, cable attachment, position of PCBs etc. were subject to change. With the goal to develop a disassembly system which ranks highly on Lansink's ladder the impact of these differences within the LCD structure are significant as they impact on the ability to achieve clean and total separation of the product in a cost effective manner.

However before deciding on an approach to developing a method of disassembly it is first necessary to establish and quantify the materials present in the LCD. By having an accurate representation of the spectrum of materials only then it is possible to investigate means of salvaging these materials. The following section outlines a material composition analysis undertaken on the disassembled LCD screens.

3. LCD material analysis

A fundamental of the WEEE Directive (Parliament, 2003) is a target to recycle 75% of the product by weight, an understanding of the composition of the LCD assembly could allow recyclers to target key component to achieve this 75% target in a minimal amount of process steps thereby improving the economic efficiency of the process. Accurately targeting key components would ensure that the recycling process becomes more streamlined and structured and therefore more cost effective. This ensures that both the environment agencies and the recycler are satisfied.

During disassembly the individual components were segregated and weighed, the data was then combined and summarised in Figs. 5 and 6. This data represents the breakdown of the material for all units disassembled.

From Fig. 6 is its apparent that a number of key components in the LCD structure contribute significantly to the overall weights of the unit.

- Lightbox casing, with an average weight of 2.4 kg represented 18% of the overall LCD weight,
- PCB Mounting Panel had an average weight of 2 kg and contributed to 14% of the overall LCD weight,
- Back cover contributed 14% and Printed Circuit Boards 10% of the overall LCD weight.

Table 2 identifies the average percentage weight associated with the individual components for the various screen sizes – for the LCDs detailed in Table 1.

From Table 2 it is apparent that for most components the range in percentage weight across screen sizes is quite small <5%. The internal structure variation between the screen sizes contributes to range variation for example the 40 inch LCD requires greater

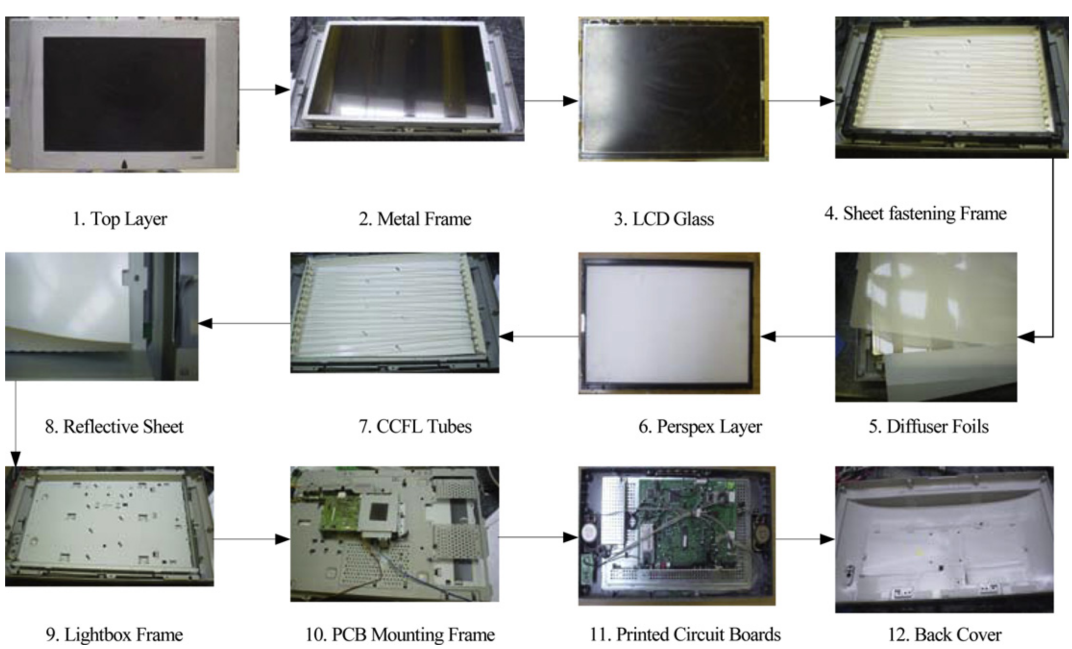

Fig. 4. Flow of disassembly through the layers of an LCD display.

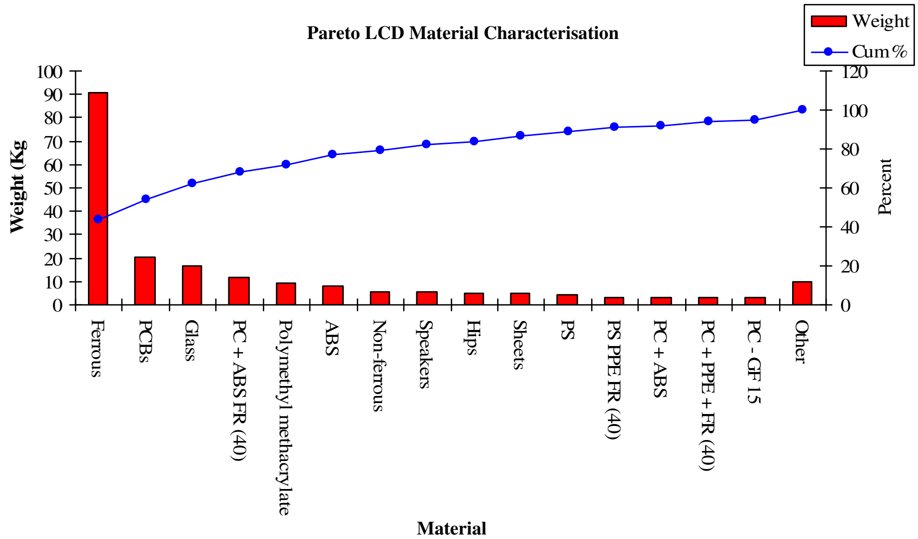

Fig. 5. Pareto of material type by weight.

structural support than a 20 inch LCD therefore the lightbox casing contributes 30% of the overall weight of the 40 inch unit. In a 20 inch unit the Perspex plate is made from 6 mm to 8 mm thick Perspex compared to in units >23 inch where the Perspex plate is only 2 mm thick – this variation again contributes to the range variation.

It can be stated therefore that a disassembly system which can actively target these weighty components will help achieve the minimum 75% target in a more cost effective manner.

Thus from this analysis of the material to achieve the minimum 75% recycling target, it is necessary to recover the ferrous metal, plastics and PCBs. Obviously it should be stated that the 75% target is a minimum expectation and efforts should be made to try and increase the percentage recycled. This can be achieved by understanding the composition of the LCD, the variations within the LCD families and targeting key items such as the back cover for example which is on average 15% of the overall weight of the LCD or the lightbox casing which is also 15% of the weight on average.

For flat screen monitors analysed halogen free plastics e.g. PC + ABS + FR (40) or PC-FR (40) were found, if separated properly these plastics can be recycled for use in similar applications (Franke et al., 2006). A significant percentage of the weight is ferrous metal this is encouraging as the separation of ferrous metal is a relatively old technology using electromagnets to draw the material from waste streams.

The CCFL tubes represented 1% of the overall LCD weight, however due to the potentially hazardous materials they contain the CCFL tubes merit special consideration during the disassembly process. This will need special attention during the design of the disassembly process. Other potentially hazardous materials which require special attention during disassembly are detailed in Section 3.1.

3.1. Potentially hazardous materials

When analysing the constituent parts of the LCD module it should be noted that there are a number of potentially hazardous materials.

Cold cathode fluorescence lamps (*CCFLs*) which contain small quantities of mercury require special treatment. CCFLs must be disassembled from the LCD module (Franke et al., 2006). It is estimated that between 290 kg and 480 kg of mercury will ultimately have to be disposed of for all 80 million LCD’s in use worldwide in

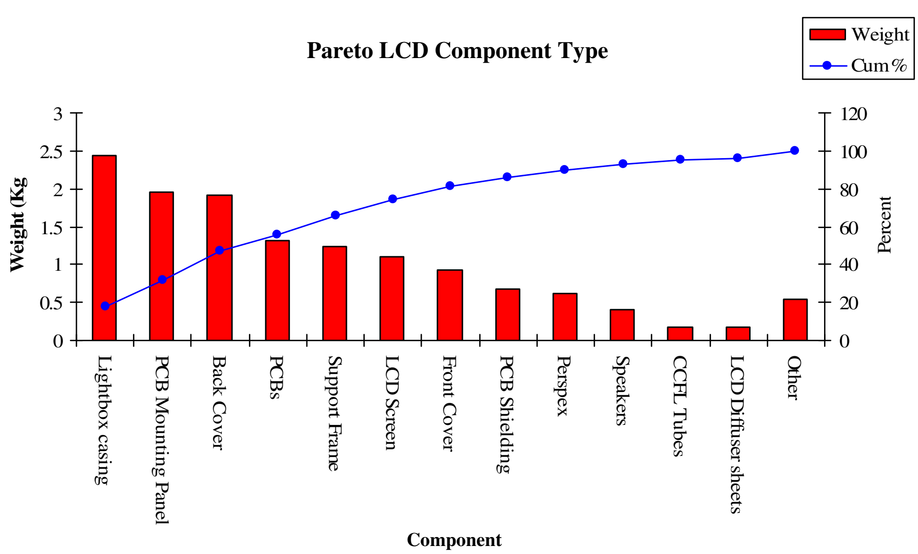

Fig. 6. Pareto of component by weight.

Table 2
Screen size component characterisation.

LCD Component	Screen Size percentage of overall screen weight (%)						
	32″	40″	23″	27″	20″	range	average
LCD Screen	8	10	11	9	8	3	9
Front Cover	7	7	8	6	5	3	7
Back Cover	14	15	19	15	14	5	15
LCD Clamping Frame	2	2	2	1	2	1	2
Tube holders	1	2	0	0	0	2	1
Lightbox casing	18	30	10	9	10	21	15
PCB mounting panel	14	8	24	18	23	16	17
PCB protectors	5	5	6	9	2	7	5
Support frame	9	5	0	14	0	14	6
Backlighting tubes	2	2	1	1	1	1	1
PCBs	11	6	8	9	11	5	9
Diffuser sheets	1	2	2	1	0	2	1
Polarising Sheet	1	0	0	1	0	1	0
Perspex	3	6	6	7	22	19	9
cables	0	0	0	0	0	0	0
Speakers	4	0	3	0	2	4	2

2010 (Displaysearch, 2007). With LCD sales predicted to rise the quantity of mercury to be disposed of as these LCD reach their EoL is also increasing. It is essential therefore that any disassembly system/process developed is equipped to handle this volume of mercury and CCFL tubes.

The liquid crystal display: the LCD glass is made up of a number of layers, these typically contain 25 or more components. These include, glass, foil and liquid crystal compounds (Behrendt and Erdmann, 2004). While the German Federal Environmental Agency have issued a statement stating the LCDs do not require special disposal due to the content of liquid crystals (Martin, 2005), and a report published by MERCK (liquid crystal manufacturer) claims that liquid crystals are “not acutely toxic, are not suspicious of carcinogenicity and are not toxic to aquatic organisms” (Martin et al., 2004), the European Union does not agree. In the WEEE Directive (Parliament, 2003) it is stated that for liquid crystal displays (together with their casing where appropriate) of a surface greater than 100 square centimetres have to be removed from any separately collected WEEE. Accordingly as the EU are of the view that the LCD glass panel represents an environmental risk it is currently necessary to segregate and process the LCD glass aspect of the TV separately.

Printed circuit boards: Due to the mandatory disassembly and separate treatment of printed circuit boards these need to be separated from the LCD unit (Franke et al., 2006). The EU WEEE directive also states that PCBs greater than 10 cm^2 need to be removed from waste electrical and electronic equipment. Printed circuit boards are a constituent components of all electronic and electrical equipment and can contain various metals such as copper (Cu), iron (Fe), lead (Pb), zinc (Zn), gold (Au), silver (Ag), platinum (Pt),(Becker et al., 2003). The substrate of the printed circuit board is a thermoplastic material with contents of flame retardants and according to Bi et al. (2010) PCBs are not easy to recycle.

4. Discussion

It is apparent from the above analysis of a number of LCD panels from different manufacturers and of varying sizes that there is significant variability within the LCD structure. This variation has considerable effect on disassembly. Design for disassembly and recovery is to the forefront of modern manufacture however as has been illustrated by previous work by the authors LCD manufacturing is a complex process with numerous fastening and joining technologies. These variables ensure that disassembly is difficult and time consuming. Going forward LCDs should be designed with a view to End-of-Life material recovery to rank highly on Lansink’s ladder however this does not address the issue of millions of LCDs currently in production and use worldwide. Key decisions such as the level of manual intervention required, the level of automation needed and the flexibility of the system need to be addressed before a disassembly process to deal with these existing LCDs can be established.

However the characterisation of constituent components of the LCD is a vital step in the structuring a disassembly sequence. It was established that a significant percentage of the material is ferrous metal – which can be recovered easily from a waste stream using magnetic separators while other non ferrous metals can be separated using eddy current separators.

It was found that a number of key components within the LCD assembly contributed significantly to the overall weight of the LCD. By targeting these components it may be possible to improve recycling efficiency and the economic return gained from recycling. It is the objective of this research to use the data obtained from the analysis of LCD structures to develop a targeted disassembly system

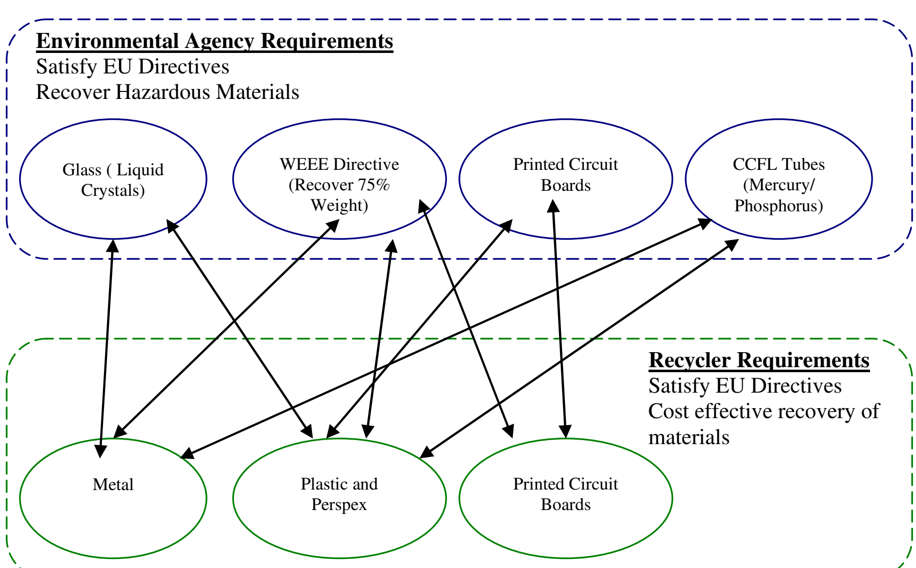

Fig. 7. Interaction between recycler and environmental regulatory authorities.

to facilitate multiple LCD sizes. This system should aim to rank highly on Lansink's ladder and promote the reuse of materials and components where possible.

A key fundamental to achieving successful recycling is to ensure that there is an economic gain from the disassembly process. To achieve this the recycled waste much be recovered in such a manner as to ensure that there is a market for the product, i.e. it needs resale value. It must then be possible to isolate this material from the overall assembly in a timely and efficient manner to ensure that labour overheads are maintained as low as possible.

The environmental regulatory authorities need to ensure that specific targets with regard to the recycling and/or disposal of LCD screens are adhered to. However it should be possible to use both the requirements of the environmental regulatory authorities and the recyclers to ensure that an economically viable and environmentally considerate disassembly process is developed. Fig. 7 illustrated this interrelationship.

This figure aims to illustrate the balance of requirements between the environmental agencies and the LCD recyclers. In Section 3.1 it was established that the Liquid Crystal glass panel was deemed hazardous and as such needs to be removed from the LCD assembly for further processing. From a recyclers perspective to gain access to the potentially valuable ferrous metal and plastic the liquid crystal display needs to be removed – thus both bodies are satisfied.

In Section 3.1 it was established that the mercury in CCFL tubes represents a concern for the environment and as such needs to be removed from the assembly. Again for the recycler this removal will facilitate access to metal and plastic materials which can then be marketed further.

The requirement of a minimum 75% recycling of the product represents opportunity for both parties. The challenge is to develop a disassembly processes which provides access quickly and easily to the relevant materials e.g. lightbox casing, this will ensure that 75% recover can be achieved in a repeatable manner.

In essence the recycling of LCD screens must balance the needs of the recycler and the environmental agencies to ensure that recycling of LCDs can be encouraged.

5. Conclusions

This paper has aimed to illustrate the requirement for a systematic approach to LCD recycling. It has illustrated that the numbers of LCD reaching the end of their useful life are expected to rise over the next number of years.

It has outlined a structural overview of the LCD assembly and detailed a material composition of the LCD structure. This information is critical to establishing the needs of a recycling process. The paper the moved to discuss potentially hazardous materials within the LCD assembly, this ensures that key environmental concerns and requirements are designed into the processes from the fundamental stages. Finally the paper illustrated the trade off between the recycler and the environmental agency need not be confrontational, that in reality both require the same materials to be removed from the assembly to ensure the process is successful.

From this investigation it would appear that the best approach to recycling or disassembling LCD systems would appear to be a hybrid system of manual and automated processes. This would ensure the economic sustainability associated with high volume automated processes and also ensure the flexibility associated with manual processes. This flexibility is critical when adapting to the variation in LCD screens.

Acknowledgements

The authors would like to acknowledge the funding received from the Environment Protection Agency and the National Development Plan.

References

Becker, W., Simon-Hettich, B., Honicke, P., 2003. Toxicology and Ecotoxicology Investigations for Liquid Crystal and Disposal of LCDs.
Behrendt, S., Erdmann, L., 2004. Display-Märkte im Umbruch Neuorientierungen für Umweltschutzstrategien. Institut für Zukunftsstudien und Technologiebewertung, Berlin.
Bi, X., et al., 2010. The major components of particles emitted during recycling of waste printed circuit boards in a typical e-waste workshop of South China. Atmospheric Environment 44, 4440–4445.
Displaysearch, 2007. TV Supply Chain onference, Displaysearch, Editor.
Duflou, J.R., Willems, B., Dewulf, W., 2006. Towards self-disassembling products. In: Innovation in Life Cycle Engineering and Sustainable Development. Springer, Grenoble.
Franke, C., Kernbaum, S., Seliger, G., 2006. Remanufacturing of flat screen monitors. In: Innovation in Life Cycle Engineering and Sustainable Development. Springer, Grenoble.
Kopacek, B., Kopacek, P., 1999. Intelligent disassembly of electronic equipment. Annual Reviews in Control 23, 165–170.
Lansink, A., 1980. Vergaderjaar, 15–80.
Martin, R., Becker, W., B, S.-H., 2004. Safe Recovery of Liquid Crystal Displays (LCDs) in Compliance with WEEE in Electronics Goes Green (Berlin).
Martin, R., 2005. New industrial recovery processes for LCDs – an example for sustainability. In: International Electronics Recycling Congress. Merck, Basel.
Parliament, T.E., 2003. Directive 2002/96/EC of the European parliament and of the council of 27 January 2003 on waste electrical and electronic equipment (WEEE). Official Journal of the European Union 46, 24–38.
Parlikad, A., McFarlane, D., Kulkarni, A., 2006. Improving product recovery decisions through product information. In: Innovation in Life Cycle Engineering and Sustainable Development. Springer, Grenoble.
Patel, R., 2010. Samsung Takes Lead in U.S. LCD-TV Market in Q1.
Ryan, A., O'Donoghue, L., Lewis, H.J., 2010. Investigating the recyclability of liquid crystal display TV's. In: 20th International Conference on Factory Automation & Intelligent Manufacturing (FAIM). California State University, San Francisco.
Voorhees, S., 2009. Worldwide TV Forecasts, Displaysearch, Editor.