Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 15 (2014) 251 – 256

www.elsevier.com/locate/procedia

21st CIRP Conference on Life Cycle Engineering

Automatic Dismantling Challenges in the Structural Design of LCD TVs

Kristofer Elo[a]*, Erik Sundin[a]

[a]*Linköping University, Department of Management and Engineering, Linköping University, Linköping, 581 83, Sweden*

* Corresponding author. Tel.: +46 13 28 11 64. *E-mail address:* kristofer.elo@liu.se

Abstract

Many liquid crystal display television sets (LCD TVs) end up in the waste stream today. The combination of hazardous materials such as mercury and liquid crystal, and the labor-intensive disassembly of LCD TVs, make the recycling process interesting to automate. However, since there are so many manufacturers the variation of LCD TVs is high, making automation a challenge. Today's most common automatic process utilizes shredders, resulting in degradation of recycled material and possible decontamination of machine equipment. This paper aims to investigate the challenges related to the structural design of LCD TVs for an automatic dismantling process for the recycling of LCD TVs. The challenges identified during the empirical study were related to the mixture of materials, inhomogeneous materials, thin design, separation of the different components and finding a suitable dismantling sequence without unnecessary removal of components.

Keywords: *structural design; dismantling; liquid crystal display television sets; mercury; liquid crystal; automatic dismantling*

1. Introduction

There are numerous electrical and electronic equipment (EEE) products which end up as waste in Europe today. The amount of collected EEE waste in 2010 was in total 3.61 million tons [1]. One subgroup of EEE waste is consumer equipment, and the amount of discarded products in 2010 was 640 thousand tons [1-2]. One of these consumer products is the liquid crystal display (LCD) television (TV), which contains liquid crystals and can contain mercury [2]. Common automatic LCD TV recycling processes in Europe consist of shredding followed by sorting and separation processes [3]. To cope with the mercury vapors released the shredding system needs to be fitted with systems [4]. However, the highest concentration of mercury which can be found in the cold cathode florescent lamps (CCFLs) of the LCD TVs is amalgamated to the electrodes in the CCFLs, and not found as vapors [5]. This makes it difficult to extract all of the mercury from LCD TVs using the shredding process. Another way to recycle LCD TVs is to disassemble them by hand; however, this is labor intensive and the operators are at risk of inhaling mercury vapors if the disassembled LCD TVs contain broken CCFLs [6]. The inability of the shredding process to remove amalgamated mercury and the labor-intensive disassembly makes it interesting to find a new way to automate the dismantling of LCD TVs. There are automated dismantling and disassembly systems found in the research literature that are capable of disassembling products such as LCD TVs and LCD monitors. The system utilizes flexible and complex grippers and tools to be able to remove the components with some minor damage [7-8]. However, the structural design of LCD TVs is challenging due to the wide variation of manufacturers and the constant product development. This makes it important to investigate if there are any challenges related to the structural design of today's LCD TVs.

2. Aim

The aim of this paper is to identify the challenges related to the structural design of LCD TVs for an automatic dismantling process for the recycling of LCD TVs.

doi:10.1016/j.procir.2014.06.058

3. Methodology

During the work for this paper a literature review was performed, as well as an empirical study where 12 LCD TVs were disassembled. 12 TVs were chosen for disassembly as this was the number of TVs available at the time of the analysis. In the literature the number of analyzed TVs ranges from 11 to 41 [9-11]. The LCD TVs were collected in 2013 from a recycling center in Linköping, Sweden. A recycling center is where visitors can discard waste, e.g. large-sized household equipment, hazardous wastes and EEE waste [12]. The reason for collecting TVs from the recycling center was to be able to get samples from the present waste stream in Sweden. No effort was put into collecting specific brands, models or sizes; the only feature which was prioritized was that the TVs were LCD TVs.

4. Liquid crystal display television

The development of TVs began with the cold ray tube (CRT) TV at the end of the 19th century [13]. Between 2000 and 2005, CRTs were replaced by LCD technology [14]. Besides the TV application, LCD technology is used in e.g. calculators, mobile phones, and laptop computers [14].

4.1. Structural design of LCD TVs

In the research literature, the structural design of LCD TVs is described in one general way as illustrated in Figure 1, but with two main designs of the lighting units. The two lighting unit designs are direct-illuminated in an LCD light box (Figure 2) or edge-illuminated in an LCD module (Figure 3) [14-16]. The general design can be described as a stack of components.

The design of newly manufactured LCD TVs contains light-emitting diodes (LEDs) [17] instead of the CCFLs. Among the twelve LCD TVs analyzed in this empirical study, only one had en edge-illuminated LCD module with LEDs.

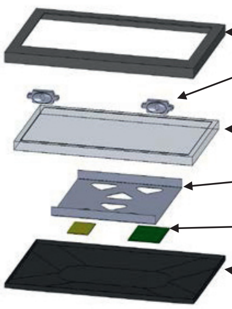

Fig. 1 General structural design of LCD TVs where LCD light boxes are used for direct-illumination and LCD modules are used for edge-illumination [15-16].

4.1.1. Direct-illuminated design with a light box

A direct-illuminated LCD TV with a light box contains a set of CCFLs placed directly behind the screen, as shown in Figure 2. Between the screen and the CCFLs are a set of diffuser sheets which spread the light evenly onto the screen [15-16]. Components not illustrated in Figure 2 are: power supply cables to the CCFLs; printed circuit boards for controlling the screen; flexi foils for connecting the LCD screen to the printed circuit boards; holders for the CCFLs between the CCFL end points; and the fixating screws.

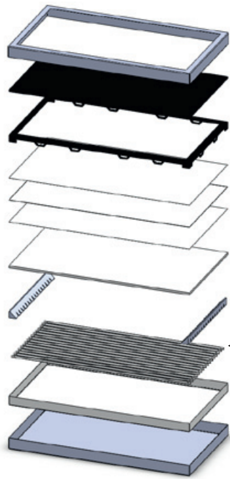

Fig. 2 Exploded view of the structural design of an LCD light box (modified from Ryan et al. [9] and McDonnel et al. [5]).

4.1.2. Edge-illuminated design with an LCD module

The general design of an LCD module is illustrated in Figure 3. The light is illuminated by the CCFLs or LEDs into the long-sides of the light guide. The light is further distributed to the LCD screen via the light guide and diffuser sheets. The reflection sheet directs light traveling from the screen towards the screen instead [5, 9]. Only one long-side can be utilized to illuminate the LCD screen to make the structural design of LCD TVs even thinner [18]. Components which are not shown in Figure 3 are the power supply cables to the CCFLs, the printed circuit boards for controlling the LCD screen, the flexi foils for connecting the LCD screen to the printed circuit boards, and the fixating screws. The

LCD module in a TV is similar to an LCD desktop monitor; the difference is the size.

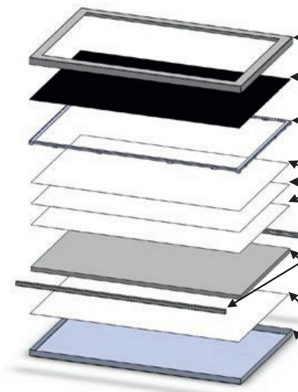

Fig. 3 Exploded view of the structural design of an LCD module (modified from McDonnel et al. [5] and Matharu et al. [12]).

4.2. Mercury content in CCFLs

The number of CCFLs to expect in an LCD TV can vary, depending on, among other things, the structural design. The direct-illuminated LCD TV can contain up to 82 CCFLs [19]. More common numbers of CCFLs are between 2 and 28 lamps [5, 20-23]. The amount of mercury in a CCFL used in LCD TVs ranges from 0.1mg per lamp to 10mg per lamp, depending on the author [5, 14, 19, 23-25]. The span of mercury in TV CCFLs is expected to be due to differences in size, the amount of mercury fitted into the CCFLs when manufactured, the hours used, and how the measurement was performed. Industrial references state that the amount of mercury in CCFLs is less than 3mg per lamp [26-27]. The number of CCFLs and the amount of mercury per lamp means that the amount of mercury may be more then 300mg per LCD TV [13]. The amount of mercury evaporated into the air when CCFLs are broken has been studied by Elo and Sundin [6]. They conclude that the mercury vapors from CCFLs can be high right after opening an LCD TV for disassembly if there are broken CCFLs inside. The highest concentration measured was 0.250mg/m^3. This value can be compared with the mercury vapor thresholds allowed in the working environmental in e.g. Sweden, which is 0.1mg/m^3. However, since the high levels are reduced rapidly in a well-ventilated working environment, there are no working environment problems as long as the ventilation works properly.

4.3. Recycling processes for LCD TVs

The two common general recycling processes for recycling LCD TVs are a semi-automatic shredding process and manual disassembly process [4]. In shredding process there is usually manual sorting or disassembly steps of components such as removal of cables [28]. Such shredding process is illustrated in Figure 4. To be able to sort the different materials after the shredding processes several sorting processes can be utilized; include magnets, density and mechanical separations like jigging [28]. Since LCD TVs with CCFLs contain mercury, the systems are fitted with ventilation systems for managing the mercury vapors [4].

There are alternative processes to the shredding process for opening LCD TVs and LCD desktop monitors. One such process presented by Elo et al. [29] is a circular saw cutting process; here, the LCD TVs are not shredded but instead opened, and the components are sorted into respective material fractions. This process results in less damage to the components, and the CCFLs do not break during this process as long as the cut is not made in the CCFLs themselves [29]. O'Donoghue et al. [30] also utilize an alternative technology to shredding, namely a cutting process with a circular saw or a slot mill.

4.1. Challenges with LCD TV recycling

Several authors have identified challenges with the recycling of LCD TVs:

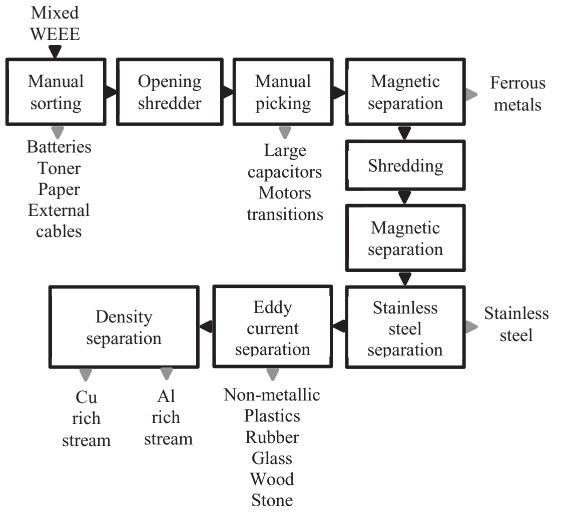

Fig. 4 Process flow for a shredding system including manual process steps (modified from Kell [3]). The black arrows represent the flow of waste materials. The grey arrows represent the refines material fractions.

- LCD TVs may contain the hazardous mercury [31].
- The components in LCD TVs are becoming more integrated and contain less material (sleeker) compared to older TVs [17, 32], which makes recycling challenging since recyclers get paid on a recycling weight basis. With more work for less weight, there is less economic motivation for recycling LCD TVs which are sleeker.
- There is a lack and difficulty to obtain of information about the material content of LCD TVs [11].
- The weight distribution between the different materials in LCD TVs varies, but the types of materials are generally the same [16, 32-34] (figures in weight %):
  - Ferrous metals (47%)
  - Plastics (33%)
  - Glass (7%)
  - Printed circuit boards (7%)
  - Non-ferrous metals (4%)
  - Cables and wires (1%)
  - Other materials (1%)

There are also challenges specifically associated with utilizing automated processes in the recycling industry. Some of the challenges are: *many different products*; *low product-specific volumes*; *products that are not designed for disassembly*; *general problems with the reverse logistics of materials to the recycling plants* and *variations in the quantity of products arriving at the recycling plants* [35]. However, despite the challenges with automation in the recycling industry and the challenges with the recycling of LCD TVs, there are some factors motivating automatic recycling processes for recycling LCD TVs. One motivation is that the automatic process can be *more cost-effective and with higher productivity*; another motivation is the *reduction of human contact with the hazardous material mercury during the recycling* [36].

5. Analysis of the structural design of LCD TVs

During the empirical study related to this paper the 12 LCD TVs presented in Table 1 were analyzed. None of the analyzed LCD TVs contained broken CCFLs.

Table 1. The LCD TVs used during the empirical study. The column "Year" represents the year of manufacturing. The years marked with * are estimated since this information was not labelled on the TVs. The sizes of the LCD TVs presented in the column "Sizes" are all in inches, measured diagonaly accross the screen [37].

No.	Brand	Model	Year	Sizes	No. CCFLs
1	Andersson ©	A404FDC	2010*	40	14
2	Andersson ©	A401FD	2010*	40	16
3	Finlux ©	32FLD845H	2010	32	12
4	Hyundai ©	HLT-32v2	2009*	32	16
5	LG ©	32LC52-ZC	2007	32	16
6	LG ©	42LC55-ZA	2007	42	18
7	LG ©	37LC51-ZA	2007	37	16
8	Philips ©	37PFL3212/10	2010	37	16
9	Samsung ©	LE37R89BD[R]	2010	37	16
10	Sharp ©	LC32SH340E	2010	32	14
11	Sony ©	KDL40W4500	2008	40	20
12	Sony ©	KDL-46NX720	2012	40	LEDs

5.1. Structural design differences in LCD TVs

In the empirical analysis it was found the older LCD TVs contained a higher number of CCFLs, while the newer TVs were larger in size. To keep the illumination at a good level, the number of CCFLs also needs to increase with the screen size. However, the ratio of CCFLs per TV size was lower for newer LCD TVs than for older TVs. This shows that the overall development trend of LCD TVs is that they are getting larger and that CCFLs are being used more effectively used. For all the LCD TVs investigated, the structural designs were in detail different from each other. There are also differences between the LCD TVs from the same manufacturer. However, the overall design with components and purpose of the components was similar, which was also found by other researchers [5, 9, 13-15].

5.2. Challenges identified when conducting the empirical structural design analysis

During the empirical study some interesting observations were made. In general, the LCD TVs follow the structural design presented in the literature. There are, however, some structural design features which would cause challenges for an automatic dismantling process. The following challenging features have been identified during the empirical study.

The *inhomogeneous material* content in the LCD TVs makes it difficult to plan a cutting path with one feeding rate for a cutting tool like a circular saw or a slot mill with optimal setting. The inhomogeneous materials make is necessary to change the feed rate or the rotation speed to optimize the cutting process, depending on the material content. An example is the structural design feature with the metal plate reinforcing the LCD TV stands, which will make it necessary to decrease the feeding rate to be able to decrease the wear of the cutting tool.

The *mixture of materials* will make the settings of a cutting tool difficult to optimize. An example is the case when cutting with a circular saw in both plastic and metal. To cut in plastic the rotation speed needs to be lower than for metal to prevent the plastic from melting and sticking to the cutting tool and making it malfunction. However, tests have shown that the thin plastic covers and the metal sheets combined makes cutting with a circle saw plausible. This is because the metal sheet cleans the circular saw of the melted plastics stuck to the saw. The cutting process was adjusted to fit the cutting of metal [37].

The *sandwich construction and thin design* of LCD TVs make the fixation of the TVs challenging. If some of the sides of the TVs are the location for applying a dismantling tool, then the fixation needs to be applied on the front side of the back side. The fixation cannot be applied on both sides at the same time, due to the splitting of the LCD TV along its sides. This also leaves one side of the split LCD TV loose and uncontrolled after dismantling. Another related issue is the integration of materials. One example is the aluminum sheets holding the LED in LCD TV No. 12 in Table 1, which was integrated with the LEDs. The LED strip and the aluminum sheet were glued together, making separation of the LEDs and the aluminum difficult.

Another challenge is to *find the component location* and where one component ends and another starts when the components are located side by side, are of the same material and have the same shape. Some of the structural design features are made to look seamless between components, an example is the edge where the front plastic frame and the plastic back cover meet each other on LCD TVs.

A final challenge identified is to find a suitable *dismantling sequence*. In some cases there is a need to remove components, but in others not before the valuable materials and components together with the hazardous CCFLs for the dismantling. The challenge is to find the optimal dismantling sequence to reach the CCFLs and other valuable materials and components without unnecessary removal of components. The CCFLs are prioritized to be removed due to the mercury, which needs to be separately treated.

In summary, the following five main challenges related to the structural design of LCD TVs have been identified during the empirical analysis of the twelve LCD TVs:

- *Machining through inhomogeneous materials*
- *Machining through a mixture of materials*
- *Fixating the thin sandwich construction*
- *Locating the components*
- *Finding a suitable dismantling sequence*

6. Discussion of potential solutions to the challenges found in the empirical structural design analysis

During the empirical study it was revealed that *inhomogeneous materials* and the *mixture of materials* in LCD TVs makes optimization of machining challenging. One way to cope with these challenges is to collect information about the materials during the machining of the LCD TVs and feedback the information to the machining system. Examples of such feedback systems are force feedback and momentum feedback systems. The feedback systems will change the machining parameters, depending on e.g. the material thickness and composition. By using force or momentum feedback, it will make the process more complex and expensive to invest in. Another approach is to scan or x-ray the LCD TVs before machining to collect knowledge about the materials inside the TVs. This will also make the investment cost higher compared to a system without this equipment. Still another approach, without adding complex processes, is to utilize the structural design features which are the most suitable for a dismantling process. An example is the use of a process where the local variation of material is lowest in the structural design of the LCD TV. Examples of where the material composition is low in an LCD TV are along the long and short-sides, where the construction is mostly made of plastics and metal. A further suitable location which has a low material composition is the LCD screen where the material composition is mainly glass and plastics. This structural design feature has been utilized by O'Donoghue et al. [30] for cutting open LCD TVs and getting access to the CCFLs.

The *thin structural design* of the LCD TVs was found in the empirical study to make fixation challenging due to the need for holding the components in place while dismantling. The challenge is to be able to not fixate the components for disassembled, fixate the remaining components and in the same time not damage any component. By using a vacuum gripper on one the front or back side of the TVs will fixate the TVs before the opening, but the components will be lose after the opening and needs to be controlled so the CCFLs are not damage by lose components. An initial trial of a vacuum fixture for fixation of an LCD TV in the LCD screen has been tested by Elo et al. [37]. The vacuum fixture was able to hold down the LCD TV during the process, and none of the CCFLs were damage during the trials.

When the *location of components* of the same material and of the same design fit close to each other, as the lesson from the empirical study shows, even manual disassembly becomes challenging. The edge between the components can easily be confused with other edges which are used for esthetical purposes. This challenge is difficult to address and can be avoided by making the slitting of the components in other locations than where the components were united during assembly. The drawback is the need for making new points of separation, which takes time.

The final challenge found during the empirical study, to optimize the *dismantling sequence*, will be possible to manage with manual disassembly experience. Another approach is to use a flexible, automatic system which adapts to the product and performs a disassembly or dismantling. This type of approach needs a complex system with sensors and equipment to gather information about the product. The system needs to gather information for each product and will not learn from previous products. The complexity of this type of system can be lower, but it depends of the complexity of the product disassembled. If an automatic dismantling system can use structural design features which are general for all LCD TVs, or nearly all TVs, then the complexity will decrease for the dismantling system. This is because the structural design features will be used, and the information which needs to be gathered will be reduced. This will also decrease the complexity of the automatic dismantling system.

The challenges found in the empirical study are plausible for LCD TVs designed with a light box or module, since EEE products are continually are being developed and introduced.

The literature contains little information about alternative automatic processes beside the shredding process. Some of the exceptions are: Seliger et al. [7]; Kernbaum et al. [8]; Franke et al. [10]; and O'Donoghue et al. [30]. Since the valuable materials are getting more expensive, the economic motivation for alternative processes for recycling of materials should become more interesting for the recycling industry.

7. Conclusion

The following challenges related to the structural design of LCD TVs for an automatic dismantling process have been identified; The *inhomogeneous materials* and the *mixture of materials* make the machining of LCD TVs challenging. Another challenge is the *thin design* of the LCD TVs, making fixation difficult. The different *component location* vary, depending on LCD TV, is another challenge. The final challenge identified is to find a suitable *dismantling sequence* without unnecessary removal of components.

8. Future research

The research the to this paper will continue with an investigation of what substances released to air during the processes of opening LCD TVs. Substances of particular interest are dioxins and those related to the liquid crystals in LCD screens. The research will also continue with investigating and testing potential solutions on the challenges identified in this paper.

Acknowledgements

The authors want thank the Swedish Governmental Agency for Innovation Systems (VINNOVA) and the Swedish Foundation of Strategic Research for funding this research (SSF/ProViking). The authors would also like to thank thethe following research participants: STENA Technoworld, Kuusakoski, Hans Andersson Metal, Nordic Recycling AB, Samsung, Swerea IVF and Svensk Industriautomation AB, Elkretsen and Chalmers industriteknik.

References

[1] European commision. appsso.eurostat.ec.europa.eu. sight visited 2013-11-20, information last updatet 2013-11-14, Source of data Eurostat.

[2] European commision. Directive 2012/19/EU of the European parlament and of the council of July 2012 on waste electrical and electronic equipment (WEEE) (recast). Official Journal of the European Union. 2012.

[3] Kell R. Recycling and recovery. In: Hester RE, Harrison RM, editors. Electronic waste management. The royal society of chemestry. 2009. p. 91-110.

[4] Peeters JR, Vanegas P, Dewulf W, Duflou JR. End-of-life tretment strategies for flat screen televisions: A case study. The global conference on sustaninable manufacturing 2012.

[5] McDonnel TJ, Williams KS. The location and character of mercury in waste LCD backlights, WARP Project report, Project code: MDD028, 2010.

[6] Elo K, Sundin E. Evaporation of Mercury from CCFLs during Recycling of LCD Television Sets, Proceedings of EcoDesign International Symposium, Jeju Island, South Korea, 2013.

[7] Seliger G, Keil T, Rebafka U, Stenzel A. Flexible disassembly tools. Proceedings of the IEEE international symposium in electronisc and the environment 2001. p 30-35.

[8] Kernbaum S, Franke C, Seliger G. Flat screen monitor disassembly and testing for remanufacturing. CIRP international conference on life cycle eingineering 2006. p 435- 440.

[9] Ryan C. O'Donoghue LO, Lewis H. Investigating the recyclability of liquid crystal display TV. Intrenational conference on factory automation and intelligent manufacturing 2010.

[10] Franke C, Kernbaum S, Seliger G. Remanufacturing of flat screen monitors. In Brissaud D, Tichkiewitch S, Zwolinski P. editors. Innovation in clife cycle engineering and sustainable development, Springer Nertherlands 2006. p 139-152.

[11] Venagas P, Peeters JR, Cattrysse D, Duflou JR. Information exchange requirements for cradle to cradle implementation in an industrial setting: EoL treatment of flat screen televisions. Life Cycle Management Conference location. Berlin, Germany. 2011.

[12] Sundin E, Björkman M, Eklund M, Eklund J, Engkvist I-L. Improving the layout of recycling centres by use of lean production principles. J Waste Management 2011; 31: 1121-1132.

[13] Mouromtseff IE. Electronics and development of electronic tubes, J of the Franklin Instetute 1945; 240: 171-192.

[14] Matharu AS. Liquid crystal recovery. SUMEEPnet. Loughborough university United Kingdom 2008.

[15] Matharu AS, Wu Y. Liquid crystal Displays: from devices to recycling. In: Hester RE, Harrison RM, editors. Electronic waste management. Royal society of chemistry; 2009. p 180-211.

[16] Ryan A, O´Donoghue L, Lewis H. Charactising components of liquid crystal display to facilitate disassembly. J. Clean production 2011; 19: 1066-1071.

[17] Juchneski NCF, Scherer J, Grochau IH, Veit HM. Disassembly and charicterization of liquid crystal screens. J. Waste management and research 2013; 31, 6:549-558.

[18] Tun-Chien T. A noval feasible digital laser-blasting to fabricate a light-guide-plate of gihg luminace and effeciency for TV application. J of Display technology 2013; 9: 800-806.

[19] Tavman I, Turgut A, Iz M. Thermal analysis of thin film transistor liquid crystal display (TFT-LCD) TV panels with single sided LED bras. Intrenational symposium for desing and technology in electronic packaging. 2012. p. 43-47.

[20] Buchert M, Manhart A,Bleher D, Pingel D. Recycling critical raw materials from electronic equipment. Oeko-Institute e.V. 2012.

[21] Peeters JP, Vanegas P, Duflou JP, Mizuno T, Fukushige S, Umeda Y. Effects of boundary conditions on the end-of-life treatment of LCD TVs. CIRP Annual - Manufacturing Engineering 2013; 62: 35-38.[21] Ko JH, Ryu JS, Yu MY, Park SM, Kim SJ. Initial Photometric and Spectroscopic Characteristics of 55-inch CCFL and LED Backlights for LCD-TV Applications, Journal of the Korean institute of illumination and electrical installation engineers 2010; 24. 3: 8-13.

[22] Chang TC, You SJ, Yu BS, Kong HW. The fate and management of high mercury-containing lamps from high technology industry, Journal of Hazardous Materials 2007; 141:784-792.

[23] Böni H, Widmer R. Disposal of flat panel display monitors in Switzerland. Swiss federal laboratories for material science and technology. Swico recycling. 2011.

[24] Figi R, Nagel O, Hagendorfer H. A straightforward wet-chemistry method for the determination of solid and gaseous mercury fractions in Backlight Cold Cathode Fluorescence Lamps, Talanta 2012; 100: 134-138.

[25] Monix 2013 www.monix.com.tw, Responsible publisher Monix technology co. ltd. Accessed 2013-09-04.

[26] GIO 2013 web site www.giotaiwan.com.tw, Responsible publisher GIO optoelectronics corp., Accessed 2013-09-04.

[27] Bigum M, Brogaard L, Christensen TH. Metal recovery from high-grade WEEE: A life cycle assessment. J of Hazurdus materials 2012; 207-208:8-14.

[28] Cui J, Forssberg E. Mechanical recycling of waste electric and electronic equipment: a review. J of Hazardous materials B99 2003; 243-263.

[29] Elo K, Sundin E. Concepts for a semi-automatic dismantling process of LCD television sets. Accepted of abstract to CIRP Conference on Assembly Technologies and Systems 2014.

[30] O'Donoghue L, Lewis H, Ryan. Removal of hazurdous substances from LCD displyas. Patent IE 2010/0782. Irich patent office. 2010.

[31] Boeni H, Widmer R, Figi R, Steinmann T, Birchler E. Risks and opportunities in the recycling of flat panel displays – results of a Swiss study. IERC International Electronics Recycling Congress Salzburg, Austria. 2011.

[32] Lee HM, Sundin E, Nasr N. Review of eng-of-life management issus in sustanable electronic products. The global conference on sustanable manufacturing, St. Petersdurg Russia. 2012.

[33] Salhofer S, Spitzbart M, Maurer K. Recycling of LCD Screens in Europe - State of the Art and Challenges. In: Hesselbach J, Herrmann C, editors. Glocalized Solutions for Sustainability in Manufacturing. Springer Berlin Heidelberg 2011. p 454-458.

[34] Cryan J, Freegard K, Morrish L, Myles N. Demonstration of flat panel display recycling technology. Oranisation report from WRAP (Waste and resources action program), avalable at www.wrap.org.uk, 2010.

[35] Boks C, Stevels ALN. Assessment of future developments in automated disassembly and the influence on the end-of-life scenarios. CIRP International seminar on life cycle engineering 1997; 1: 367-377.

[36] Sundin E, Elo K, Lee HM. Design for automatic end-of-life processes. J Assembly automation 2012; 32; 4: 389-398.

[37] Elo K, Sundin E. Conceptual process development of automatic disassembly of flat panel displays for material recycling. Proceedings of the first International Conference on Remanufacturing 2011; p 187-197.