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Process concepts for semi-automatic dismantling of LCD televisions

Kristofer Elo^{a*}, Erik Sundin^a^a Department of Management and Engineering, Division of Manufacturing Engineering, Linköping University, Linköping, SE58183, Sweden* Corresponding author. Tel.: +46 13 28 11 64; fax: +46 13 28 27 98. E-mail address: kristofer.elo@liu.se

Abstract

There is a large variety of electrical and electronic equipment products, for example liquid crystal display television sets (LCD TVs), in the waste stream today. Many LCD TVs contain mercury, which is a challenge to treat at the recycling plants. Two current used processes to recycle LCD TVs are automated shredding and manual disassembly. This paper aims to present concepts for semi-automated dismantling processes for LCD TVs in order to achieve higher productivity and flexibility, and in turn increase the value of the recycled materials, improve the work environment for operators and remove mercury from the recycled materials. A literature review and two empirical studies were performed to be able to present a concept for dismantling direct illuminated LCD TVs. The process used a circular saw and/or a band saw to machine two cuts in LCD TVs to gain access to the mercury-containing cold cathode fluorescent lamps inside. This conceptual process is compared to the other processes found in the literature.

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1. Introduction

The number of flat panel television sets (TVs) manufactured worldwide up until the year 2013 was 1.2 billion. 87% of those TVs were liquid crystal displays (LCD), 72% of which are illuminated by mercury-containing cold cathode fluorescent lamps (CCFLs). This brings the number of LCD TVs with CCFLs put on the market to 751.68 million units. The remaining (28%) of LCD TVs contain LEDs instead of CCFLs and are mercury-free. [1] The mercury in the CCFLs can be found in the electrodes, glass and powder. This makes it important to be able to take care of the CCFLs during their end-of-life treatment [2-4]. The LCD TVs containing CCFLs are in general direct illuminated through a light box; newer LCD TVs fitted with LEDs have another structural design and are edge-illuminated [5-6].

There are two common ways to recycle LCD TVs in Europe: automatic shredding processes and partial manual disassembly [7]. Investment cost and the cost for workers, together with the low value of the materials recycled, makes

these alternatives difficult to motivate economically [7-8]. There are several main technical issues to consider when recycling LCDs. LCD TVs could contain hazardous materials such as mercury. LCD TVs also contain a variety of materials, yet there is a lack of information about the material composition in LCD TVs [9-11]. A final technical issue to consider is that electrical and electronic equipment products are getting sleeker, meaning they now contain fewer materials and have more integrated components [12].

Due to the environmental issues associated with mercury, there are technical and economic problems with current common recycling processes, and thus the need for new ways to recycle LCD TVs. For example, when LCD TVs are shredded, the equipment and residues could be contaminated by the hazardous mercury.

This paper aims to explore process concepts of semi-automatic dismantling of LCD TVs in order to achieve high flexibility and productivity in the recycling industry.

2. Methodology

The research methodology for this study consisted of a literature review, two empirical product studies and an process concept evaluation.

2.1. Disassembly analysis

To be able to complement the literature and get a first-hand understanding of the recycling difficulties, the researchers performed disassembly analysis on 12 LCD TVs. The data specifying the disassembled LCD TVs is illustrated in Table 1. The analysis was divided into two steps. The first step was performed to understand the general structural design. This step was performed through a master’s student thesis presented at the university under supervision of the authors. The second step complements the first with measurements of the different dimensions of specific design features possible to utilize during automatic opening of LCD TVs.

Table 1. Data from the LCD TVs used during the disassembly analysis. The size of the LCD TV is the diagonal measurement in inches of the screen.. The LCD TVs marked with an * in the number column were used during the second stage of the structural design analysis.

No.	Brand	Model	Year	Sizes	No. CCFLs
1	Andersson ©	A404FDC	-	40	14
2*	Andersson ©	A401FD	-	40	16
3*	Finlux ©	32FLD845H	2010	32	12
4*	Hyundai ©	HLT-32v2	-	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

2.2. LCD TV light box opening

The machining of the two LCD TV light boxes was performed to investigate their robustness and to determine if any CCFLs were damaged. During the study the machine was fitted with a circular saw. The light boxes used are presented in Table 2. The sizes were selected to be able to fit the light boxes onto the machining table of the milling machine.

Table 2. Data about the LCD TV light boxes.

Manufacturer	Model	Size	# of CCFLs
Chi Mei optoelectronics	-	30 inch	16
Sharp	LQ315T3LZIK	32 inch	16

2.3. Process concept evaluation

During the evaluation of the different dismantling processes a scoring evaluation method was used. The method is divided into five stages. The first stage involves creating a matrix of the alternatives and criteria. In the second stage,

alternatives from the criteria are evaluated. The third stage includes ranking the alternatives, depending on how the alternatives fulfill the criteria. Next, the fourth stage results in possibly combining and improving the alternatives, and starting over again from stage one if necessary. The fifth and final stage includes evaluation of the results and the scoring process [13].

3. LCD TV structural design – a literature review

The following two sections will describe the two common structural designs of LCD TVs. Both designs can contain CCFLs; however, the design with edge-illuminated LCDs more often contains LEDs as a light source [5-6, 14].

3.1. Direct illuminated LCD TVs

The structural design of a direct illuminated LCD TV can be divided into several layers, as illustrated to the left in Fig. 1. From the top, the components are: plastic frame, speakers, light box, metal frame, printed circuit boards and plastic back cover. The figure does not illustrate cables, remote receiver and control buttons, but these components can be found in the same layer as the printed circuit boards [15-16].

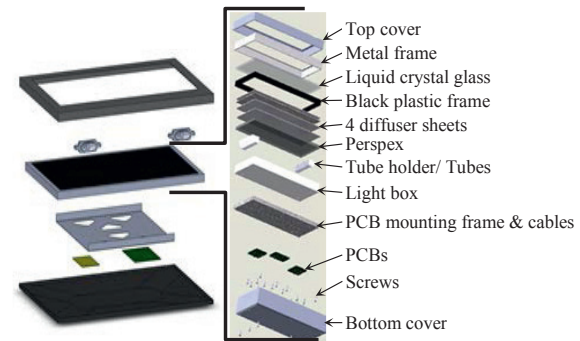


Fig. 1. Structural design of a direct illuminated LCD TV. Modified from Ryan et al. [15] and Juchneski et al. [16].

The structural design of the light box can also be divided into several layers. Starting from the top of the right-hand side of Fig. 1, the structure begins with a metal frame or top cover and ends with a metal back cover (bottom cover). The CCFLs are placed parallel to each other between the fixation points (tube holders) in a parallel plane with a distance from the LCD screen (liquid crystal glass) [15].

3.2. Edge-illuminated LCD TVs

The structural design of an edge-illuminated LCD can be found in LCD monitors used together with desktop computers. The structural design of a LCD monitor is illustrated in Fig. 2. From the top and to the right-hand side of Fig. 2, the design starts with a plastic front frame, continues with a LCD module and a metal frame, and ends with a plastic back cover. The printed circuit boards are located in-between the metal frame and the plastic back cover [17].

The difference in the structural design between edge-illuminated LCD monitors and LCD TVs is the size and additional components such as speakers, a receiver for the remote control and additional printed circuit boards found in TVs. The additional components are found in the area between the module and the back cover, while the speakers are located in the same location as found in direct illuminated LCD TVs.

There are LCD TVs with a structural design where only one of the long sides is fitted with edge-illuminating LEDs, something which makes these TVs even thinner [14].

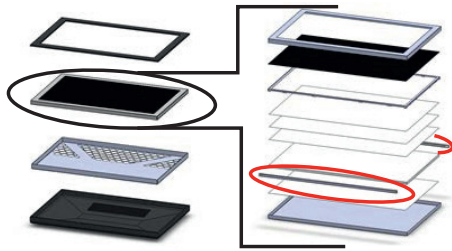


Fig. 2. Structural design of an edge-illuminated LCD monitor. The two red markings show the position of the CCFLs. Modified from Matharu et al. [17]

3.3. LCD TV dismantling and disassembly processes

The following processes are used to dismantle or disassemble LCD TVs or LCD monitors.

Researchers from the University of Limerick, working in cooperation with the company ARL innovation[®], have developed an automatic process which removes the CCFL glass and illuminating powder in LCD TVs. The process opens the LCD TVs via the front of the LCD screen by cutting away the LCD glass panel. The CCFLs are then crushed and the glass and other particles are removed by a suction system. The remaining components are then recycled with a conventional shredding process followed by material separation [18].

Swedish researchers have been illustrating process concepts to remove CCFLs within LCD monitors by cutting the long sides of the LCD monitors to remove the CCFLs from the remaining components [19-20]. Felix et al. [20] describe a cutting process which removes the CCFLs from LCD monitors with the same approach as described by Elo et al. [19]. This process is only utilized on LCD modules from LCD desktop monitors. The preprocess steps are performed manually.

In Germany, automatic disassembly processes have been developed using flexible unscrewing rigs and flexible gripping tools. These processes only partly damage the components which are being disassembled [21]. Kernbaum et al. [22] developed a semi-automated disassembly system for LCD monitors which utilized both manual and automated disassembly stages for the disassembly system.

4. Empirical studies

There were two empirical studies performed during the work for this paper. The first was a structural design analysis

to get more hands-on knowledge and an understanding of the LCD TV's general structural design. The second empirical study was a machining study of two LCD TV modules to understand the robustness of LCD TV modules and the effects of cutting open a LCD TV light box.

4.1. LCD Structural design investigation

The LCD TVs used in the structural design analysis were collected from a recycling center in Linköping, Sweden. Recycling centers are facilities run by municipalities for waste collection where visitors can bring, sort and discard e.g. large-sized household, hazardous, and electrical waste [23]. None of the LCD TVs collected contained broken or damaged CCFLs. One of the LCD TVs was fitted with LEDs (LCD TV No. 12 in Table 1); this TV was also edge-illuminated and the LEDs were located along both long sides.

Several features were identified as a result of the disassembly analysis and are listed below, and most of the features are illustrated in Fig. 3 as well.

- All LCD TVs had speakers positioned in the bottom long side of the screen.
- Four of the twelve LCD TVs did not contain any control buttons, while the remaining LCD TVs had buttons placed along one of the short sides or at the bottom long side.
- All LCD TVs contained a receiver for the hand control which was located on the bottom long side.
- Six of the LCD TVs were fitted with a reinforcing metal plate located in the white area illustrated in Fig. 3. Four of the six LCD TVs were fitted with stands entirely made of plastic. Two of the LCD TVs were not fitted with a stand when collected.
- The fasteners used were mainly screws; snap-fits were also present, however only on the LCD TV light boxes. Another difference between the light boxes and the rest of the LCD TVs was the change in the type of screw, which means that different tools were needed to perform the disassembly.

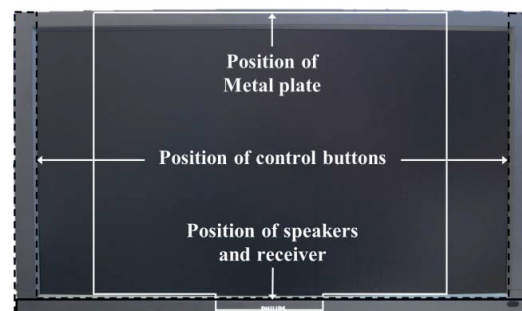


Fig. 3. An illustration of the component positions in a front-facing LCD TV. This TV was not used during the disassembly analysis.

In order to determine where the cuts were most suitable to position, six of the twelve LCD TVs were measured and investigated. Fig. 4 illustrates the positions found for the cuts. The cuts were located parallel to the long sides, perpendicular to the screen plane and parallel to the screen plane. To be

most efficient, the order of the cuts was to first remove the long side and then split the rest of the LCD TVs.

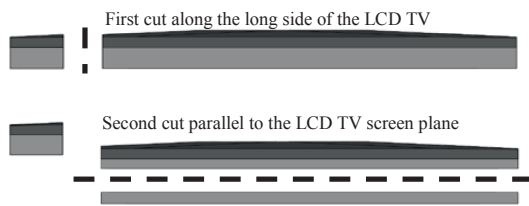


Fig. 4. Illustration of where to place the cuts during the dismantling approach for opening a direct illuminated LCD TV to get access to the CCFLs.

The dimensions to follow when cutting a LCD TV open are illustrated in Fig. 5. The first dimension to follow to not damage the CCFLs in the light box is 35mm (B in Fig. 5) from the edge of the LCD TV screen's lower long side. The distance between the lower long side of the LCD TV screen and the outer lower long side of the LCD TV light box (A in Fig. 5) was not found to be more than 25mm; the added 10mm is a safety margin. The second dimension to follow is measured from the plane of the LCD TV screen and measures 10mm in to the LCD TV (D in Fig. 5). The distance between the backside and the diffuser films inside the light box (C in Fig. 5) was found to be a minimum of 20mm.

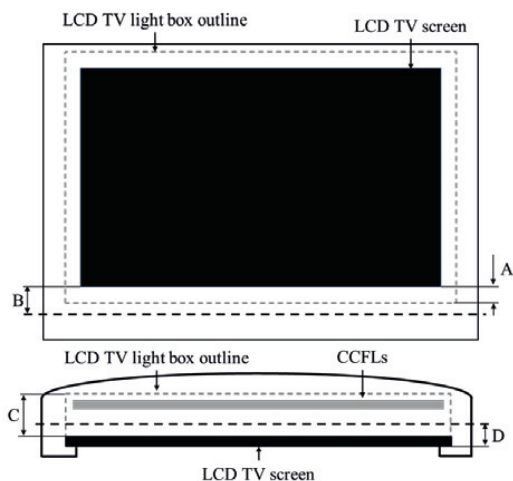


Fig. 5. Illustration of the positions of the cuts during the approach for opening a direct illuminated LCD TV. The fine dashed line in the figure represents the outline of the light box within the LCD TV. The bold dashed lines in the figure represent the positions of the cuts.

4.2. LCD TV light box opening

The purpose of opening the LCD TV light boxes was to investigate if the vibrations caused by the cutting tool would break the CCFLs in the LCD TV light boxes. The purpose here was not to optimize the process cycle time. However, the opening process cycle time used for the tests was approximately 5min per LCD TV light box.

The opening process was performed with a milling machine (Mazak[®] VTC-20B) fitted with a 125mm diameter

circular saw (Dormer[®] D763). The cut was placed parallel to the LCD TV screen shifted 10mm in height from the screen plane (measurement D in Fig. 5). The fixture in Fig. 6 was used and specially made for the purpose. The six vacuum cups used were PIAB[®] model FCF50P while the ejectors were SMC[®] model ZH10B. The maximum combined vertical suction force from the vacuum copes was 432N at a vacuum pressure of -60kPa [24]. The two ejectors used created the vacuum pressure of -48kPa [25]. The pressure providing the vacuum cups will make the vacuum cups provide a clamping force of 80% of the maximum force, i.e. 345N.

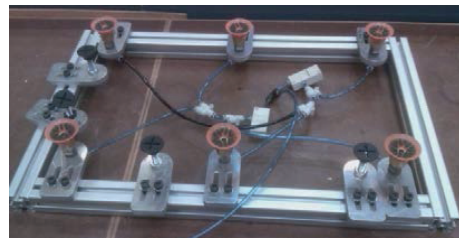


Fig. 6. Fixture used for cutting LCD TV light boxes open during empirical study.

The size of the LCD TV light boxes made it necessary to make the cut in two steps: first, a cut was made through one long and one short side, then the light box needed to be rotated 180 degrees, and then the next long and short sides could be cut. The limitation of the machining table made it necessary to rotate the light boxes to be able to cut all long and short sides of the light boxes. The light boxes were placed with the LCD screens facing downwards in the fixture.

Both LCD TV light boxes were inspected before they were cut open, and none of the CCFLs were damaged. After the light boxes were cut open, the CCFLs were inspected again and none of the CCFLs were found to be damaged or broken.

5. Recycling process concepts

5.1. Dismantling approach

The approach chosen to open LCD TVs for recycling is to firstly remove all the CCFLs (since they are hazardous); secondly remove the printed circuit boards (since they have high material value); and thirdly, remove other valuable materials. The opening of the LCD TV is done through two cuts, both illustrated in Fig. 4 and Fig. 5. This generates three different fractions, two low-risks and one high-risk. The two low-risk fractions contain plastics, metal, speakers, LCD screen and other low-valued electronics. The high-risk fraction contains the CCFLs, all the printed circuit boards in the TVs, metals and plastics. Once the CCFLs are removed, the plastic back cover can be removed and then the printed circuits boards. The low-risk fractions can then be sent directly to a conventional shredding facility. By utilizing manual disassembly of the LCD TVs to the point where the LCD TV light box is the remaining component and then performing the automatic opening, it will make the conditions better for the process. This is due to fewer different materials

in the machine, and will also make it possible to cut the light box open with one single cut. This approach will help prevent mixing of the hazardous CCFLs and the valuable printed circuit boards.

5.2. Process concepts

The list of processes, the criteria and the rating of the criteria, all defined below, have been developed in cooperation with the industrial partners in the research related to the authors.

The following processes have been presented for opening LCDs on a small scale to get an understanding of the performance in machining products such as LCD TVs. The processes are: *manual disassembly* (reference process) [19], *circular saw* and *band saw* [19], *cutting* [20], *milling* with a shank end mill, *laser cutting* [19] and *water jet cutting* [19]. The processes were evaluated by the following criteria [19]:

- *Capacity*: the number of products processed per hour.
- *Duration*: the ability of the process to fit with existing and new equipment.
- *Investment cost*: the cost of the process when purchased.
- *Operation cost*: the cost per month for using the process.
- *Work environment*: the suitability of the environment for the workers and the environment surrounding the process.
- *Product flexibility*: the ability of the process to manage different types of products.
- *Ease-of-use*: the knowledge needed to operate the process.

The scoring of the different processes was done by the authors. In Table 3, the scoring evaluation of the processes is illustrated. The laser cutting process was excluded from the scoring evaluation due to the high investment cost and ability to only cut through one layer of materials before the laser beam diverges and becomes unfocused and thus unable to remove the remaining materials.

Table 3. Process concept scoring results where *rating* is how the opening processes fulfil the *criteria* compared to the manual process (reference). The *score* is the product of the *weighting* and *rating*. The *scores* are then summarised into a *total score* and ranked compared to the other processes.

Criteria	Weighting	Processes									
		Manual (ref.)		Band saw / Circle saw		Water jet		Milling		Cutting	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Capacity	0,31	3	0,93	4	1,24	2	0,62	2	0,62	5	1,55
Duration	0,15	3	0,45	3	0,45	2	0,3	2	0,3	4	0,6
Investment cost	0,13	3	0,39	2	0,26	1	0,13	1	0,13	2	0,26
Operation cost	0,12	3	0,36	2	0,24	1	0,12	2	0,24	2	0,24
Working environment	0,11	3	0,33	3	0,33	4	0,44	3	0,33	3	0,33
Product flexibility	0,12	3	0,36	4	0,48	1	0,12	4	0,48	4	0,48
Ease-of-use	0,06	3	0,18	2	0,12	1	0,06	2	0,12	2	0,12
Total score			3		3,12		1,79		2,22		3,58
Rank		3		2		5		4		1	
Continue?		Yes		Yes		No		No		No	

The processes selected for continuation are *manual disassembly*, *band saw* and the *circle saw*. The *circle saw* is suitable to utilize when cutting the long sides away, while a *band saw* can be utilized when the light box is divided into two sections. The cutting process is excluded because the process is expected to damage the CCFLs inside the LCD TVs during the process. The *water jet* and the *milling* processes are excluded due to their poor performance in the scoring table.

6. Discussion

6.1. Dismantling approaches

The only industrially utilized automatic dismantling process found which removes the glass and fluorescent powder from the CCFLs in LCD TVs is the process developed at the University of Limerick. The authors await an answer on if the process is able to remove the CCFLs' electrodes. According to McDonnell et al. [2] the electrodes contain the highest concentration of mercury in CCFLs [2]. The approach of opening the LCD TVs through the LCD screen has several advantages, for example few materials to machine in and the screen having a distinct characteristic to identify by 3D and 2D sensors.

The unscrewing approach presented by Seliger et al. [21] and Kernbaum et al. [22] has an advantage compared to the other approaches, namely that less material and components are damaged during the process [21-22]. Due to the quantity, complexity and the rapid changes in EEE product design, an automatic disassembly system needs to be flexible and productive. This makes an automatic disassembly system complex and expensive, which may be the reason for its lack of implementation in the recycling industry.

The process concept proposed in this paper requires manual preparation of the LCD TVs before the TVs are included in the automatic recycling process. The preparations include removing any stands or cables that are present. However, this is also the case with the process developed with the University of Limerick. [18] The process' ability to fulfill the aim has not been empirically validated; the flexibility needs to be tested together with the productivity which, according to the authors, is the greatest challenge.

6.2. Disassembly study

During the disassembly study the different screws found in the light boxes and the rest of the LCD TVs were due to the different designs by the different manufacturers. The light boxes are in general less suitable for disassembly due to several disassembly directions of the screws, snap fits in plastics and metal and different types of screw heads compared to the rest of the LCD TVs.

The results from the opening of the light boxes show that it is possible to cut open a LCD module without breaking the CCFLs. The study also shows that the fixture with the vacuum grippers is able to secure the LCD module during processing. This makes it a good alternative for securing LCD TVs and can be utilized as a robot gripper for handling LCD TVs.

6.3. Selected process concept

The selection of the process *circular saw* and *band saw* for opening LCD TVs is supported by O'Donoghue et al., since the same process is utilized in this approach [18]. The empirical studies presented in this paper and the earlier experience from this research also indicate the suitability to use *circular saw* or *band saw* or some other cutting technology to open products such as LCD TVs. The challenge for further exploration is to find the right tools to achieve the productivity demanded from the recycling industry.

7. Conclusion

There are several issues to consider when recycling LCD TVs, namely: LCD TVs contain hazardous materials and a variety of materials; there is a lack of information regarding the material composition of LCD TVs; and LCD TVs are getting a sleeker structural design. There are few approaches of automatic LCD TV dismantling beside the shredding approach, only a few are described in research papers. An additional and novel approach is described in this paper; dismantling direct illuminated LCD TVs by utilizing a circular saw and/or a band saw opening process to perform two cuts to gain access to the hazardous CCFLs inside the LCD TVs.

8. Future research

As Lee et al. [12] state, electronic products will continue to be sleeker, more complex and their components will be more integrated. This will require more complex processes and new ways to be able to reuse and recycle electronic products.

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