AUTOMATION IN THE RECYCLING INDUSTRY
RECYCLING OF PLASTICS AND LARGE LIQUID CRYSTAL DISPLAYS
ABSTRACT

In a world of growing population and increasing prosperity, the demand for new high-technology products is increasing together with the demand for raw materials. To be able to deal with the demand for new raw materials and the increasing amount of waste, the recycling industry needs to prepare itself to cope with these changes. If the waste can become the new raw materials, then the recycling industry has a bright future. The implementation of new ways to recycle products can be the solution to succeeding in this challenge.

The objective of this research is to investigate, from a technical perspective, automation in the recycling industry. More specifically, the objective is to identify problems and solutions in the recycling of plastics and large liquid crystal displays in order to better cope with current recycling requirements.

This research was inspired by the research methodologies of industry-as-laboratory, action research, experimental research and two concept development methods.

The results related to the recycling of plastics come from a theoretical investigation of the possibilities for a plastic sorting facility. The investigation resulted in two concepts for recycling systems, implementable with today’s state-of-the-art technology and a more futuristic concept for sorting and separating the different plastics of interest. The systems are designed with standardised processes and are arranged in a flexible way to be able to manage with current industrial requirements.

The results related to large liquid crystal displays include a clarification of the requirements for an automatic recycling plant, concept generation, and practical testing of different technologies. Two preferred processes for dismantle large liquid crystal displays are the circle saw and band saw. Additional results are the semi-automatic process structure to manage with current industrial requirements for large liquid crystal displays.
ACKNOWLEDGMENTS

The contribution to my research comes from several people and in several forms. First of all, I would like to send a thank you to my main supervisor, Docent Erik Sundin, for great guidance on the way to reach licentiate degree. I would like to send my co-supervisor, Doctor Kerstin Johansen, a thanks as well for her great support, both in my development as a person and researcher. Co-supervisor Professor Mats Björkman is also a person I would like to sincerely thank. A special thanks goes to Doctor Marie Jonsson, for our interesting discussions about research and for contributing so much to the work at the division – even though I had problems keeping her from stealing the space in my lovely easy chair. I would also like to thank my other colleagues at Linköping University in the division for Manufacturing Engineering for being great colleagues, always there with support and help whenever and regardless of whatever was needed.

Secondly, I would like to thank all participants in the research projects AutoDisA and HÄPLA for their support with information, equipment and financing needed in the research. Special thanks to Bill Letcher, Johan Felix, Göran Lundholm and Henrik Saldner for your fantastic work in the AutoDisA project.

Thirdly, I would like to thank the research financiers, namely the research program ProViking, the Swedish foundation for strategic research (SSF) and the Swedish governmental agency for innovation systems (VINNOVA), for providing the possibility for me to perform the research.

Last but certainly not least, I would like thank my family for always staying positive and supportive during my PhD studies. I would also like give my heartfelt appreciation to my closest family, my partner Emilie and our daughter KlaraMy, for giving me support and so much in life. You are truly one of my sources of energy.

KRISTOFER ELO
LINKÖPING, FEBRUARY 2013
APPENDED PAPERS

The following papers are the author's main publications describing the research presented in this licentiate thesis. As well as with the greatest novelty from a scientific standpoint.


PAPER II  Elo K. and Sundin E. (2010) Requirements and needs of automatic material recycling of flat panel displays, in proceedings of Going Green Care innovation, Vienna, Austria, paper 107 on CD.


OTHER PUBLICATIONS

The following papers were published during the research presented in this licentiate thesis, but are publications with less novelty or outside the scope of the research.


# TABLE OF CONTENTS

1 Introduction .......................................................................................................................1
   1.1 Challenges in the Plastics Recycling Industry ..............................................................2
   1.2 Large Liquid Crystal Display Recycling Challenges ....................................................2
   1.3 Challenges with Automatic Recycling Processes ..........................................................6
   1.4 Objective ....................................................................................................................7
   1.5 Research Questions .....................................................................................................7
   1.6 Delimitations ...............................................................................................................8

2 Research Method ............................................................................................................9
   2.1 Industry-as-Laboratory ...............................................................................................9
   2.2 Action Research ........................................................................................................10
   2.3 Experimental Research .............................................................................................11
   2.4 Concept Development Methods ................................................................................12
   2.5 Method Usage ...........................................................................................................15
   2.6 Recycling Projects .....................................................................................................18

3 Theoretical Foundation ................................................................................................21
   3.1 Theoretical Context ....................................................................................................21
   3.2 Swedish Recycling Industry .......................................................................................23
   3.3 Plastics ......................................................................................................................24
   3.4 Large Liquid Crystal Displays ...................................................................................29
   3.5 Manufacturing Automation .......................................................................................34
   3.6 Disassembly ...............................................................................................................42

4 Research Results ............................................................................................................47
   4.1 Automatic Recycling of Plastics .................................................................................47
   4.2 Requirements for Automated Large Liquid Crystal Display Recycling .................53
   4.3 Conceptual Process Development .............................................................................56
   4.4 EEE Recycling Systems ............................................................................................60

5 Discussion and Conclusions .........................................................................................61
   5.1 Discussion ..................................................................................................................61
   5.2 Conclusions ..............................................................................................................69
   5.3 Contribution to Academia .........................................................................................71
   5.4 Contribution to Industry ............................................................................................71
   5.5 Future Research ........................................................................................................71

References ..........................................................................................................................73

Appended Papers ..............................................................................................................81
   Paper I .............................................................................................................................83
   Paper II ...........................................................................................................................91
   Paper III .........................................................................................................................101
LIST OF FIGURES

Figure 1 Collected WEEE in Sweden between 2003 and 2011 ........................................ 4
Figure 2 Estimations of the value of displays sold worldwide 2006 to 2012 ............... 5
Figure 3 Industry-as-laboratory process ........................................................................ 10
Figure 4 Action research process .................................................................................. 11
Figure 5 Research steps ................................................................................................. 15
Figure 6 Example of incoming material (left) and sorted LCD-monitor material (right) ................................................................. 16
Figure 7 Surrounding research areas related to the research presented in this licentiate thesis .................................................................................................................. 21
Figure 8 Diagram of the content of this chapter ............................................................. 23
Figure 9 A chemical schema of a polystyrene monomer ............................................. 24
Figure 10 Plastics production from 1950 to 2010 ............................................................ 26
Figure 11 Amount of plastic available and recovered in Sweden between 1998 and 2011 ..................................................................................................................... 27
Figure 12 Government’s goal and percentage of total amount of plastics on the Swedish market between 1998 and 2011 ....................................................................... 28
Figure 13 Exploded view of a LCD monitor, cables and printed circuit boards are excluded in the figure ........................................................................................................ 29
Figure 14 Exploded view of a LCD monitor ..................................................................... 30
Figure 15 Exploded view of a LCD module ................................................................. 31
Figure 16 Cross section of a liquid crystal panel ............................................................ 32
Figure 17 Twisting the light’s wavelength ..................................................................... 33
Figure 18 Linkage between vital automation system parts .......................................... 35
Figure 19 Equation for calculating the degree of automation ....................................... 35
Figure 20 Workspace sharing ....................................................................................... 36
Figure 21 Workspace and time sharing ....................................................................... 37
Figure 22 Waste hierarchy ............................................................................................ 38
Figure 23 Process flow for mixed EEE recycling .......................................................... 41
Figure 24 Disassembly cost ......................................................................................... 44
Figure 25 Sorting and separation steps ......................................................................... 48
Figure 26 Alternatives 1 and 2 in Process Step 1 ............................................................ 49
Figure 27 Alternative 1 in Process Step 2 ..................................................................... 50
Figure 28 Alternative 1 in Process Step 3 ..................................................................... 50
Figure 29 Alternative 1 in Process Step 4 ..................................................................... 51
Figure 30 Sorting process of plastics using Criterion plus™ ....................................... 51
Figure 31 Alternative 2 in Process Steps 2 to 5 ............................................................. 52
Figure 32 WEEE cages ......................................................................................... 54
Figure 33 Recycling process stages...................................................................... 57
Figure 34 Lamps made of reused components from LCD monitors ............... 67
**LIST OF TABLES**

Table 1 Categories and examples of EEE ........................................................................................................ 3
Table 2 Example of screening table .................................................................................................................. 14
Table 3 Example of scoring table .................................................................................................................... 14
Table 4 Clarification of weighting .................................................................................................................... 15
Table 5 Relationship between RQs and methods ............................................................................................ 17
Table 6 Relationship between RQs and published papers ............................................................................. 18
Table 7 Level of manufacturing automation ................................................................................................. 35
Table 8 General DFD principles ....................................................................................................................... 46
Table 9 Requirements with weighting ............................................................................................................... 58
Table 10 Process concept scoring table ......................................................................................................... 59
Table 11 Relationship between the type of RQ and research area ................................................................. 61
Table 12 Survey participants ............................................................................................................................ 65
Since the work in this thesis is related to people in both academia and industry, some clarification might be needed due to the different view on different terms frequently used.

**AUTOMATION**
A process performing a task by itself without human interference; the purpose is often to perform a dangerous, repetitive, fast, or high-precision task instead of humans. (Nof, 2009)

**SEMI-AUTOMATIC PROCESS**
A semi-automatic process is a process where equipment and human workers work to execute tasks. The equipment and the humans do not work together. Rather, they are geographically separated or take turns in sharing the same workspace but not at the same time. An example is an assembly line divided in several workstations; in half of the stations operators perform assembly operations, and in the other half robots perform assembly operations. The stations are linked together with conveyor belts. (Krüger et al., 2009)

**HYBRID AUTOMATIC PROCESS**
A hybrid automatic process is a process where humans and equipment execute tasks together at the same time. The humans and equipment in the system are not separate from each other geographically and share the same work space. An example is when an operator moves a robot by force feedback via a forces sensor to the position the operator wishes. (Krüger et al., 2009)

**ENERGY RECOVERY**
Energy recovery is when energy is recovered from materials by incineration in different processes for recovery of heat energy in the material. (European Environment Agency, 2012a)

**RECYCLING**
Recycling means that materials are collected and processed to be used in a new or the same application as originally attended (European Environment Agency, 2012b, US environmental protection agency, 2012).

**REUSE**
Using components from products and using them again in new products for the same purpose as originally intended (Johansson, 1997).
REFURBISH
Refurbishing is when a product is restored close to its original status, by cleaning, replacing worn parts and repainting. All these measures can be done if is needed. (Penev, 1996)

DISASSEMBLY
Disassembly of a product is when components are removed from a product without causing any damage to the removed and remaining components of the product (Penev, 1996).

DISMANTLING
Dismantling of a product is when components are removed from a product; this is done with some damage to the components or to the remaining components of the product (Penev, 1996).

SORT
Sorting is when things are put into a particular arranged order in groups, e.g. depending of material type, size, rank etc. (Longman, 1995)

SEPARATION
Separation is when two things which are stuck to each other are removed from each other and no longer connected. (Longman, 1995)
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>Acrylonitrile Butadiene Styrene</td>
</tr>
<tr>
<td>AutoDisA</td>
<td>Automated Disassembly of Flat Panel Displays</td>
</tr>
<tr>
<td>BLU</td>
<td>Backlight Unit</td>
</tr>
<tr>
<td>CCFL</td>
<td>Cold Cathode Fluorescent Lamp</td>
</tr>
<tr>
<td>CRT</td>
<td>Cathode Ray Tube</td>
</tr>
<tr>
<td>DFD</td>
<td>Design for Disassembly</td>
</tr>
<tr>
<td>EEE</td>
<td>Electrical and Electronic Equipment</td>
</tr>
<tr>
<td>FTI</td>
<td>The Swedish Organisation for Packaging and Paper Collection, Förpackning och Tidnings Insamlingen</td>
</tr>
<tr>
<td>FPD</td>
<td>Flat Panel Display</td>
</tr>
<tr>
<td>HDPE</td>
<td>High Density Polyethylene</td>
</tr>
<tr>
<td>HÅPLA</td>
<td>Sustainable Recycling of Flat Panel Displays</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
</tr>
<tr>
<td>LDPE</td>
<td>Low Density Polyethylene</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>OLED</td>
<td>Organic Light Emitting Diode</td>
</tr>
<tr>
<td>PA</td>
<td>Polyamide</td>
</tr>
<tr>
<td>PDP</td>
<td>Plasma Display Panel</td>
</tr>
<tr>
<td>PET</td>
<td>Polyethylene Terephthalate</td>
</tr>
<tr>
<td>PMMA</td>
<td>Polymethyl Methacrylate</td>
</tr>
<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>PS</td>
<td>Polystyrene</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinylchloride</td>
</tr>
<tr>
<td>RQ</td>
<td>Research Question</td>
</tr>
<tr>
<td>WEEE</td>
<td>Waste Electrical and Electronic Equipment</td>
</tr>
<tr>
<td>wt%</td>
<td>Weight Percentage</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

This chapter includes a general introduction of the plastics recycling industry and large liquid crystal display recycling industry, together with an introduction of the general challenges in these recycling industries. The chapter continues with the objective and research questions for the research presented in this licentiate thesis. At the end of this chapter there is a presentation of the delimitations for the research performed.

New types of products are continually being introduced in the marketplace, while the old used products are discarded into the waste stream. Together with growing population in the world (Worldometer, 2012) and increasing prosperity (Central Intelligence Agency, 2012), this increases the consumption of products. The recycling industry needs to cope with the growing amount of waste in the waste stream and the increasing number of complex products. The complex products contain more valuable materials, but at the same time the materials are harder to extract. However, new product development also includes sleeker products containing less material and which are more energy efficient; because of this, they are more environmentally friendly as well. (Lee et al., 2011)

Disassembly of these sleeker products, however, has created a challenge.

The reason why the recycling industry exists and acts is the possibility to make money. Recyclers make money through charging a fee for taking care of the waste from customers, and through selling refined waste materials to other customer’s e.g. smelting plants. (STENA Recycling, 2013, Kuusakoski, 2013, Hans Andersson Recycling, 2013, IL Recycling, 2013, Rang-sells, 2013, SimS Recycling, 2013) Some of the companies in the recycling industry also offer their customers different types of services, e.g. collection and removal of waste, destruction of sensitive materials such as documents and electronic storage, and cleaning or sanitation. (STENA Recycling, 2013, Hans Andersson Recycling, 2013, Rang-sells, 2013, SimS Recycling, 2013)

Other challenges related to the incoming material in the collection phase of the waste material are the variations in and lack of control of quantity, quality and timing. The lack of control in the collection phase also affects the recycling processes used after the collection phase, in particular in the lack of control of timing and quantity. (Lundmark et al., 2009)
INTRODUCTION

1.1 CHALLENGES IN THE PLASTICS RECYCLING INDUSTRY

In Sweden, there are several companies that collect plastic waste from households and industry, but there is only one company that sorts out the different plastics to enable them to be recycled into finer fractions (Nilsson, 2008). Because of this, there is a market for recycling facilities that separate plastic waste in Sweden. The challenge is to find an automated technology which fulfils the requirements of high capacity in volume (tonnes per hour), low environmental impact and economic profitability. The economic requirement is strongly linked to the companies’ ability to secure quantities of incoming material for recycling.

The reasons for focusing on plastic recycling are the industrial interest and the lack of processes capable of performing plastic sorting and separation in Sweden at the present time.

1.2 LARGE LIQUID CRYSTAL DISPLAY RECYCLING CHALLENGES

Electrical and electronic equipment (EEE) (see examples in Table 1) is one type of equipment becoming more common in the waste stream (El-Kretsen, 2011, Seeger, 2011, El-Kretsen, 2012b). Electronic equipment is any electronic device containing printed circuit boards, e.g. computers, television sets, digital clocks and cellular phones. Electrical equipment is any kind of device using electricity and which traditionally does not contain printed circuit boards, e.g. toasters, refrigerators, electrical stoves and cables. (European Commission, 2002)

However, there are devices which in the past did not contain printed circuit boards but do so today, for example electrical stoves, which still are categorised as electrical equipment.
According to Greenpeace (2011), the amount of waste electrical and electronic equipment (WEEE) generated every year worldwide is between 20 and 50 million tonnes. The European Union published a directive in 2002 with the aim to have all the European countries collect 4 kilograms WEEE per inhabitant and year (European Commission, 2002). The collection rate in Sweden in 2011 was 16.09 kilograms per inhabitant. Waste collection in Sweden during the period 2003 to 2011 is illustrated in Figure 1. The categories in Figure 1 are “All WEEE” collected and various “Brown WEEE” products such as personal computers, children’s toys, tools, televisions and computer monitors as well as liquid crystal display (LCD) monitors. The category All WEEE represents Brown WEEE, large white goods, refrigerators, light sources and batteries. (El-Kretsen, 2012b)
A flat panel display (FPD) is a device projecting an image for visual interpretation of information. Common FPD applications include television sets, desktop computer monitors, laptop computer monitors, mobile telephones, and other types of displays. The most common types of displays are cathode ray tube (CRT), liquid crystal displays, plasma display panel (PDP) and organic light emitting diode (OLED). A CRT monitor was the first technology to project an image which was developed in the end of the 19th century (Mouromtseff, 1945). Today, this technology is replaced with other new technologies (Lambert and Gupta, 2005). The most common display technology today is the LCD, which is illustrated in worldwide display sales shown in Figure 2 below (Matharu, 2008, Ryan et al., 2010). Because LCDs are the current most common FPD type, it is an important product to solve the recycling problems for. That is why the LCD monitor was selected to be the product of interest, together with plastic, in the research presented in this thesis. The challenges with recycling LCDs are explained later in this section.
According to market analysts and other experts, the OLED is expected to take over market dominance from LCDs, just as LCDs did from CRT monitors and televisions between 2000 and 2005 (Matharu, 2008).

FPDs are often divided into categories depending on their size, i.e. small FPDs, medium FPDs and large FPDs. Small and medium FPDs are displays smaller than 10 inches in diagonal, while large FPDs are larger than 10 inches in diagonal (DisplaySearch, 2012b).

The challenges within the area of recycling FPDs, and in particular LCDs, is the wide variety of LCD brands and models, the other types of FPDs which can be mistaken for LCDs, the mixture of other products and the content of a LCD monitor. It is common that the light in a LCD is created by a lamp which contains the hazardous substance mercury. The liquid crystals within the LCD also need to be considered. (Matharu and Wu, 2009) The WEEE directive states that all LCDs with a display larger than 100 cm² shall be removed from any other type of WEEE for reuse, recycling or energy recovery (European Commision, 2012).
INTRODUCTION

1.3 CHALLENGES WITH AUTOMATIC RECYCLING PROCESSES

To remain competitive, recycling companies need to be able to deliver products to their customers in the correct quality and quantity and at the right time. One way to do so is to implement automated recycling processes, both to increase productivity and to improve the staff’s work environment. This is important, since more advanced products contain a greater amount of different materials and in some cases, hazardous materials.

There are challenges in creating an automatic process which is flexible, able to cope with the variations in incoming materials and able to identify the incoming material (Ejiri, 2001). The identification is important to be able to apply the optimal available recycling process. Beside flexibility and the ability to identify material, the process needs to be reliable and robust to cope with the incoming materials that the process is not designed to process, e.g. stones, chains and chemicals. According to a delphi study by Boks and Stevels (1997) there are five main obstacles for automatic disassembly of WEEE, namely:

- Many different products
- Low product-specific volumes
- Products are not designed for disassembly
- General problems in the reverse logistics chain of materials to the recycling plants
- Variations in material quantity returning to the recycling plants

To these five obstacles an additional obstacle can be added: The need to take care of hazardous materials (Matharu and Wu, 2009).

The reason for the focus on the recycling of LCD monitors with an automatic process is the lack of automatic recycling facilities in Sweden. The facilities need to cope with the estimated amount of material which needs to be taken care of in the future. This is combined with the industrial interest and the lack of research in the area of automatic disassembly of LCDs. All of this makes the area important to investigate to effectively cope with the current and the expected future challenges.
1.4 OBJECTIVE

The overall objective of this licentiate thesis is to investigate, from a technical perspective, automation in the recycling industry. More specifically, the objective is to identify problems and solutions in the recycling of plastics and large liquid crystal displays. The results of the investigation will be used as a foundation for creating technical solutions to better manage with current recycling requirements.

1.5 RESEARCH QUESTIONS

To be able to fulfil the objective of this thesis the following research questions (RQs) will be answered. In order to understand the direction of the research and focus on the actual problems in the recycling industry, RQ 1 and RQ 2 are essential in this thesis. RQ 1 and RQ 2 are as follows:

RQ 1 What technical problems may occur in automatic sorting and separation for the recycling of plastics?

RQ 2 What technical problems may occur in automatic dismantling of large liquid crystal displays?

The next set of questions will be used to validate the results findings by investigating solutions to problems found in RQ 1 and RQ 2. These RQs also contribute to give the problem owners, the recycling industry, more knowledge related to these problems. RQ 3 and RQ 4 are both linked to the same question: Which types of automatic solutions can be suitable to use in recycling processes with some level of unknown incoming material? RQ 3 and RQ 4 are as follows:

RQ 3 What processes can be utilised in automatic sorting and separation for the recycling of plastics?

RQ 4 What processes are suitable to utilise in automatic dismantling of large liquid crystal displays?
INTRODUCTION

1.6 DELIMITATIONS
The focus in this thesis is on the recycling process, from a technical perspective, and thus not on environmental, work environment and economic issues. This makes it hard to say if the process contributes to a positive effect on the environment or is economically plausible.

The products focused on in this thesis are plastics from households and industry, together with LCD monitors; no other products were considered in the research presented in this thesis. This focus is the result of discussions with industry to identify products of specific interest. The work does only involve the recycling industry in Sweden; the industries in the study are geographically located in Sweden, some of the companies have activities in other countries as well.
AUTOMATION IN THE RECYCLING INDUSTRY

2 RESEARCH METHOD

This chapter is dedicated to the method which has been used throughout the research. The first set of sections contain short presentations of the research methodologies, namely industry-as-laboratory, action research and experimental research. The chapter continues with a presentation of two concept development methods, concept screening and concept scoring. The next section discusses the researcher relationship to the different methods and how the work in the research has been progressed. The last section contains a description of the research projects the research resulted in. The presentation of this thesis, for example, has been a collaboration with other research projects in the area.

2.1 INDUSTRY-AS-LABORATORY

According to Potts (1993), there are several benefits when a researcher selects industry-as-laboratory as a research method, for example.

- The information about the problem is more directly presented to the researchers from the problem holders.
- Less information is lost in the transfer of information from the researchers to the problem holders.
- In the future, the research becoming more focused on problems.

To prevent the researcher from focusing on the wrong problem or presenting the result in a - as the problem holder sees it - problematic or incomprehensive way, Potts (1993) suggests that the researcher, instead of working in isolation, works in a more integrated way with the problem owner. The researchers should also have a continuous discussion about what the problem is and where the focus is moving, a process illustrated in Figure 3 below. Through working in this way, the researcher is always updated on the problem they are facing, and they are facing the correct problem based on empirical data. When the researcher has a discussion with the problem holder, the researcher and the problem holder develop an understanding of how to transfer information between each other without any information getting lost through misunderstanding.
2.2 ACTION RESEARCH

Action research is a method for researchers who perform practical research and want to improve and gain understanding of the area of practice. This method is useful if you want to be flexible, or involve the problem holders in the research, or gain change during the research, or when the research project is too ambitious to satisfy the focused research questions the researcher has or when the research project is a pilot-project. (Dick, 2011, Oosthuizen, 2002)

A researcher who works with action research is in general working according to the process illustrated in Figure 4 below. The method starts with planning the next steps in the research together with the other participants in the research project. The next step is to perform a number of tests, experiments or other actions. The following step is to cease work in the project so all project participants can gather and analyse the actions made and question the results and methods used. The last step in the method is to reflect on the results collected and learn from these results. The next stage is to start all over again if the result is not satisfying for the research project, or end the project if the result is satisfying. The action research method is by nature cyclic and questions the research regularly, where the result and methods are challenged and possibly rejected and replaced by others. (Dick, 2011, Oosthuizen, 2002)
2.3 EXPERIMENTAL RESEARCH

Experimental research is a research method designed to make a strong link between cause and effect. The method is used when the researcher wants to be able to control the experiment’s environment and the variable or variables which contributed to the effect. The result of this method is that the work is focused on solving problems. (Tanner, 2002a)

According to Christensen (1993), some advantages of using the experimental method are:

- The relation to the causation of the problem is unravelled.
- There is a possibility for the researcher to control the variable or variables which have a link to the effect.
- The method is useful and leads to research results and or awakens new research questions.

The experimental method also has a number of drawbacks or weaknesses, such as: (Christensen, 1993)

- Some criticise the method for not being entirely scientific as the method does not consider the experiment in an uncontrolled environment. The settings of the experiments are set so the effects are more controlled then they would be outside of the experiment.
- The creation of an experiment, both the environment and the possibility to control the variable or variables, can be time consuming and the experiment itself can be time consuming to perform.
- The experimental method is an insufficient method when it comes to the study of human behaviour, since the human is difficult, to control, if not impossible, through changing the settings of one or several variables.
2.3.1 Field and Laboratory Experimentation

There are two types of experimentations to perform within the experimental method: field experimentation and laboratory experimentation. The types are each other’s opposites; field experimentations advantages are laboratory experimentations disadvantages, and vice versa. (Christensen, 1993)

Field experimentation does not have the problem with the creation of an experimental environment, since the experiments are performed in reality and are therefore not sensitive to artificial input from an artificial environment. This also means that this type of experimentation is faster to create, since the experimental environment already exists. (Christensen, 1993) On the other hand, the field experimentation has a drawback when it comes to controlling the environment and variable, or variables, which lead to different effects on the subject investigated. This is related to interference from the surrounding environment and the possible change of circumstances, for example the change from day to night or some other unexpected happening. (Tanner, 2002a)

The laboratory-experimentations advantage is the possibility to control the environment the experiments are performed in, due to it is artificial and possible to modify to fit its purpose. One other advantage is the possibility to control the variable or variables with shall be used to change the effect of the experiment. (Tanner, 2002a) The drawback of the laboratory experimentation is the artificial environment, there is a possibility that the artificial environment projects a fair image of the reality and therefore do not works in the same way. One other drawback is the time to create the artificial environment. (Christensen, 1993)

2.4 Concept Development Methods

To be able to evaluate the different equipment and technologies efficiently, tools like concept screening and concept scoring can be used. Both methods use six steps. The reference to the content in this section comes from Ulrich and Eppinger’s (2008) book Product Design and Development if nothing else is mentioned in the text. According to Ulrich and Eppinger (2008), the concept selection process contains the following six steps:
1. Create a matrix that contains the different alternatives and the different criteria.
2. Evaluate the different alternatives from the criteria.
3. Rank the different alternatives depending on which alternatives fulfil the criteria best.
4. Combine and improve the alternatives.
5. Select one or more.
6. Evaluate the result and the process.

It is not necessary to use the tools together, as concept screening and concept scoring work separately as well. Concept screening is a quick tool which does not give an accurate result due to no priority of the criteria with which it is used. The concept scoring tool more time-intensive, but also more accurate due to priority of the criteria used. The main purpose of both the tools is to be used by the user to compare different product development concepts; the tools also can be used to compare different types of equipment, technologies and processes. The important thing is which different criteria are used.

2.4.1 Concept Screening
Concept screening is a rough evaluation used for avoiding alternatives that do not fulfil the criteria as well as the other alternatives. An example of a concept screening table is seen in Table 2 below.

In Table 2, Alternative 1 is selected as the reference alternative, as denoted by the marking (ref.). All other alternatives are compared with the reference alternative. If another alternative fulfils a criteria better than the reference alternative, it is marked with a plus (+); if the alternative fulfil the criteria poorly the alternative is marked with a minus (-); and if the alternative fulfils the criteria equivalently to the reference alternative it is marked with a zero (0). When this is completed, the result from all alternatives is summarised, the total points are calculated and the hierarchy is set. If a combination of alternatives has a satisfying result, then the combination has the possibility to continue.
**RESEARCH METHOD**

Table 2 Example of screening table, modified from Ulrich and Eppinger (2008)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Rating</th>
<th>Rating</th>
<th>Rating</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt. 1 (ref.)</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Alt. 2</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Alt. 3</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Alt. 4</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Sum +</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Sum –</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Sum 0</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>Hierarchy</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Continue?</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

2.4.2 CONCEPT SCORING

Concept scoring, which is illustrated in Table 3, is a more precise tool to evaluate different alternatives as compared to screening. To get a more precise evaluation, weighting is used. This tool is used in the same manner as concept screening, i.e. a reference alternative is selected to which the other alternatives are compared. The results alternative from the concept screening method, used earlier in this section, continues in the evaluation with the concept scoring tool.

Table 3 Example of scoring table, modified from Ulrich and Eppinger (2008)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Rating</th>
<th>Point</th>
<th>Rating</th>
<th>Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt. 2 (ref.)</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Alt. 3</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Criteria 1</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Total point</td>
<td>18</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hierarchy</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continue?</td>
<td>No</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The rating of the alternatives is made between 1 and 5, as shown in Figure 4 below, as compared to the reference alternative. The rating between the alternatives is not the only rating that is performed; a weighting between the different criteria is also performed. By multiplying the weighting of the criteria and the rating of the alternatives, a score for the alternative, the point, is generated. After multiplying all the alternatives, the remaining steps are to summarise the total score, to order the alternative in a hierarchy and to select the final alternative/alternatives to continue with.
AUTOMATION IN THE RECYCLING INDUSTRY

Table 4 Clarification of weighting, modified from Ulrich and Eppinger (2008)

<table>
<thead>
<tr>
<th>Fulfilling comparing to reference</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very poor</td>
<td>1</td>
</tr>
<tr>
<td>Poor</td>
<td>2</td>
</tr>
<tr>
<td>Equal</td>
<td>3</td>
</tr>
<tr>
<td>Better</td>
<td>4</td>
</tr>
<tr>
<td>A lot better</td>
<td>5</td>
</tr>
</tbody>
</table>

2.5 METHOD USAGE

The research resulting in this licentiate thesis has a connection to the recycling industry, as well as other industries such as automation integration and recycling equipment integration. The work within the research has been performed together with all of the research project partners depending on the focus of the research projects. To be able to get several different ways of addressing the problems, all of the actors have been an important input to the research. Since the first two RQs are to investigate the problems with using automatic recycling processes in the recycling industry, getting several views of this will be an important contribution to answering these two RQs.

The research has been performed as shown in Figure 5. The research has been an interactive process and answering RQ 1 and RQ 2 been performed during the entire research process. The main investigation of RQ 1 and RQ 2, however, has been performed in the two first stages of the research, as illustrated in Figure 5.

Initially the challenges were identified through working together with recyclers and an automation integrator in Sweden, and information was collected during discussions with the companies and during study visits at recycling sites. To get an understanding of the complexity of some of the incoming materials in the recycling process, LCD monitors were dismantled by hand and analysed by the researcher in the university’s laboratory. Examples of incoming monitors and
sorted LCD monitor materials are illustrated in Figure 6. The work with suggesting different concept solutions was something that the researchers did by themselves and then modified through discussions with others within the research projects. To be able to verify the functionality of the concepts after modifications of technical solutions, early experiments and tests were performed together with companies which were capable of helping the researchers, and also within Linköping University’s own laboratory. An overview is illustrated in Figure 5 above.

Figure 6 Example of incoming material (left) and sorted LCD-monitor material (right)

The literature review presented in this licentiate thesis was conducted to get an overview of the research area and to collect information about the different subjects discussed. Some areas for the literature review included theory and research of plastics, and theory and research about EEE, both from a technical and environmental perspective.

The connection between the research presented in this thesis and action research is that the author did not know where to start and has been testing his way forward, especially when it comes to developing different concepts for technical solutions. The work has been largely according to Plan – Action – Result – Reflection; once completed, the author has started again at the beginning to plan new tests or actions.

The inspiration from experimental research is mostly from the field experimentation approach, since most of the information and tests, as well as the problems itself, come from the real-life situation of the participant industry and institutions within the research projects. The work in the research is problem-focused, which is the reason why RQ 1 and RQ 2 are to find the main challenges and RQ 3 and RQ 4 is to find answers to the challenges. To address the challenge, the work was tightly linked to the industrial partners, and the discussion was important to get an understanding of the problem and identify
the challenges. This relation with the industry is something which is described in the research method industry-as-laboratory approach. Both RQ 3 and RQ 4 have been addressed in collaboration with industry.

The concept development methods described earlier in this chapter have been used in the theoretical evaluation of the practical testing of the different technical concepts and have not been used to compare products but technologies and equipment. Also, the methods have also been a help with the definition of the requirements necessary to validate and compare the different concepts of technologies.

2.5.1 RELATIONSHIP BETWEEN RESEARCH QUESTIONS AND METHODS
The relationship between the RQs and the methods and tools used is visualised in Table 5 below. In Table 5, the upper row shows the research methods while the left column lists the RQs. The relationship between the methods and the RQs is marked in the table with a small monitor icon.

Table 5 Relationship between RQs and methods

<table>
<thead>
<tr>
<th>RQ 1</th>
<th>RQ 2</th>
<th>RQ 3</th>
<th>RQ 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Monitor Icon]</td>
<td>![Monitor Icon]</td>
<td>![Monitor Icon]</td>
<td>![Monitor Icon]</td>
</tr>
</tbody>
</table>

The mixture of methods which have been mentioned in this chapter have all been a help when attempting to understand the available research in the area of product and production research; without picking parts from the different methods and just using one specific method, this research would not have been possible. As Table 5 above shows, the most common method related to the RQs is action research, but most of the time the research has been performed according to the industry-as-laboratory and experimental research.

2.5.2 RELATIONSHIP BETWEEN RESEARCH QUESTIONS AND PAPERS
The relationship between the RQs and the papers included in this thesis is visualised in Table 6 below.
RESEARCH METHOD

Table 6 Relationship between RQs and published papers

<table>
<thead>
<tr>
<th>RQ</th>
<th>Paper I</th>
<th>Paper II</th>
<th>Paper III</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ 1</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>RQ 2</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>RQ 3</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>RQ 4</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>

2.5.3 VALIDATION

To be able to validate the results of the research, the results have been used in the publication of articles in international conferences for an open discussion with other researchers and companies in the same research area. The practical tests in a laboratory environment have all been documented with test-plans containing the objective of the test, the expected result, the criteria for a satisfactory result and the result itself. Some of the results are also presented as physical objects, which are stored within the university’s laboratory.

The drawback with tests and experiments in a laboratory environment is the possibility to create a “perfect” environment without some of the disturbances which exist in an industrial environment. This makes the results not entirely truthful, and erroneous conclusions can be made unless the tests are also performed in a more industrial environment. The benefit with first making laboratory tests and then industrial tests is the improved understanding of the problem during the laboratory test. The more expensive industrial tests can then be executed with a shorter ramp up period and with better understanding about the problem and knowledge about what to measure. The result of this is a more cost efficient testing than if the tests where done only in industry, and more results from the tests are more accurate. The tests made in an industrial environment added vital validation to the research, and was a source of information transfer between industry and the academia within the three research projects presented in the next sub-chapter.

2.6 RECYCLING PROJECTS

The three first sections, i.e. sections 2.6.1 to 2.6.3, presents research projects which were a part of the research presented in this licentiate thesis. The additional projects presented in the last section, section 2.6.5, constitute of other research projects in the same area.
2.6.1 PLASTIC RECYCLING PROJECT
The plastic recycling project partners were made up of students from Linköping University and the recycling company IL Recycling in Linköping. The project, which involved four part-time (50%) students, began in August 2008 and ended in December 2008. The main aim of the project was to investigate possibilities for development of a recycling system for waste plastics from industry and households. The system needed to be able to cope with a mixture of soft and hard plastics and be economically profitable. The students identified two recycling systems with the same layout, but with two different setups of sensors for identification, sorting and separation of the different plastics.

2.6.2 AUTODisA - AUTOMATED DISASSEMBLY OF FLAT PANEL DISPLAYS
The research project AutoDisA aimed to investigate the possibility to create an automated recycling process which almost has the volume capacity of a shredder and the ability to separate and sort materials and components as in today’s manual process. The project involved a recycling company, a robot integrator and two research institutes. The project, which had its start in August 2009, was planned to end in August 2012. The project plan has change and extended until December 2013. This was done to finish the construction of a fully-functional industrial demonstration process, to extend the research and to include automatic recycling processes for LCD television sets.

The participants in the AutoDisA project are:
- Chalmers Industriteknik
- CIT Recycling Development
- Hans Andersson Metal AB
- Linköping University
- Nordic Recycling AB
- SVIA Industrial Automation

2.6.3 HÅPLA - SUSTAINABLE RECYCLING OF FLAT PANEL DISPLAYS
The HÅPLA research project took a wider scope then the AutoDisA project regarding the challenges of recycling flat panel displays. The HÅPLA project involved: development of an automated recycling process, development of processes for extracting high value metals from crushed LCD panels, development of new products, study of environmental impacts and work environmental impact, examination of product design for recycling, and investigation of laws and certification changes. The project had numerous different stakeholders from industry (both producers and recyclers), academia and other Swedish institutions and agencies. The project started in January 2010 and will end in June of 2013.
RESEARCH METHOD

The participants in the HÅPLA project are:

- Chalmers
- Chalmers Industriteknik
- CIT Recycling Development
- El-kretsen AB
- Hans Andersson Metal AB
- Kuusakoski Sverige AB
- IVL Swedish Environmental Research Institute
- Linköping University
- MRT system
- Samsung Electronics Nordic
- Stena
- Swerea IVF
- TCO development AB
- Hans Andersson Metal AB
- Swerea IVF
- TCO development AB

2.6.4 RELATIONSHIP TO OTHER RESEARCHERS IN THE PROJECTS

The economic, environmental and work environmental issues related to the research presented in this thesis will be investigated and validated by the different project’s partners. The consequence of this is that this research, in order to be validated, is dependent on the other partners in the research project. Since some of the partners in the project are companies with economically-driven goals, this means that the research is influenced by their economic goals.

2.6.5 OTHER RESEARCH PROJECTS IN THE EEE RECYCLING AREA

The AutoDisA and HÅPLA projects are far from the only research projects in the area of automated recycling of LCD monitors and televisions and other flat panel displays. Other projects are for example the REFLATED project (Holmes, 2010), launched in United Kingdom, the European project Liquid crystal display re-use and recycling (Ladanyi and Miklosi, 2006, Kopacek, 2010); and the Belgium project PRIME - Perfecting Research on Intelligent Material Exploitation (PRIME, 2011). The REFLATED project focused on developing a semi-automated process for the recycling of liquid crystal, indium and glass from LCD panels, using a shredding process (Holmes, 2010). The PRIME project focuses on the recycling of LCD monitors and LCD televisions through shredding the LCDs into smaller fractions, and then extracting the materials of interest (PRIME, 2011). Another project which has used shredding to process LCD monitors have been run by Swico Recycling, the aim of which was to investigate the gas emissions of mercury from a shredding process (Swico Recycling, 2011).
3 THEORETICAL FOUNDATION

This chapter contains the theoretical foundation for this licentiate thesis. The chapter starts a discussion of the research area, followed by an explanation of the Swedish recycling industry. Theory of plastic materials and liquid crystal display monitors are also explained in this chapter. The chapter concludes with an explanation of some aspects of automation in the area of production and the recycling industry.

3.1 THEORETICAL CONTEXT

Within the area of production research there are many sub-areas; some examples are manufacturing engineering, economics, logistics, maintenance and management. The research presented in this thesis uses the theories and experience from the area of manufacturing engineering and applies it to the area of recycling. Other approaches to the area of recycling come from reverse logistics, product design and environmental impact. All of these approaches have affected the research presented in this thesis through collaboration with other researchers, institutes and industry. The research presented in this thesis, however, focuses only on recycling from the manufacturing engineering perspective, an overview of which is presented in Figure 7 below.

Figure 7 Surrounding research areas related to the research presented in this licentiate thesis
Other recycling research within the manufacturing engineering area, besides the research presented in this thesis, focuses on the development of different processes, for example: shredding, separation and sorting systems (Yokoyama and Iji, 1993, Cui and Forssberg, 2003); automatic disassembly process technologies (Kopacek, 2010), e.g. circle saw, water jet cutting and laser cutting; automatic disassembly systems (Scholz-Reiter et al., 1999); semi-automatic disassembly systems (Hohm et al., 2000, Karlsson and Fugger, 1998, Knoth et al., 2002); hybrid disassembly systems (Kim et al., 2009); different sensors and analysis equipment (Jorgensen et al., 1996, Hata et al., 2008); grasping tools (Seliger et al., 2001, Feldmann et al., 1999); disassembly planning (Scholz-Reiter et al., 1999, Li-Hsing and Shun-Chung, 2007, Torres et al., 2009) and chemical processes (Hunt et al., 2010, Li et al., 2009, Kato et al., 2003). In addition to the research presented in this thesis, manufacturing engineering includes research on, for example: development of new machines and materials (Frogner et al., 2011, Svensson et al., 2012); wear of mechanical products (Björling et al., 2012); human and machine interaction (Krüger et al., 2009); and flexible automation and fixtures (Jonsson and Ossbahr, 2010).

Product design includes development of design methods, for example: design for disassembly (Sodhi and Knight, 1998, Boks and Tempelman, 1998, Bogue, 2007); active disassembly (Boks and Tempelman, 1998, Suga and Hosoda, 2000, Chiado et al., 1998); design for environment (Harjula et al., 1996, Fiksel, 1993); and finding new applications for old products and the components included in these products (Hunt et al., 2010, Felix, 2011).

Environmental impact research includes end-of-life investigations (Socolof et al., 2005, Sundin and Lee, 2012, Sundin and Lee, 2011) and analysis techniques, e.g. life cycle assessment (Gungor and Gupta, 1999, Duan et al., 2009, Dodbiba et al., 2008, Dodbiba and Fujita, 2004); and material analysis (Ryan et al., 2011, Hischier et al., 2005).

Reverse logistics involves understanding the flow of material to recyclers from customers who have been using the products in a way which makes it possible to reuse, refurbish or recycle the products. (Knoth et al., 2001, Lundmark et al., 2009)

The research areas of reverse logistics, product design and environmental impact have all been inputs to the research presented in this thesis. Reverse logistics has been important because knowledge about the incoming material to a recycling process is crucial to the processes developed. The product design...
Area has contributed with methods for analysing product design, how to disassemble the products and how to construct new products from the old. The area of environmental impact has contributed with an understanding of the consequences of an automated recycling process on the products of interest, namely plastics and large LCDs.

The following sections in this chapter will describe the relevant theory (illustrated in Figure 8) for this thesis.

Figure 8 Diagram of the content of this chapter

3.2 Swedish Recycling Industry

In Sweden, a number of actors work together to ensure that consumer and commercial products are properly collected, treated and put back on the market or responsibly discarded. Among these actors are organisations for collecting and distributing discarded products and recycling organisations.

The Swedish organisation responsible for packaging and paper collection, Förpacknings och Tidnings Insamlingen (FTI), is an organisation representing plastic and paper packaging producers. FTI provides collection and distribution of discarded plastics and paper packaging to recyclers throughout Sweden. By doing so, the plastic and paper packaging producers fulfil their environmental responsibility. (Förpacknings och Tidnings Insamlingen, 2012a)

El-kretsen is an organisation which handles EEE producers’ environmental responsibility, and is responsible for collection of EEE put on the market as well as distribution of the collected WEEE to recyclers in Sweden. This includes the
THEORETICAL FOUNDATION

recyclers presented below, but also local companies and local government organisations. (El-Kretsen, 2012a)

Since El-kretsen and FTI only have collection and distribution systems for material, there is a need for recyclers with the possibility and capacity to recycle, refurbish or reuse the waste. Some recycling companies in Sweden are listed below: (The Swedish Recycling Industries Association, 2011)

- Stena Recycling AB
- Kusakooski Recycling AB
- Hans Andersson Metal AB
- Nordic Recycling AB
- Sweden Recycling AB
- IL Recycling AB
- Rang-sells
- SimS recycling solutions

3.3 PLASTICS

Plastics are polymers based on petroleum products, and are used in a wide variety of applications, e.g. construction, electrical and electronics, automotive and packaging. The simplest plastic polymer is polyethylene, where the smallest molecular chain building block contains one carbon atom and two hydrogen atoms. Together with another set of carbon and hydrogen atoms, the blocks create an ethylene monomer, the chemical schema of which is shown in Figure 9. The “n” in Figure 9 below defines the number of monomers in the polyethylene molecule; usually the number of monomers is around $10^4$, but the number can differ in a range from $10^3$ to $10^6$. (McCrum et al., 2007)

\[
\begin{array}{cccc}
  H & H \\
  \| & \| \\
  - & C & - \\
  \| & \| \\
  H & H \\
\end{array}
\]

Fig. 9 A chemical schema of a polyethylene monomere, modified from McCrum et al. (2007)

The most common plastics in the world, polyethylene, polypropylene, polyvinyl chloride and polystyrene represent over 85% of polymers used (McCrum et al., 2007). According to Plastics Europe, polyethylene terephthalate can be added as well (PlasticsEurope, 2011). In the list below, common plastics in the Swedish waste stream are presented along with examples of application areas for each respective plastic (McCrum et al., 2007).
• Polycarbonate (PC) is used in casing in electronic and electrical equipment (McCrum et al., 2007).
• Polystyrene (PS) is common in single use coffee mugs and single use knives, forks and spoons, along with use in packaging (McCrum et al., 2007, Dodbiba and Fujita, 2004).
• Polyamide (PA) is used in a verity of tubes, hoses, cables and in e.g. plain bearings in chain conveyers (McCrum et al., 2007).
• Polypropylene (PP) is used in pipes, automobile parts and bottles. (McCrum et al., 2007, Dodbiba and Fujita, 2004).
• Polyethylene terephthalate (PET) is used in soft drink bottles, food containers and engineering plastics in precision moulding parts (McCrum et al., 2007, Dodbiba and Fujita, 2004).
• Low-density polyethylene (LDPE) is used in film packaging (McCrum et al., 2007).
• High-density polyethylene (HDPE) is used in pipes, bottles and kitchenware (McCrum et al., 2007).
• Polyvinyl chloride (PVC) is commonly used in cable tubes, cable isolation, hose, wall and floor coverage and wire (McCrum et al., 2007, Dodbiba and Fujita, 2004).
• Polymethyl methacrylate (PMMA) is used in liquid crystal display light guides (McCrum et al., 2007).
• Acrylonitrile butadiene styrene (ABS) is common used in plastic casing for electronics e.g. computer monitors and televisions, as well as in pipes, and fittings (McCrum et al., 2007, Dodbiba and Fujita, 2004).

3.3.1 ADDITIVES
Besides the variations in plastics, there are also variations in additives to the different plastics to improve specific features. One type of additive is to use a softener to decrease the stiffness and increase the ductility in the plastic. Examples of applications where softeners are used include bottles, cables and children’s toys. The opposite of this is the use of hardeners to make the plastics stiffer and more rigid. To make plastics even more rigid than can be achieved with hardeners, fibres can be applied to create a material which is both rigid and impact resistant. To create a plastic with a specific colour the plastic material can either be painted or colour pigments can be added into the plastic. Colour pigments also act as bulk material. The purpose of using bulk material is to decrease the cost of the material, since the bulk material is cheaper than the plastic; however, it also changes the mechanical properties of the plastic. One additive in plastics which has become less common is flame retardants, due to
THEORETICAL FOUNDATION

the negative impact of this additive on the environment. Flame retardant additives are used in EEE to prevent the plastic from catching fire in case of overheating equipment. Flame retardants are also used in clothing for specific purposes. (McCrum et al., 2007)

3.3.2 MIXED PLASTICS

In addition to creating better plastic properties with additives, plastic producers have started to create new plastics by mixing existing plastics. By doing so the producers are able to create new plastics with entirely new properties. This, together with the possibility to use additives and the great amount of virgin plastic available makes the variety of different plastic materials vast. (McCrum et al., 2007)

3.3.3 RECYCLING OF PLASTICS

Overall global plastic production reached 265 million tonnes in 2010, while European plastic production was 57 million tonnes. The development of global and European plastic production is shown in Figure 10 below. (PlasticsEurope, 2011)

![Plastics production from 1950 to 2010](image)

Figure 10 Plastics production from 1950 to 2010, modified from PlasticsEurope (2011)

In 2012, the amount of plastic waste generated by European consumers was 24.7 million tonnes; 10.4 million tonnes (42.1%) went to disposal, while 14.7 million tonnes (57.9%) were recovered. The recovered plastics in Europe are recycled into new products or used as fuel in energy recovery. Many of the European countries, including Sweden, use waste plastic for energy recovery to a greater extent than recycling the plastic for use in new products. (PlasticsEurope, 2011) This is also shown in Figure 11, which is a graphical summery of the amount of plastics on the Swedish market and the amount of
recovered plastics in Sweden between 1998 and 2011 (Förpacknings och Tidnings Insamlingen, 2012b, Swedish Environmental Protection Agency, 2012). The Swedish government’s goal for recycling plastic waste is that 70% of all plastics used for packaging shall be recycled and 30% of this material shall not be used in energy recovery. This means that 21% (70% · 30% = 21%) of all recycled plastics shall be material recycled. As Figure 12 illustrates, the goal of a total plastic recovery of 70%, where 30% is not for energy recovery, has not been fulfilled since the introduction of the goal in 2001 (Förpacknings och Tidnings Insamlingen, 2012b). Overall, there are three different ways of taking care of waste plastics (Dodbiba and Fujita, 2004): (1) discarding plastics in landfills, (2) using mechanical recycling to reuse the plastic as material in new, similar products or recycling the plastic on a molecular level through feedstock recycling and (3) energy recovery through plastic incineration.

Figure 11 Amount of plastic available and recovered in Sweden between 1998 and 2011 (Förpacknings och Tidnings Insamlingen, 2012b, Swedish Environmental Protection Agency, 2012)
The dip in energy recovery in Figure 11 and the dip in the total percentage collected in Figure 12 depends on new ways to collect the plastic, which resulted in a lack of responding communes in the reporting of the amount of plastic collected during 2009. (Swedish Environmental Protection Agency, 2012)

3.3.4 General Issues in the Recycling of Plastics

The following issues are present when performing recycling of plastics.

- Plastics can be recycled roughly three to four times; then the plastic is worn out and of a poor quality (Gupta, 2011, Eriksson and Finnveden, 2009).
- Many types of plastics are used, making it difficult to separate from each other and expensive to recycling (Gupta, 2011, Dodbiba and Fujita, 2004).
- Plastics can contain several additives which degrade the virgin plastic quality (Gupta, 2011).
- Plastics can be reinforced or mixed with metals and other non-plastics which degrade the plastic when recycled (Gupta, 2011, Froelich et al., 2007).
3.4 LARGE LIQUID CRYSTAL DISPLAYS

A large display is a display larger than 10 inches measured diagonally across the display. Small or medium-sized displays are smaller than 10 inches in diagonal. (DisplaySearch, 2012b) An LCD is a display using the technology of liquid crystals together with thin transistors, different filters, a light source, a power supply, and data control signals to create an image on the display (Ishii, 2007). LCDs are often used as computer desktop monitors, television sets and in other display applications. (Matharu and Wu, 2009) In general, the product design of a LCD monitor can be divided into several modules and components (Figure 13). A LCD monitor includes several components, including a LCD module. This module, in turn contains several components, including the LCD panel which contains the liquid crystals.

![Exploded view of a LCD monitor](image)

Figure 13 Exploded view of a LCD monitor, cables and printed circuit boards are excluded in the figure

3.4.1 LIQUID CRYSTAL DISPLAY MONITORS

The outer shell of a LCD monitor contains two plastic covers, one at the front-side and one at the backside. In between there are several components: the LCD module, the metal frame, printed circuit boards and other components such as speakers and buttons. Figure 14 below illustrates, from the top: plastic cover, LCD module, metal frame and plastic back cover. The metal frame is the carrier of components such as the speakers, buttons, energy power supply components and the printed circuit boards. Components such as speakers, printed circuit boards, cables, buttons, and indicators are not illustrated in Figure 14. (Matharu and Wu, 2009)
The material expected in a LCD monitor are plastics (ABS, PP, PS and PC), metal (steel, copper and aluminium) and glass (Matharu and Wu, 2009).

### 3.4.2 Liquid Crystal Display Modules

A LCD module like that depicted in Figure 15 shows a sandwich construction which is kept together with a metal frame and a metal back plate, shown at the top and bottom of Figure 15, respectively. The metal frame (1) and the back plate (7) are held in place with snap fits and in some cases a number of screws as well. In between the metal frame and the back plate there are several layers of components. The second component from the top in Figure 15 is the LCD panel (2). The third component is a plastic frame (3), which keeps the LCD panel and the optical plastic films (4) aligned correctly. The plastic films have optical properties for focusing and aligning the projected light. The next component is the light guide (5a) together with the two backlight unites (BLU) (5b), placed at either long-side of the light guide. The light in a LCD monitor is projected by the BLUs, which can be cold cathode florescent lamps (CCFL), light emitting diodes (LED) or some other BLU (DisplaySearch, 2012a). A CCFL containing BLU can contain 2-7mg of mercury (Matharu and Wu, 2009). The light from the BLU and the light guide guides the light from the BLU to the optical films. The light guide is usually made of polymethyl methacrylate (PMMA) (Granta CES, 2010, Peeters et al., 2011a, Li et al., 2009). The second component from the bottom in Figure 15 is the reflector (6), which is a plastic film which reflects all light which is travelling towards the reflection film. (Matharu and Wu, 2009)
3.4.3 LIQUID CRYSTAL DISPLAY PANEL

A LCD uses the ability of the liquid crystal to control the light in the display. Figure 16 shows a cross section of a LCD panel which contains the liquid crystal. The design is a sandwich construction of the different layers of materials with specific purposes. The two polarisation films are twisted 90 degrees in relationship to each other ensuring no light can pass through the films. To select a specific colour in a specific pixel in the display, the thin film transistors are used and controlled by a matrix of electrical conductors made of indium (Matharu, 2008). A pixel contains three cells, and each of the cells creates the colours red, green and blue. There are several types of LCD panel constructions; the type illustrated in Figure 16 is a thin film transistor LCD. The specific colour pixel is turned on when the electrical loud is turned off over the colour pixel, and vice versa. (Yeh and Gu, 1999, Matharu and Wu, 2009)

Figure 15 Exploded view of a LCD module, modified from Matharu and Wu (2009)

The materials in a LCD module are metal (steel, aluminium), plastic (PMMA, plastics containing flame retardants) and some high-value printed circuit boards. (Matharu and Wu, 2009) The high-valued printed circuit boards and cables are not illustrated in Figure 15.
THEORETICAL FOUNDATION

Figure 16 Cross section of a liquid crystal panel: (1) polarisation film, (2) glass sheet, (3) colour filter, (4) passive electrode made of indium tin oxide, (5) liquid crystal, (6) thin film transistor, (7) glass sheet and (8) polarisation film. Modified from Yeh and Gu (1999)

3.4.4 LIQUID CRYSTALS

To be able to let light through the panel the liquid crystal medium and the transistors are used. The liquid crystal molecules are by nature aligned in orientation to each other. When the liquid crystal is uninfluenced by an electrical load the molecules change their orientation and become twisted. This ability is used for example to bend the direction of the wavelength of the light let through the first polarising film in the LCD panel. This makes it is possible for light to pass the second polarising film, and the pixel lets through light of the selected colour, as illustrated in Figure 17 below. There are several types of liquid crystal with different features. (Yeh and Gu, 1999, Matharu and Wu, 2009)
The liquid crystal medium itself is a mixture of chemicals bounded together to create a robust and stable composition of chemicals (Yeh and Gu, 1999). One of the common components in this mixture of chemicals is fluoride, a reactive substance with suitable electro-optic abilities. The common concentration of liquid crystal in a LCD is .5mg per cm², which in a 30 inch LCD television becomes 1.2g liquid crystal medium. If this amount is multiplied by the number of LCD televisions sold in 2007, the amount of liquid crystal produced for 30 inch LCD televisions in 2007 equals 93 tonnes. (Matharu and Wu, 2009) According to one of the liquid crystal manufacturers, liquid crystal medium:

“are not acutely toxic”

(Merck, 2012a)

and

“are not easily biodegradable.”

(Merck, 2012a)

The recommended way to recycle liquid crystal medium in metallurgical melting processes is by incineration of the liquid crystal medium (Merck, 2012a). There are few long-term investigations of how the liquid crystal affects the environment at this time, something which might be interesting to investigate (Matharu and Wu, 2009).

3.4.5 GENERAL ISSUES IN LIQUID CRYSTAL DISPLAY MONITOR RECYCLING

In the area of recycling LCD monitors there are several issues to consider, some of which are illustrated in the bullet list below.
THEORETICAL FOUNDATION

- A lack of efficient recycling processes capable of coping with the amount of LCDs in the waste stream (Kopacek, 2010, Peeters et al., 2011b)
- Some of the LCD monitors contain hazardous materials such as mercury (Peeters et al., 2011b, Salhofer et al., 2011, Boeni et al., 2012, Kim et al., 2009)
- The LCD monitors contain a variety of material (Socolof et al., 2005, Schlummer et al., 2007, Peeters et al., 2011b, Salhofer et al., 2011, Boeni et al., 2012)
- A lack of information about the material composition of the products, and existing information that is difficult for the recycling industry to obtain (Salhofer et al., 2011, Vanegas et al., 2011, Peeters et al., 2011a)

An example of the amount of mercury put on the market is described by Matharu and Wu (2009). Approximately 78.2 million 30 inch LCD television sets were shipped from producers in 2007. If that number of television sets is multiplied by the amount of mercury per television set (300mg), the amount of mercury put on the market would equal approximately 23.46 tonnes worldwide.

3.5 MANUFACTURING AUTOMATION

The definition of automation can be stated as a process performing a task by itself (Nof, 2009, Nationalencyklopedin, 2012). This means an automation process can be any task without human intervention, for example a conveyor belt moving objects from one place to another without any help from a human. This is often the case when only one type of simpler task is required. As soon as more advanced tasks are required for moving objects from one place to another with specific positioning accuracy and time, this type of task requires more equipment and information needs to be exchanged with the surrounding environment. A good example is the usage of industrial robots. These systems involve information exchange within the robots control system and can include information exchange with surrounding equipment such as a programmable logic controller or the controller to industrial equipment. This entire system can also be connected to an organisation’s local area network for access to information, controlling and planning of the equipment. (Hodge, 2004, Nof, 2009)

3.5.1 MANUFACTURING AUTOMATION IN GENERAL

According to Groover (2008), the most vital parts of an automated system are (1) the power supply for all the parts of the system, (2) the instruction program to manage the system, and (3) the control system of the actuators which perform the instructions. A more detailed image is seen in Figure 18 below.
AUTOMATION IN THE RECYCLING INDUSTRY

Figure 18 Linkage between vital automation system parts (Groover, 2008, p.88)

The hierarchy in automation can be seen in five levels (Table 7), each of which relates to the level of abstraction focused on. Level 1 focuses on local devices, for example the feedback loop of information from a position sensor in an electrical motor in a robot joint. Level 5, another abstraction level, focuses on functionalities. (Groover, 2008)

Table 7 Level of manufacturing automation, modified from Groover (2008)

<table>
<thead>
<tr>
<th>Level</th>
<th>Geographic</th>
<th>Description and examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Enterprise</td>
<td>Corporate information system, master production planning</td>
</tr>
<tr>
<td>4</td>
<td>Factory</td>
<td>Production system,</td>
</tr>
<tr>
<td>3</td>
<td>Cell system</td>
<td>Robot cell, production line, group of machines</td>
</tr>
<tr>
<td>2</td>
<td>Machine</td>
<td>Robot system, CNC machine</td>
</tr>
<tr>
<td>1</td>
<td>Device</td>
<td>Robot joint, one CNC axis</td>
</tr>
</tbody>
</table>

There are several types of automation, depending on the degree of automation used. The degree of automation can be measured using the equation show in Figure 19, where an operation is a stage in the manufacturing process, e.g. drilling a set of holes in a piece of metal. (Nof, 2009)

\[
\frac{\text{Sum of all automated operations in the system}}{\text{Sum of all operations in the system}} = \text{The degree of automation}
\]

Figure 19 Equation for calculating the degree of automation (Nof, 2009)
THEORETICAL FOUNDATION

According to Nof (2009), an automatic system can either be fully-automatic or semi-automatic. Krüger et al. (2009) have divided semi-automatic systems into two types of systems, semi-automatic and hybrid automatic systems. The systems are divided depending on how humans and the automated equipment collaborate. The following two sub-chapters will describe the two different automatic systems.

SEMI-AUTOMATIC SYSTEMS

When an automated system is semi-automatic, the system contains process stages which use human and automatic machines as resources. The work can be divided geographically, or by time when the human and the machine collaborate. The system can be built like a production line, i.e. using several stations with one resource at each station. The resources in the production line can be mixed with human and automated machines. This system divides human and machine geographically. When a human and an automatic machine are divided from each other by time, the human and the machine use the same work area, but during different periods of time. Figure 20 below shows a time and work schedule over two process stages in a production system where the human and machine, represented in Figure 20 by a robot, share the two stages, but during different times. (Krüger et al., 2009, Spath et al., 2009)

![Figure 20 Workspace sharing](Krüger et al., 2009, p.630)

HYBRID AUTOMATIC SYSTEMS

A hybrid automatic system includes human and automatic machine collaboration in two workstations and is working in the same geographic area at the same time. The collaboration requires some kind of interaction between the human and the machine. One way of doing so is by using a force feedback
system in an industrial robot system which the human uses to interact with the robot. Figure 21, a similar figure to Figure 20 shows a time and work schedule for a hybrid automated system. (Krüger et al., 2009)

![Workspace and time-sharing](image)

Figure 21 Workspace and time sharing (Krüger et al., 2009, p.630)

### 3.5.2 Processes in the Recycling Industry

In general, the recycling industry is divided into processes involving large automated process plants for the recycling of materials, and manual disassembly processes with recycling of materials and components. The use of semi-automated dismantle processes is still not common practice in industry today. (Cui and Forssberg, 2003, Yokoyama and Iji, 1993, Kopacek and Kopacek, 2006, Rousis et al., 2008)

The process starts with collection of the waste through a network of collection stations and a transportation network. Material is often already roughly manually sorted at the collection stations. The next step, at the recycling plant, is to make a further manual sortation of materials into fractions. The third step is to use a grinder or a shredder to decompose the material into fine fractions. The fourth step is to use several different extraction processes such as flotation, magnetism and eddy current (Rem et al., 1997). The final stage is to refine the material, e.g. plastic material to plastic pellets and metal in a smelting process, to create the final products. (Kell, 2009, Kellner, 2009)
THEORETICAL FOUNDATION

RECYCLING OF PLASTICS
There are in general three main ways to recover waste plastics: through energy recovery or by chemical or mechanical material recycling (PlasticsEurope, 2011). Plastics recovered as fuel are often incinerated in water heating or power plants. These types of plants are often fitted with advanced filtration systems to prevent hazardous gases from being released into the environment (Eriksson and Finnveden, 2009). Using plastics as fuel in energy recovery is fourth place in the waste hierarchy (European Commission, 2008). The waste hierarchy is illustrated in Figure 22 below.

Recycling of plastics can be done by chemical processes or by mechanical processes. In the chemical recycling process, the plastic molecule components are separated from each other through the chemical, often a thermal, process. The desired plastic molecule structure is then reconstructed and the new plastic is created. The chemical recycling process does, however, create by-products often different gases. These gases can be used as fuel in an energy recovery process. (Miskolczi et al., 2006) Mechanical recycling contains a mechanical process for separating the different plastics on a macro-level. The plastic can be sorted in the original size or be shredded into smaller fractions and then sorted. The European state-of-the art in mechanical plastic recycling plants includes several different processes: decomposition, separation and sorting, and granulation of the plastic products. The decomposition includes processes such as shredding and grinding. Separation is often done by mechanical feeders, while the sorting is done using flotation by the different densities of materials. Other sorting processes are aerodynamic separation, electrostatic, Eddy current (Rem et al., 1997), magnetic separation and manual sorting. (Froelich et al., 2007) There are also technologies such as optical sensors and the use of melting properties for the sorting of plastics (Malcolm Richard et al., 2011).
In the following list of technologies for the mechanical recycling of plastics, the variation of available technologies today is apparent, and some of them are used in industry.

The following nine technologies in the list below show the variation of available technologies today for identifying different types of materials. Some of them are used in already existing equipment.

1. Infrared spectroscopy – Identification of material using infrared light (Sherman, 2000).
2. Near-infrared spectroscopy – Uses the same technology as the infrared, but only in the near infrared spectrum (Salomonsson, 1995).
3. Electrostatic identification – Identification of materials by measuring the materials’ ability to lose an electric charge over time (Hearn and Ballard, 2005).
4. Flotation – Identification of material by using the material’s density (Shent et al., 1999).
5. Fluorescent markers – The plastic is marked by a substance/substances that contain information on what type of plastic it is (Ahmad, 2000).
6. Laser – A laser heats up the surface of the material and the material’s ability to conduct heat is measured, making it possible to identify the material (Flaferkamp et al., 1994).
7. Vision/optical grey scale – This technology compares an object against the background and reference colour, to detect brighter and darker objects. Filters and different lights can be used to identify objects with specific colours, but the main purpose is to identify brighter and darker objects (Riise et al., 2001).
8. Vision/optical colour scale – A technology that has the ability to identify objects with different colours (SICK, 2009).
9. Ultrasound – When a sound wave with high frequency travels through an object the sound waves become weakened by the materials’ ability to absorb sound waves. By comparing the sound before and after it passes through an object it is possible to identify the object (Lotfi and Hull, 2003).

To complement the list above, two lists below contain some equipment used in different plastic recycling processes. The list is split into two parts: initially a list for sorting equipment, and then a list for cleaning equipment.
1. **Gassner Retec™** – A machine constructed only for sorting and separation rigid and non-rigid plastics (Gassner Retec, 2008).
2. **Rotating disks** – A machine with the same purpose as Gassner Retec™ mainly used today to separate different types of paper and cardboard (Jonsson, 2008).
3. **Flotation** – Plastics are sorted by density in a chain of vats with fluids which have different densities (Hillertz, 2008).
4. **Centrifuge** – Same principle as flotation but requires less water; the number of objects to be sorted should be relatively small (Flottweg AG, 2008).
5. **Criterion plus™** – Sorts different kinds of plastics, requires some manual labour with incoming material (Binder-co, 2012).
6. **MSS Vydar™** – Uses x-ray to sort two different types of plastic flakes (Franz-Kahl, 2008).
7. **MSS Sapphire™** – Uses NIR sensors to identify five of the selected plastics (Magsep, 2009c).
8. **MSS Binary BottleSort™** – Sorts five of the selected plastics, but only rigid plastic (Franz-Kahl, 2009).
9. **MSS Aladdin™** – Developed for sorting plastic bottles, maximum of three kinds (Magsep, 2009a).
10. **Scanmaster II™** – Sorts plastics by colour (Satake, 2009).
11. **Colour vision sensor** – Sorts objects by colour or colour combinations (SICK, 2009).
12. **Photocell** – Uses a reflector to identify transparent and non-transparent objects (SICK, 2009).
13. **Colour photocell** – Sorts objects by colour (SICK, 2009).
14. **MSS Plastic Elpac™** – Sorts plastic and metal, both magnetic and nonmagnetic. Requires small objects, flakes (Magsep, 2009b).
15. **Magnets** – Five types of techniques using magnets were investigated as well. Static magnet (Storch Magnetics, 2008, EP Maskin AB, 2008).

The cleaning equipment is presented in the following list.

1. **MR75™/MR110™** – Cleans plastics without water and requires plastic flakes (30-50mm in diameter) (Pal.to, 2008).
2. **KS-WLC300-2B™** – Cleans plastics with water/fluid with no requirements on the incoming material (Stephanie, 2008).

All three lists above show some of the available technologies and equipment for usage when sorting and cleaning plastics materials in a recycling process; when refining the plastic materials, however, some other types of processes are
needed. The processes are shredders and smelters, which make plastic pellets. The shredders can be used before or after the cleaning process, depending on the requirements for the incoming plastic material to the cleaning process. The process which makes the plastic pellets is often located after the shredding or cleaning process. (WRAP UK, 2012, Tsai et al., 2009)

**Recycling of large liquid crystal displays**

LCD monitors are recycled using automated processes designed for a wide variety of EEE; some processes, however, are developed to treat LCD monitors more specifically. The common approaches for LCD monitor recycling are large plants with shredders or manual disassembly. The shredding process is often followed by a series of separation equipment to sort out ferrous and non-ferrous metals, plastics and glass. (STENA Technoworld, 2011, Vanegas et al., 2011) The separated metals are sent to smelters to become new raw material. (UmiCore, 2012, Boliden, 2012) The plastic is sent to refining facilities and also finally re-used in new applications. (WRAP UK, 2012, Tsai et al., 2009) LCD recycling using this process flow is often mixed with other WEEE products. An overview of the shredding and separation stages, adapted from Kell (2009), is illustrated in Figure 23 below.

![Figure 23 Process flow for mixed EEE recycling (Kell, 2009, p.96)](image-url)
A list with examples of equipment used in these processes is presented below.

2. **Chewer** – A form of shredding which is used to shear waste into smaller fractions (Kellner, 2009, Stessel, 1996).
3. **Magnetic separation** – Magnets are used to separate ferrous metals from the remaining waste stream (Kell, 2009, Froelich et al., 2007, Cui and Forssberg, 2003, Stessel, 1996).
5. **Density separation** – The materials’ different densities are used to separate materials from each other. Types of processes are cyclones and different liquid mediums, which can be used separately and in combination with each other (Hillertz, 2008, Flottweg AG, 2008, Cui and Forssberg, 2003, Stessel, 1996). Another type of separation process is Jigging (Cui and Forssberg, 2003).
6. **Electronic separation** – The materials different electrostatic features are used to separate the materials (Kell, 2009, Cui and Forssberg, 2003).

**Manual Liquid Crystal Display Recycling**

In the recycling industry, manual labour is often used in stages before the main processes, such as shredding, for example in the dismantling of the products to remove unwanted materials and remove materials of easy access and of high value, and in the sorting of incoming materials to remove unwanted or separate products or material of special interest. Using manual separation is an effective way to make the first sorting and separation of the incoming materials. (Kellner, 2009)

**3.6 Disassembly**

The disassembly of a product can be divided into several operations; some examples are identification of parts, orientation of product and fixation. (Johansson et al., 1997) However, in the recycling industry there are often one or several operations with sorting material before the actual disassembly operations begin (Kell, 2009). When recycling plastics products the separation of the products is not an issue. The issue, rather, is more related to sorting and identification of the different plastics products. (Rios et al., 2003) The issue with disassembly is revealed in the case of large LCD product recycling. A LCD is in general not designed for disassembly (Matharu and Wu, 2009).
When disassembling a product, the disassembly is done with the purpose of reaching the components of interest. The components can be homogenous components, complex components, or modules. A homogenous component is a component of one solid item and contains no sub-components; an example of such a component is the plastic back casing on a LCD monitor. A complex component is a component containing two or more homogenous subcomponents. This component cannot usually be disassembled due to the integration of the subcomponents. Examples of complex components are; printed circuit boards, transformers, cathode ray tubes, rotors and stators. The final target component is modules, and a module is a composition of homogenous and complex components that can be disassembled. If a module is disassembled then its functionality is lost, and the item loses its value for remanufacturing. Examples of modules are electric motors, optical units, cables, batteries, and engines (Lambert and Gupta, 2005).

When a disassembly or dismantling process is performed in the recycling industry, the process is performed to a breakpoint. The breakpoint is when the process reaches the maximum profit for the actor performing the disassembly or dismantling. All disassembly or dismantling before the breakpoint contributes to an increase in revenues; after the breakpoint, disassembly contributes with a decrease in revenues. Finally, the disassembly generates an economic loss after the point marked with a $Q$ in Figure 24. Some factors which decide the breakpoint are: the materials recycled, the components recycled, the material and component values, the cost of disassembly and the cost of material sent to landfills. (Penev, 1996) The disassembly of a single product can be plotted as in Figure 24, where the disassembly of the product is illustrated by the negative slope of the disassembly curve. As soon as a component is removed from the product the curve takes a step in a positive direction as the part removed brings revenue at a specific time $t_s$, e.g. $t_1$ and $t_2$. As Figure 24 illustrates, not all disassembled parts complements the disassembly time multiplied with the disassembly cost (the negative slope of the disassembly curve) with enough of revenues. From the environmental perspective, all parts removed during disassembly generate a positive environmental impact. (Lambert and Gupta, 2005) The challenge for the recycling industry is to be able to judge the breaking point for the products to be disassembled. (Penev, 1996, Gungor and Gupta, 1999)
3.6.1 **General Disassembly Issues**

The following issues are some of the reasons why there are challenges with the disassembly of products, done both manually and automatically:

- No clear product specification (Penev, 1996, Santochi et al., 2002).
- A lack of information about the product and the components within the product (Penev, 1996).
  - Lack of information about what material the components are made of (Penev, 1996).
  - Lack of information on what service has been done with the product (Penev, 1996).
  - Lack of information about where the connection points are (Penev, 1996).
  - Lack of information about the quality of the materials in the products (Penev, 1996, Santochi et al., 2002).
  - Lack of information about if any hazardous material is present within the product, e.g. mercury and batteries (Lambert and Gupta, 2005).
- Difficulty to decide the breakpoint when disassembling unknown products (Penev, 1996, Gungor and Gupta, 1999).
- Variations in the time to perform the disassembly (Penev, 1996).
- Difficulties in predicting the material value (Santochi et al., 2002).
3.6.2 Manual Disassembly
Manual disassembly within the recycling industry is often performed at work stations equipped with all the disassembly tools the operator needs. Examples of tools are: rotation tables, clamping mechanisms, pneumatic screw drives, pneumatic cutting devices, trays, crowbars, and hammers. (Penev, 1996, Lambert and Gupta, 2005)

3.6.3 Automatic Disassembly
When using automatic disassembly systems for reusing, refurbishing, or recycling products the systems are often limited to a single product or a group of products. The quantity of the product or group of products needs to be sufficient to make the system economically profitable. (Steinhilper, 1998, Kopacek and Kopacek, 2006) The number of automatic disassembly systems is few, and only pilot projects have been performed at research institutes. This is mainly due to the development of automated systems in the area of assembly, and not in the area of disassembly. (Kopacek and Kopacek, 2006)

3.6.4 Design for Disassembly
To design a disassembly-efficient product the valuable components need to be able to be removed first, and the disassembly needs to end before the point where it becomes uneconomical. (Forss and Terselius, 1994) When designing a product according to design for disassembly (DFD) the design can be applied at different levels of complexity. The different levels are the company level, product level, product structure level, component level, and connecting method level. (Johansson, 1997) General DFD principles related to the different product levels presented above are illustrated in Table 8 below. The general principles are generated to be able to design disassembly-friendly products. (Johansson, 1997)
### Table 8 General DFD principles (Johansson, 1997, p.88-89)

<table>
<thead>
<tr>
<th>Disassembly property</th>
<th>DFD principle</th>
<th>Product level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ease of identification</strong></td>
<td>Separation points should be visibly located</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Connectors should be visibly located and possible to disassemble by use of standard tools</td>
<td>Product structure/ Choice of connector method</td>
</tr>
<tr>
<td></td>
<td>Hazardous parts should be clearly marked</td>
<td>Component design</td>
</tr>
<tr>
<td></td>
<td>Mark all plastic parts and similar parts for ease of identification</td>
<td>Component design</td>
</tr>
<tr>
<td></td>
<td>Fasteners should be easy to access</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Locate draining points for easy access</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Locate non-recyclable parts in one area which can be quickly removed and discarded</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Locate parts with the highest value in easily accessible places</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Access and break-points should be made obvious</td>
<td>Product structure</td>
</tr>
<tr>
<td><strong>Accessibility</strong></td>
<td>Minimise the number of different types of materials</td>
<td>Component design</td>
</tr>
<tr>
<td></td>
<td>Use non-aging/corrosive materials</td>
<td>Component design</td>
</tr>
<tr>
<td></td>
<td>Make subassemblies and inseparable parts from the same or compatible materials</td>
<td>Component design</td>
</tr>
<tr>
<td></td>
<td>Connectors should be easy to remove</td>
<td>Choice of connection method</td>
</tr>
<tr>
<td></td>
<td>Hazardous parts should be easily removed</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Eliminate incomparable labels on plastic parts</td>
<td>Component design</td>
</tr>
<tr>
<td></td>
<td>Avoid moulded-in metal inserts on plastic parts</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Standardise connecting techniques</td>
<td>Choice of connection method</td>
</tr>
<tr>
<td></td>
<td>Uniform disassembly direction</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Minimise the number of connectors</td>
<td>Choice of connection method</td>
</tr>
<tr>
<td></td>
<td>Try to use connectors of material compatible with the components joined</td>
<td>Choice of connection method</td>
</tr>
<tr>
<td></td>
<td>If two parts cannot be compatible make them easy to separate</td>
<td>Choice of connection method</td>
</tr>
<tr>
<td></td>
<td>Make designs as modular as possible, with separation of function</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Eliminate adhesives unless compatible with both parts joined</td>
<td>Choice of connection method</td>
</tr>
<tr>
<td></td>
<td>Connections can be designed to break as an alternative to removing fasteners</td>
<td>Choice of connection method</td>
</tr>
<tr>
<td><strong>Ease of separation</strong></td>
<td>Minimise the number of parts</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Avoid non-rigid parts</td>
<td>Component design</td>
</tr>
<tr>
<td></td>
<td>Leave surface available for grasping</td>
<td>Component design</td>
</tr>
<tr>
<td></td>
<td>Avoid reorientation operations during disassembly</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Design parts for stability during disassembly</td>
<td>Component design</td>
</tr>
<tr>
<td><strong>Ease of handling</strong></td>
<td>Minimise the number of parts</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Avoid non-rigid parts</td>
<td>Component design</td>
</tr>
<tr>
<td></td>
<td>Leave surface available for grasping</td>
<td>Component design</td>
</tr>
<tr>
<td></td>
<td>Avoid reorientation operations during disassembly</td>
<td>Product structure</td>
</tr>
<tr>
<td></td>
<td>Design parts for stability during disassembly</td>
<td>Component design</td>
</tr>
</tbody>
</table>
4 RESEARCH RESULTS

This chapter will be the part of the thesis that will answer the research questions (RQs) previously asked in Chapter one, Introduction. The chapter is divided into three sections, each related to the appended papers.

4.1 AUTOMATIC RECYCLING OF PLASTICS

The text presented in this section is generated from the paper written by Elo and Sundin (2009) with the title Automation of Plastic Recycling – A Case Study (Paper I).

This section is linked to RQ 1 and RQ 3, presented in Section 1.5, Research Questions, and aims to answer these questions. The aim is also to present an investigation of the possibilities to create an automated plastic recycling plant capable of sorting, separating, cleaning and granulating plastics common in Swedish household and industry disposal waste.

The research resulting in the Automation of Plastic Recycling – A Case Study was performed in cooperation with the recycling company IL Recycling. The project was performed according to the methodology presented by Ulrich and Eppinger (2008). The data were collected through literature review and discussion with employees at IL Recycling’s plants in Linköping and Örebro.

4.1.1 REQUIREMENTS OF THE AUTOMATED PLANT

The main tasks for automated recycling plants are to sort, separate, clean and granulate plastics for recycling. The sorting of plastics for recycling can be divided into the following stages:

1. Sort and separate metals from other materials
2. Sort and separate plastics and non-plastics
3. Sort and separate rigid and non-rigid plastics
4. Sort and separate coloured and non-coloured plastics
5. Sort and separate the selected common plastic groups

The selected common plastic groups in Sweden are PET, PP, LDPE, HDPE, PVC, PS and other plastics. The reason for the selection of these groups was that these groups are defined by the DIN 6120 standard, and labelling and grouping according to this standard is recommended by the Swedish
RESEARCH RESULTS

organisation Registrering för Producentansvar (REPA, 2011). The cleaning of the respective sorted plastics needs to be done individually, and the plastics cannot be mixed again due to the need for new sortation if the plastics are mixed.

4.1.2 CONCEPTS
The result of the literature review of technologies, interviews and industrial visits was the identification of two concepts of automated plastic recycling plants. The first alternative consisted of conventional technologies which use sensors for detecting plastics and other materials. The second alternative uses a combination of sensors and added markers in the plastics to identify the plastics of interest.

The two resulting alternatives use the same five steps to sort the incoming material. The sorting order is seen in Figure 25 below. The materials which are products from the sortation are: non-rigid plastics and non-coloured plastics sorted in the fractions of the plastic types; PET, PP, LDPE, HDPE, PS, PVC and other plastics; and coloured plastics sorted in the fractions. The remaining by-products are metal and non-plastic materials such as gravel, wood and paper.

Figure 25 Sorting and separation steps, modified from Elo and Sundin (2009)
The separation and sorting steps in Figure 25 above are realized by using the five following technologies:

Step 1. A magnetic roll (Figure 26), together with a conveyor belt, which separates metals and non-metal materials. The speed of the conveyor belt makes it possible to separate objects made of non-ferrous metals from other materials. (Storch Magnetics, 2008, EP Maskin AB, 2008)

```
- Non-metal material
- Non-magnetic metal material
- Magnetic metal material
- Direction of material flow
```

Figure 26 Alternatives 1 and 2 in Process Step 1, modified from Elo and Sundin (2009)

Step 2. Non-metallic objects made of e.g. wood, paper, cardboard etc. are separated from the material flow using a technique called electrostatic identification/charge relaxation (Figure 27). The different materials’ electrical relaxation is used to identify the material. The incoming materials are at first bombarded with electrodes by an ionizing bar. The electric charge is then measured at measurement station one. The object is left to rest during the transportation to measurement station two where the electrostatic charge is measured again. Finally, the electrostatic relaxation is calculated and the object is categorised depending on the material’s electrostatic characteristics. (Hearn and Ballard, 2005) The separation of the materials is done using a pneumatic system which uses air bursts to change the falling object’s trajectory. When an object is affected by the air burst, it lands on a different conveyor belt than if the object were not affected by the air burst.
Step 3. To separate rigid and non-rigid plastics the mechanical process Gassner Retec™ is used. This process step is illustrated in Figure 28. The Gassner Retec™ machine uses the mechanical properties of rigid and non-rigid plastic to separate the plastics. The non-rigid plastics catch on to hooks on the tilting conveyor belts and travel upwards, while the rigid plastics skid on the tilting conveyors and fall down to a conveyor on a lower level. (Gassner Retec, 2008)

Figure 28 Alternative 1 in Process Step 3, modified from Elo and Sundin (2009)

Step 4. For the separation of coloured and non-coloured plastics a colour sensor and a reflector are used (Figure 29). The sensor uses the optical properties of the coloured and non-coloured plastic to be able to separate them. (SICK, 2009) In this process step, the incoming plastics are aligned
and then investigated by a colour sensor. The sensor signals the next stage in the process, the pneumatic system, depending on if the object is to be sorted to another conveyor or not. The pneumatic system is the same as used to sort the different plastics in Process Step 2, as illustrated in Figure 27 above.

Figure 29 Alternative 1 in Process Step 4, modified from Elo and Sundin (2009)

Step 5. To be able to separate PET, PP, LDPE, HDPE, PS, PVC and other plastics the machine Criterion plus™ is used (Figure 30). The machine uses near infra-red sensors to separate the different plastics. (Binder-co, 2012, Sherman, 2000)

Figure 30 Sorting process of plastics using Criterion plus™ (Elo and Sundin, 2009, p.939)
RESEARCH RESULTS

FLUORESCENT MARKERS
The sorting and separation steps in Figure 25 above are realized using one ultraviolet sensor, together with a set of fluorescent markers added in the plastics and the same technology used in the first step of the concept. In today’s technology, a magnetic roll is used together with a conveyor belt (Figure 26). The magnetic roll and the conveyor separate metal objects from the flow of material. The sorting and separation of step 2 through 5 is made using the sensor and the fluorescent markers added in the plastic. This process step is illustrated in Figure 31 below.

![Diagram of fluorescent markers process](image)

Figure 31 Alternative 2 in Process Steps 2 to 5. Modified from Elo and Sundin (2009)

4.1.3 SUMMARY OF AUTOMATIC RECYCLING OF PLASTICS
Both the alternatives for automated plastic recycling plants work if all the requirements are fulfilled. A common requirement for both alternatives is that the incoming material should be spread onto the conveyor instead of staying in pressed plastic bundles. Alternative two, fluorescent marking, also requires that all incoming material is marked in a predefined way, and that the marking can be interpreted independent of the orientation of the material on the conveyor.

The common requirements to spread material onto a conveyor are possible to solve even today. There are several different types of equipment that solve this problem, one of these types is already owned by IL Recycling and used daily. Florescent marking requires that all incoming plastic to industry and households should be marked. This means that all producers that deliver plastic products to Sweden have to mark their plastic. To be able to do this, there must be a global standard plastic marking.
The theoretical section treats sorting of pure plastic. The effect of how the sorting will be affected by mixed plastics is not known, and needs to be investigated further. The results are conceptual in nature, and thus not verified by implementation in industry.

4.2 REQUIREMENTS FOR AUTOMATED LARGE LIQUID CRYSTAL DISPLAY RECYCLING

The text presented in this section is generated from the paper written by Elo and Sundin (2010) with the title Requirements and Needs of Automatic Material Recycling of Flat Panel Displays (Paper II).

This section is linked to RQ 2, presented in Section 1.5, Research Questions, and aims to address this question. The objective is also to show the different requirements to develop an automated recycling plant for the recycling of large liquid crystal displays.

4.2.1 REQUIREMENTS

SWEDISH REGULATIONS

Some liquid crystal display (LCD) monitors contain cold cathode florescent lamps (CCFLs) which contain mercury, and because of this the plants need to fulfill all Swedish regulations, environmental laws and work environmental laws. The Swedish work environmental authority requires that the limit value of airborne mercury cannot be higher than 0.01mg/m$^3$ during eight hours in the work environment. Airborne mercury comes in the form of dust, gas, fog, smoke or steam. (Swedish Work Environment Authority, 2005)

The Swedish chemical agency requires that storage and safe-keeping of mercury or material contaminated by mercury shall be carried out in a closed and locked space which is unreachable for children and none authorized persons. The mercury, material contaminated by mercury and its container shall be treated as hazarded material and shall not be released into the environment. (Swedish Chemical Agency, 2010)

INCOMING MATERIAL

The general waste flow of WEEE in Sweden is through two separate waste flows, the first controlled by El-kretsen and the second by the recycling companies themselves. The waste flow controlled by El-kretsen is distributed to the recycling companies and delivered in cages, as illustrated in Figure 32 below. The plants need to handle all incoming materials. In order to automate
the plant some requirements are needed on the incoming material, and to be able 
to fulfil these requirements the incoming material needs to be identified and 
sorted. The identifications that need to be carried out are as follows. The 
incoming displays need to be identified due to the possibility that the incoming 
material will include material that is not some type of display. An additional 
identification is the identification of the different types of displays (LCDs, 
plasma display panel, organic light emitting diodes etc.), due to the different 
structural designs and the components which require different recycling 
approaches. If a LCD monitor or LCD television is present in the sorting stage it 
also needs to be identified for the same reason as the previous identification. 
Depending on if the display contains a CCFL or a light emitting diode (LED) 
back light unit, the display can be treated in different ways; this is why displays 
need to be identified depending on if they contain CCFL or LED back light 
units. A damaged LCD monitor or television with a broken CCFL also needs to 
be identified. If a damaged monitor or television is undetected and separated 
there is a risk of contaminating the processed materials. The separation of the 
incoming materials needs to be done according to the same structure as the 
identification of the incoming materials. The separation stages are: displays and 
other incoming material; the different display types; separation of LCD 
monitors and LCD televisions; and separation of the displays, which are thought 
to contain broken CCFLs or mercury-contaminated material.

Figure 32 WEEE cages (Elo and Sundin, 2010, p.6)
MATERIAL AND COMPONENTS OF INTEREST TO PRODUCE
The available materials in a LCD monitor and of interest for recycling are: metal (42.8wt%), plastic (24wt%), cables (0.4wt%), glass (25.5wt%), printed circuit boards (6.9wt%), pollutants (0.3wt%) and other materials (0.4wt%). (Swico Recycling, 2009)

The materials and components which are to be processed in a waste recycling facility include: plastics like polymethyl methacrylate (Peeters et al., 2011a, Li et al., 2009), common as a light guide; acrylonitrile butadiene styrene (Granta CES, 2010), common in the external plastic hood; metals like copper, which are found in the printed circuit boards and cables; and aluminium or sheet metal, found in back plates and frames. Printed circuit boards can be divided into two fractions, one with high-valued printed circuit boards and one in with low-valued printed circuit boards. If there is no interest, e.g. no economic benefit, in recycling the LCD panel as a component, then it is possible to recycle the glass material in the LCD panel. If there is interest, then there are several materials or components that can be recycled. The recyclable materials are indium and polyvinyl alcohol, while the components are liquid crystals and polarization film. (Hunt et al., 2009, Shin-Lian et al., 2008, Park et al., 2009) These materials and components need to be identified, sorted and separated.

RECYCLING PROCESS
The automated recycling plant needs to handle the incoming material and identify, sort, separate and handle the resulting products. It may be economically difficult to motivate the automation of all production processes, and therefore manual operations should be considered. For example, the identification and separation of some uncommon displays may be done manually in order to achieve high flexibility and accuracy. Other production processes that are needed besides the identification and separation are disassembly or dismantling, material transport, material storage and storage of mercury and mercury-contaminated material.

4.2.2 SUMMARY OF REQUIREMENTS
The requirements to create an automated recycling plant with focus on liquid crystal displays are:

- The plant or process shall fulfil all rules and regulations stated by the Swedish government and it is agencies.
- The plan or process shall be able to handle all the incoming material, e.g.: different types of displays (LCDs, PDPs, OLEDs and other types) and other electronic waste.
The plant shall be able to identify the incoming material e.g. type of display (LCDs, PDPs, OLEDs and other types), monitors and televisions. The plant or process shall also be able to identify what type of backlight unit the monitor or television contains and if it is damaged.

- Sort and separate the incoming materials.
- Disassemble or dismantle the incoming materials.
- Sort and separate the components and materials of interest, e.g.: plastics, metals, high and low-value printed circuit boards and LCD panels.

### 4.3 Conceptual Process Development

The text presented in this section is generated from the paper written by Elo and Sundin (2011) with the title *Conceptual Process Development of Automatic Disassembly of Flat Panel Displays for Material Recycling (Paper III)*.

This section is linked to Section 1.4, *Research question*, with the aim to answer RQ4. The aim is also to explore different technical concepts of an automated recycling plant which copes with the requirements and needs mentioned. The result presented in the previous section, i.e. a list of requirements needed by an automated recycling plant, is the foundation for the results in this section.

#### 4.3.1 Concept Development

**Recycling Process Stages**

In the beginning of the concept development phase, the recycling system is divided into three stages: the pre-process stage, the main process stage and the post-process stage. The pre-process stage entails taking care of incoming products, and includes preparing, controlling and sorting. Preparing the products includes e.g. removal of cables and stands from LCD monitors. Controlling the products includes investigating the products and identifying if the products are of the specific type desired. After controlling the products, they are sorted according to product type. The unwanted products are separated from the material flow and do not continue to the main process stage. The main process includes dismantling of the products and removal of the CCFLs in the products. The post-process stage includes separation and sorting of the materials in the products which have been opened. The separation includes removing the different materials of interest from the rest of the product, and then sorting the materials into containers dedicated to the specific material. Figure 33 visualises the overall view of the process chain of the automated recycling process.
To get the chain of the pre-process, main process and post-process to work together, all the processes need to be fulfilled. To develop one of the processes, inputs or outputs are needed from the other processes. This means that to develop one of the processes, the others need to be developed first. The research group decided to develop one of the processes without having a clear picture of the other processes and the decision came to develop the main process first. This is because the development of the main process influences both the pre-process stage and the post-process stage, and the main process stage contained the largest challenge for the research group.

**INVESTIGATION OF DISASSEMBLY PROCESS CONCEPTS**

Since the main processes were selected to be the key process in the research project, the work started with investigating different types of technologies for opening and removing the CCFLs in LCD monitors.

The exploration of different technologies for the main process came to a list of several technologies suitable for the purpose. The list of the technologies is presented below.

- **Manual** – this was the reference concept which is in use in many recycling companies today.
- **Band saw** – saw machine with a band blade which mechanically removes material from LCD monitors. The monitors are handled with an industrial robot.
- **Circular saw** – saw machine equipped with a circular saw that removes material from LCD monitors the same way as a band saw. The monitors are handled with an industrial robot.
- **Double circular saw** – similar to the circular saw concept the different being that this equipment uses two saw blades mounted beside each one another and rotating in opposite directions. The monitors are handled with an industrial robot.
- **Circular saw fixture** – a circular saw is used together with a fixture to fixate the LCD monitors before the cuts.

---

**Figure 33 Recycling process stages (Elo and Sundin, 2011, p.199)**

To get the chain of the pre-process, main process and post-process to work together, all the processes need to be fulfilled. To develop one of the processes, inputs or outputs are needed from the other processes. This means that to develop one of the processes, the others need to be developed first. The research group decided to develop one of the processes without having a clear picture of the other processes and the decision came to develop the main process first. This is because the development of the main process influences both the pre-process stage and the post-process stage, and the main process stage contained the largest challenge for the research group.

**INVESTIGATION OF DISASSEMBLY PROCESS CONCEPTS**

Since the main processes were selected to be the key process in the research project, the work started with investigating different types of technologies for opening and removing the CCFLs in LCD monitors.

The exploration of different technologies for the main process came to a list of several technologies suitable for the purpose. The list of the technologies is presented below.

- **Manual** – this was the reference concept which is in use in many recycling companies today.
- **Band saw** – saw machine with a band blade which mechanically removes material from LCD monitors. The monitors are handled with an industrial robot.
- **Circular saw** – saw machine equipped with a circular saw that removes material from LCD monitors the same way as a band saw. The monitors are handled with an industrial robot.
- **Double circular saw** – similar to the circular saw concept the different being that this equipment uses two saw blades mounted beside each one another and rotating in opposite directions. The monitors are handled with an industrial robot.
- **Circular saw fixture** – a circular saw is used together with a fixture to fixate the LCD monitors before the cuts.

---
RESEARCH RESULTS

- **Water jet** – a mixture of high-pressure water and abrasive (fine sand) erosion removes material from LCD monitors. The water transports and removes the materials, while the abrasive speeds up the removal of materials. The monitors are handled with an industrial robot.

- **Laser** – a laser beam evaporates the material that the laser beam focuses on. The vapours are removed with a ventilation system. The monitors are handled with an industrial robot.

REQUIREMENTS

To be able to prioritise the different technologies mentioned in the previous section, the different requirements for the processes were identified and weighted. The weighting is visualised in Table 9 below, with the following requirements:

- **Capacity** – the production capacity in terms of monitors per hour.
- **Ease of use** – the education level needed to run the equipment.
- **Durability** – the ability of the equipment to fit with existing or new equipment.
- **Product flexibility** – the ability of the equipment to process a variety of products.
- **Investment cost** – the amount of investment into the process equipment.
- **Working environment** – the environment for the worker using the equipment or in the area surrounding of the equipment.
- **Operational cost** – the cost to run the equipment during a year.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>31%</td>
</tr>
<tr>
<td>Durability</td>
<td>15%</td>
</tr>
<tr>
<td>Investment cost</td>
<td>13%</td>
</tr>
<tr>
<td>Operational cost</td>
<td>12%</td>
</tr>
<tr>
<td>Working environment</td>
<td>11%</td>
</tr>
<tr>
<td>Product flexibility</td>
<td>10%</td>
</tr>
<tr>
<td>Ease of use</td>
<td>6%</td>
</tr>
</tbody>
</table>

Table 9 Requirements with weighting (Elo and Sundin, 2011, p.201)

The weighting of the list was done by the participants in the research project AutoDisA, and within the framework of a bachelor’s thesis by Sundberg (2010) at Linköping University.
4.3.2 Concept Evaluation

The concepts and the requirements presented in the previous section were used in an evaluation table called concept scoring, which is described in Section 2.4. The exception, and omitted from the matrix, is laser technology. The reason for this is that the investment cost of the technology does not motivate further investigation of the technology. The results from the concept scoring method are illustrated in Table 10 below.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Manual (ref.)</th>
<th>Band saw</th>
<th>Circular saw</th>
<th>Double circular saw</th>
<th>Circular saw fixture</th>
<th>Water jet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weighting</td>
<td>Rating</td>
<td>Score</td>
<td>Rating</td>
<td>Score</td>
<td>Rating</td>
</tr>
<tr>
<td>Capacity</td>
<td>31%</td>
<td>3</td>
<td>0.93</td>
<td>5</td>
<td>1.55</td>
<td>5</td>
</tr>
<tr>
<td>Durability</td>
<td>15%</td>
<td>3</td>
<td>0.45</td>
<td>3</td>
<td>0.45</td>
<td>3</td>
</tr>
<tr>
<td>Investment cost</td>
<td>13%</td>
<td>3</td>
<td>0.39</td>
<td>2</td>
<td>0.26</td>
<td>2</td>
</tr>
<tr>
<td>Operational cost</td>
<td>12%</td>
<td>3</td>
<td>0.36</td>
<td>2</td>
<td>0.24</td>
<td>2</td>
</tr>
<tr>
<td>Working environment</td>
<td>11%</td>
<td>3</td>
<td>0.33</td>
<td>3</td>
<td>0.33</td>
<td>3</td>
</tr>
<tr>
<td>Product flexibility</td>
<td>10%</td>
<td>3</td>
<td>0.30</td>
<td>4</td>
<td>0.40</td>
<td>4</td>
</tr>
<tr>
<td>Ease of use</td>
<td>6%</td>
<td>3</td>
<td>0.18</td>
<td>2</td>
<td>0.12</td>
<td>2</td>
</tr>
<tr>
<td>Total score</td>
<td>2.94</td>
<td>3.35</td>
<td>3.35</td>
<td>3.29</td>
<td>2.94</td>
<td>1.77</td>
</tr>
<tr>
<td>Rank</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Continue?</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

The two conceptual processes for automatic disassembly of flat panel displays with the highest scoring are the band saw and the circular saw. These two “winning” concepts both use the same type of mechanical cutting, but with different cutting tools. Therefore, only one of the sawing processes needs to be investigated in practice with more tests in the future research. However, the selected sawing method is the circular saw due to a higher number of different types of cutting tools available on the market. The other concepts which have been investigated in this paper are the double circular saw, the circular saw fixture, the laser and the water jet. Future work will be to test the winning.
RESEARCH RESULTS

concept in practice to see if the concept is plausible on an industrial scale and economically defendable.

4.3.3 SUMMARY OF CONCEPTUAL PROCESS DEVELOPMENT
The LCD monitor dismantling process to develop is initially divided into three sub-processes, namely pre-process, main process and post-process. The main process was decided to be the key process, and for that reason developed first. The technologies selected for investigation of if they were suitable for the main process were several. The technologies were evaluated with the support of the process requirements defined in Paper II, presented in the previous section. The evaluation was made according to the concept scoring method. The most suitable technologies according to the scoring method were the band saw and circular saw technologies. The remaining technologies were omitted.

4.4 EEE RECYCLING SYSTEMS
A recycling system for recycling flat panel displays shall fulfil all of the requirements presented in Section 4.2, Requirements for Automated Large Liquid Crystal Display Recycling. A hybrid automated recycling system using the process presented in Section 4.3, Conceptual Process Development, will fulfil the technical requirement. However, a hybrid system will have problems fulfilling the work environmental requirements since the operator will share the environment with the process equipment, both in time and space. This environment will contain the hazardous materials mercury and liquid crystal. The operator could use protection equipment such as protective glasses, respiratory protection equipment, and a protective suit. This would not be a step forward from the work environment perspective. However, the capacity will probably increase, which is a positive contribution to industry. If a semi-automated system is implemented instead, then the operator is able to be geographically separate from the process and the work environment will fulfil the requirements. The semi-automatic process fulfils requirements in the same way as a hybrid system, but without the drawback of the work environment. This process will also have a better production capacity compared with a manual recycling process.
5 DISCUSSION AND CONCLUSIONS

This chapter is dedicated to discussions and conclusions based on the previous chapters in the thesis. The chapter begins with the presentation of the industrial and academic contribution of the research, along with a discussion. The chapter continues with the research’s relationship to other research projects and the linkage to the recycling industry. Next is the conclusion, which contains answers to all four RQs posed in Chapter 1, before the chapter ends with suggestions for future research.

5.1 DISCUSSION

5.1.1 SELECTION OF RQs

The four RQs can be divided into two areas: one related to research involving recycling of plastics, and one related to research concerning recycling of large LCD monitors. Both areas are divided into two types of RQs (see Table 11); the first type is to help get an understanding of the problems in the area of research, while the other is to gather knowledge and develop solutions to the problems found in the previous type of question.

<table>
<thead>
<tr>
<th></th>
<th>Problem-oriented</th>
<th>Solution-oriented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycling of plastics</td>
<td>RQ 1</td>
<td>RQ 3</td>
</tr>
<tr>
<td>Recycling of large liquid crystal displays</td>
<td>RQ 2</td>
<td>RQ 4</td>
</tr>
</tbody>
</table>

Dividing the RQs into two types has contributed to first obtaining knowledge and discovering problems in the research areas, and second being able to find new knowledge and develop solutions to the problems discovered. If the research only had been focused on developing solutions and discovering new knowledge from the start, the risk would had been greater for looking problems of the past from industry and the academic points of view. (Potts, 1993) The drawback with the approach of first investing the problems and then developing solutions is that the research is influenced by the problem holders, i.e. the recycling industry. This means that the objectivity of the research can be questioned. As long as the involved researchers have an awareness of the questionable objectivity, the more likely the researchers are to manage the
DISCUSSION AND CONCLUSIONS

objectivity. Research closely linked to industry is more likely to contribute to society in a shorter time span than other research. This is because of the possibility of overhearing of the information between industry and academia. (Potts, 1993)

5.1.2 SELECTION OF METHODS

The research methods used in the research presented in this thesis (see Chapter 2) are industry-as-laboratory, action research and experimental research. Initially, when the research problem was the focus, as in RQ 1 and RQ 2, the research methods industry-as-laboratory and action research were utilized. When the research matured and became more focused on solving problems, as in RQ 3 and RQ 4, the methods utilized shifted, mainly from using industry-as-laboratory to being complemented with the use of action research and experimental research.

There are some disadvantages with using the methods industry-as-laboratory, action research and experimental research. For example, industry-as-laboratory states how research shall be executed, but does not offer techniques for how to gather information or any guidelines (Potts, 1993). The lack of techniques has been compensated for with the use of techniques taken from action research, experimental research and the concept development methods. Examples of techniques are literature reviews, focus groups (Oosthuizen, 2002) and one-group pre-tests (Tanner, 2002a). Another example of a drawback is related to the method experimental research, which is focused on hypothesis testing using experiments. This requires the researcher have an understanding of the problem and have general principles to test. (Tanner, 2002a) Since the problems were initially unclear, the method was only useful in the later stages of the research. Another example is the techniques related to the action research method, were in many cases the techniques were not useful due to the research method being related to the research field of social science (Oosthuizen, 2002). Some techniques where however utilized in the research.

The usage of concept development methods in the research was done when different types of technologies and processes were evaluated and selected. Worth considering when using these types of methods is the impact on the results of: the selection of the reference alternative, the selected requirement together with the weighting, and the person or persons who performs the weighting and prioritizing. The methods are, however, a structured, effective and concrete way of evaluate product, system or process alternatives compared to a reference alternative.
All the research methods presented in Chapter 2 have been used; however, none of the methods have been used entirely, i.e. none of the methods have been followed completely. The reason for this is that none of the methods completely fit with the research performed. During future research, the selection of the research method should be reconsidered and be discussed with senior researcher to be able to find a fitting research method.

5.1.3 RECYCLING OF PLASTICS

The results in the paper *Automation in the Recycling Industry – A Case Study* were entirely theoretical, and no tests in a laboratory environment or industrial environment were done. The results, two non-validated processes, require some kind of validation before any conclusion can be made to put the systems into an industrial application. In particular, the compatibility between the different processes in the proposed systems must be verified. Another factor which needs to be further investigated in the system is the setup of the sorting steps. There are five sorting steps in the systems presented in Figure 25 for separation of plastic into a total 15 different fractions. It is ambitious to separate all 15 fractions and industry might only need to focus on some of the fractions; for example, it might only focus on separation of rigid non-coloured plastic into the different plastic types PET, PP, LDPE, HDPE, PS, PVC and other plastics due to the DIN 6120 standard (REPA, 2011). The other fractions to sort might be non-rigid plastics and coloured rigid plastics. In other words, do not separate coloured rigid plastics into the fractions PET, PP, LDPE, HDPE, PS, PVC and other plastics.

As mentioned in Section 4.1 the second recycling alternative, the system using fluorescent marking, requires that all plastic to recycle is marked according to a standard (Ahmad, 2000). Introducing such a marking standard will require that all plastic producers and recycling companies need to agree to use this marking standard. A possibility is to use and complement the existing labelling. Another alternative is that the Swedish government, European Union or some environmental organisation engage in implementing a marking standard. However, the recyclers can still use other recycling technologies to recycle plastic, and do not need to use the fluorescent markers for recycling plastics. Thus, if it is possible to separate and sort plastics for recycling without using fluorescent markers, why use the markers? There is an extra investment for the society to invest in a marking system when other technologies can do the same thing without fluorescent markings. The positive side of using fluorescent markings in plastics for identification is the possibility to make faster and more accurate measurements during the sorting process (Ahmad, 2000). The plastics
can also be sorted into finer fractions within the same plastic type, i.e. plastics of the same type but with different purity can be sorted and separated (Ahmad, 2000). However, additional additive to be able to perform identification via fluorescent markings will degrade the plastic quality (Gupta, 2011). To summarize the drawbacks of implementation of fluorescent markings the following list is presented:

- A new labelling standard is required
- The plastic material requires an additive to be identified
- The labelling needs to be implemented on all household and industrial plastics
- The recyclers need to be able to secure a satisfactory quantity of plastic to be able to invest in a plant applying the technology with fluorescent marking.

At this time, the alternative with fluorescent markers is probably a greater cost then an ecological and economic win when implementing florescent marking, due to the drawbacks and the competition of the state-of-the-art technologies available.

5.1.4 Recycling of Large Liquid Crystal Displays

The results presented in Section 4.3 and in Paper III, which is presented in the appendix, say that the circular saw and band saw processes are suitable for the dismantling of LCD monitors. The processes presented are not newly developed processes; they have been present in the manufacturing industry since the late 19th century (Richter et al., 2009, Woodbury, 1960). However, the application of these processes in the recycling industry has not occurred before in any greater scale. The reasons for the possibility to use the processes are the development of the tool’s user in the processes and the change of requirements, and the approach in the recycling industry.

In the investigation of the requirements for the recycling process for LCD monitors, industry representatives and the other partners in the recycling projects were included in an exploratory survey (Tanner, 2002b). The result is presented in Table 9, while the number of responses, in total seven persons, is presented in Table 12 below. This number of responses is not enough for statistic validity, and the result to be seen more as a guideline. Since seven persons have been asked to weight the requirements in the survey, the answer were different depending on person due to the different backgrounds, knowledge and experience. However, the results were validated through discussions with all participants in the research group and the results have been
accepted to be used as guidelines in the research projects. The requirements are suited as a translation of some issues presented in Section 3.4.5 and 3.6.1, which indicates that the requirements are relevant for the research.

Table 12 Survey participants (Elo and Sundin, 2011, p.201)

<table>
<thead>
<tr>
<th>Type of organization</th>
<th>Number of people responding to the survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>System integrator</td>
<td>1</td>
</tr>
<tr>
<td>Recycling company</td>
<td>1</td>
</tr>
<tr>
<td>Research institute</td>
<td>2</td>
</tr>
<tr>
<td>University</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
</tr>
</tbody>
</table>

Since the technical tests of dismantling processes were made in a small-scale laboratory environment at a university, the equipment at the test site was not optimal. The purpose of the tests was to give the researchers an understanding of the problem and, by studying the worst-case scenarios, get an understanding for the possibilities for the different technologies. This is in line with the research methodology experimental research (Christensen, 1993). The equipment used in the tests was considered to be sufficient to be used in the laboratory tests due to the purpose of the tests. What the test did not show were the long-term effects of using the different technologies, and these kinds of tests are required to secure the suitability of the technologies to fulfil the requirements for an LCD monitor recycling process. The research done only shows that this is one way of creating a recycling process for EEE recycling, and does not show the absolute best and only solution. The number of selected and tested technologies was in total seven in the beginning, and later was reduced to six technologies. It is not possible to claim that these six technologies are the ones that fulfil the requirements. There is a possibility that there are other technologies, not investigated in this research, which fulfil the requirements which have been the starting point for the technology investigation. To be able to find other technologies, further investigation is required with another composition of industrial representatives and persons from academia to ensure that the problems and technologies are put into another perspective. Since the research methodologies used, i.e. industry-as-laboratory and action research, are both cyclic, this makes it easy to update and include new technologies. This does also include the concept development methods.

The suitability of a semi-automatic recycling process needs to be validated before any future work can be done. One validation which will contribute to determining the suitability is to perform a simulation showing the expected size.
DISCUSSION AND CONCLUSIONS

of the system and how the system can be scaled up or down in capacity. This is important as the capacity is the highest rated requirement. The use of semi-automatic recycling processes for the recycling of LCD monitors is in its initial stages, and is not exploited in industry with the exception of some pilot plants, but the idea of a semi-automatic process is supported by researchers in academia (Kopacek and Kopacek, 1999, Ryan et al., 2010, Scholz-Reiter et al., 1999, Kim et al., 2009).

The dismantling of LCD monitors requires information which needs to be collected. Information in the exterior features such as shape, size, position and orientation can be mined in several ways, e.g. via vision systems and different sensors. However, the information about the material content and the structural design of the monitors is challenging to collect, and is one of the important issues in the recycling industry according to Penev (1996), Santochi et al. (2002), Lambert and Gupta (2005).

The generated conceptual process for dismantling LCD monitors is done for one key purpose, removal of cold cathode fluorescent lamps, before further processing for recycling. However, is not the recycling problem with LCD monitors a temporary problem, since the mercury-containing LCD monitor will be phased out with time? Yes, the problem is temporary. The LCD monitors and other LCD units using cold cathode fluorescent lamps as backlight units are expected to be replaced. The replacement is LCDs with a backlight unit containing light emitting diodes, or to be entirely replaced by organic light emitting diodes (Boeni et al., 2012). The problem is temporary but still important to manage, and for two reasons. First, to remove the mercury in the cold cathode fluorescent lamps from the material waste stream, and second, to minimize the loss of materials due to the mercury contamination of material (Sundin et al., 2012). A reminder is the example from Matharu and Wu (2009) were the amount of mercury in LCDs close to the end-of-life can be approximately 23.46 tonnes worldwide. There is expected to be a decrease in products containing CCFL in approximately four to six years (Boeni et al., 2012). Until then, the amount of mercury will increase in the waste stream.

The resulting technology of the circular saw, presented in Section 4.3, might be possible to use in a similar recycling process for another type of EEE product causing problems for the recycling industry, e.g. LCD televisions and other FPDs. Another product from the automotive industry which needs to be recycled is car batteries from hybrid cars powered by a combustion engine and electrical motors.
RELATION TO OTHER RESEARCH PROJECTS
The research presented in this thesis has investigated processes, from a technical perspective, to remove material and components from LCD monitors which contain mercury. The processes are not of the kind that utilise shredding before further processing and recycling. These types of processes are also presented by Ladanyi and Miklosi (2006) and Kopacek (2010). The research related to the research presented in this thesis complements the research presented by Ladanyi and Miklosi (2006) and Kopacek (2010) with: testing alternative technologies for LCD monitors, LCD laptop screens and LCD television dismantling; showing the possibility to create new products from rejected LCD monitors (Felix, 2011); and presenting guidelines for new environmental legislation and environmental labelling (Jönbrink, 2012). Some examples of products created from LCD monitor components which are related to this research is presented by (Felix, 2011, BOID, 2013). The products are different types of illuminating flat lamps as illustrated in Figure 34 below. Another example of material reuse from LCD monitors is the result presented by Hunt et al. (2010), where Polyvinyl-alcohol in LCD monitors is reused in medical applications (Hunt et al., 2010).

Figure 34 Lamps made of reused components from LCD monitors (BOID, 2013)
DISCUSSION AND CONCLUSIONS

One of the results presented by Kopacek (2010) shows that the usage of circular saws for dismantling a LCD module is not suitable. This is because the composition of the LCD monitors makes it difficult to use a circular saw with the correct profile fitting the materials in the monitors. The wear of the circular saw is due to the glass in the monitors reducing the lifespan of the circular saw.

The difference between the results from Kopacek (2010) and the results from the research presented in this thesis is probably due to the setup of the tests. In the case presented by Kopacek (2010), the circular saw used was one dedicated for cutting wood, and not optimized for cutting materials such as aluminium and plastics. The tests performed in the research presented in this licentiate thesis were done using a circular saw, as it is also called, a slot milling tool designed for processing metals such as aluminium and steel, and therefore more suitable than a circular saw made for processing wood. Another difference in the tests outlined is that in the case presented by Kopacek (2010), the cutting was made in LCD modules, while in the results presented in this thesis, the cutting was made in LCD monitors. The difference between these setups is that an LCD module is thinner, has materials, and no air pockets, making the fixation of the object less problematic. This makes the conditions for cutting the LCD monitor less suitable than for cutting a LCD module. Validating the statement, by Kopacek (2010), that a recycling process using a circular saw is not economically suitable compared to manual disassembly cannot be done yet. This is because the conditions have changed, new and more suitable equipment is available and there have been changes to the LCD monitor product design since the research done by Kopacek (2010).

5.1.5 RESEARCH CLOSELY LINKED TO INDUSTRY

Is a researcher influenced by industry if industrial partners are included in research projects where the researcher also is included? The answer to this question is “yes”. The drawback is that industry directly influences the research in its decisions, making the researcher’s objectivity questionable. The positive thing with using industry directly in research is that the researcher has: direct access to information from industry; a possibility to investigate real industrial problems; the possibility to change focus faster when the conditions change in industry; and the possibility to influence industry. This reasoning is supported by the research methodology industry-as-laboratory (Potts, 1993). In this thesis, the researcher has worked together with industry and has managed influences from industry. The possibility the researcher has is to influence industry with the results from the research and the knowledge discovered.
5.2 CONCLUSIONS

To conclude the previous chapters and answer the RQs formulated from the objective in this research the following RQs will be answered in this section.

RQ 1 What technical problems may occur in automatic sorting and separation for the recycling of plastics?

In the plastic recycling industry there are several problems, some related to incoming material and some related to technological solutions. The problems are stated in Section 4.1 Automatic Recycling of Plastics and in Paper I, and are listed again here:

- The problems related to the incoming material are the mixture of:
  - Non-coloured rigid plastic types.
  - Non-coloured non-rigid plastic types.
  - Coloured rigid plastic types.
  - Coloured non-rigid plastic types.
  - Other materials.

- The problems with the technical solutions are:
  - The capacity of the equipment.
  - The equipment’s ability to identify the specific plastic types and the compatibility between the different processes.
  - Finding equipment which is compatible.

RQ 2 What technical problems may occur in automatic dismantling of large liquid crystal displays?

The problems with an automated recycling process for large liquid crystal displays are stated in Section 4.2, Requirements for Automated Large Liquid Crystal Display Recycling, and in Paper II, as well as below:

- The expected increase of large liquid crystal displays in the waste stream makes it difficult to process with current recycling processes.
- Finding processes capable of removing mercury in large liquid crystal display monitors is difficult. The hazardous mercury-contaminated materials and the mercury itself needing to be removed from large liquid crystal display monitors require special treatment.
- The product design of a large liquid crystal display monitor is a problem, due to the sandwich construction along with the frames with snap-fits and screws holding the product design together, making the product hard to disassemble.
- The unpredictable changes in incoming material.
DISCUSSION AND CONCLUSIONS

- The change in the different material value is a problem for the recycling industry; this affect, together with the changes in incoming material, the conditions for investing and operating an automated recycling process.

RQ 3 What processes can be utilised in automatic sorting and separation for the recycling of plastics?

The answer to this RQ is answered in more detail in Section 4.1, Automatic Recycling of Plastics, and in Paper I, but to conclude this section the following paragraph will succinctly answer RQ 3.

In general, a flexible automated recycling system containing standardised equipment such as conveyor belts and different processes for identifying, separating and sorting will solve a lot of the problems in the plastic recycling industry. There are several types of equipment and processes already available on the market for the plastic recycler to use. By using the system components and conveyors, the recyclers can reorganize the equipment so it fits the incoming type and amount of incoming material and the products produced at the time. This approach means that the recyclers need to rearrange the equipment from time to time, which costs resources in both labour and production stops. It is also shown in this licentiate thesis that there are technologies for separating and sorting the different plastics of interest.

RQ 4 What processes are suitable to utilise in automatic dismantling of large liquid crystal displays?

Due to the specific design of large liquid crystal display monitors, an automated recycling process needs to be devoted to recycling products with the same shape and with the same design as a large liquid crystal display monitor. The two technologies found most suitable for creating an automated recycling process for large liquid crystal displays were the circular saw and the band saw. A semi-automatic process will probably create a recycling process fulfilling all requirements of a recycling process for large liquid crystal displays. The process will combine automatic equipment and manual operators to be able to receive incoming materials, to identify, separate, and sort materials, and to possibly refine the products. The process will at the same time create an environmentally friendly work environment for the operators.

Section 4.3, Conceptual Process Development, and Paper III will answer RQ 4 in more detail.
5.3 CONTRIBUTION TO ACADEMIA

The academic contributions from the research presented in this licentiate thesis are:

- A case study of what alternative process technologies are available in plastic recycling systems
- An understanding of the requirement on an automated dismantle process for large liquid crystal display monitor recycling
- Knowledge about what types of processes needed in the recycling industry for the recycling of large liquid crystal display monitors

5.4 CONTRIBUTION TO INDUSTRY

The industrial contributions from the research presented in this licentiate thesis are:

- A mapping of available technical alternatives for a plastic recycling system
- An investigation of the requirements for a large liquid crystal display recycling system
- A presentation of several technological solutions for use in large liquid crystal display recycling

5.5 FUTURE RESEARCH

The questions and areas to investigate were developed during the research resulting in this thesis. Some of these questions are:

- Are there any ecological or economic wins or costs when implementing fluorescent marking?
- When using automatic recycling processes for recycling of plastics, how does dirt-contaminated plastics and mixed plastics influence the selected processes?
- What is the mechanical wear of a circular saw when being used in an automated recycling process for LCD monitors?
- Is there a risk for pollution of mercury and or liquid crystal in a mechanical recycling process using circular saws, and if yes, how much?
- Are there other requirements for utilization of the processes for LCD monitor dismantling when it is applied on other products? If so, what are the requirements?
- How can information about the structural design and material content be extracted from large LCD by technologies suitable for being used in automatic recycling processes?
This chapter contains the references used in this thesis. The references are both physical literature publications in the form of books and articles, and electronic publications like web-pages and electronic books or articles.


REFERENCES


AUTOMATION IN THE RECYCLING INDUSTRY


GRANTA CES 2010. Edupack version 5.1.0. Granta design limited.


REFERENCES


AUTOMATION IN THE RECYCLING INDUSTRY


NILSSON, T. 2008. RE: Manager at IL Recycling AB Linköping Sweden, Personal communication.


REFERENCES


RYAN, A., O’ DONOGHUE, L. & LEWIS, H. 2010. Investigating the recyclability of Liquid crystal display TV’s. *Flexible automation and intelligent manufacturing international conference*. California, USA.


SALOMONSSÓN, L. 1995. NIR och multivariat analys som hjälpmedel för urval i fältförsök.


78
AUTOMATION IN THE RECYCLING INDUSTRY


SEEGER, M. 18th of Mars 2011. RE: Annual reports of collected WEEE in Sweden 2003 to 2007. E-mail communication, martin.seeger@el-kretsen.se.


REFERENCES


