Robotic Disassembly of Electronic Components to Support End-of-Life Recycling of Electric Vehicles

by

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CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgments or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a degree.

Jie Li (Signed)

June 2016 (Date)

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SYNOPSIS

This thesis reports on the research undertaken to analyse the factors affecting End-of-Life (EoL) recycling of future Electric Vehicles (EVs). The principle objective of the research is to generate an understanding of challenges and opportunities for the development and implementation of an automated robotic disassembly approach to aid with EoL management of electrical and electronic components within EVs.

The research contributions presented in the thesis can be considered in three main parts. The first part contains a review of advancement in the development of automotive technology, and in particular the alternative fuel vehicles. In order to understand the limitation and opportunities for future vehicle recycling, a review of existing industrial recycling technologies and processes has been conducted which highlighted a number of key challenges in the adoption of current recycling technologies for EVs. The review concludes that there is a need to develop novel flexible recycling technologies and processes to deal with the increased part complexity and material mixture in such vehicles.

In this context, the second part of the research details a framework for EoL management of EV components. This framework presents a comprehensive automated robotic disassembly approach in which three specific steps are defined, namely manual disassembly to assess and develop a comprehensive understanding of product design, initial automated disassembly to test and examine process capability, and optimisation and validation to improve speed, repeatability and overall efficiency of the robotic disassembly processes. The framework also includes the development of a multi-criteria decision-making tool that assesses the environmental, technological and economic benefits of such robotic disassembly approach.

Finally, the third part of the research outlines the case studies conducted to validate the research concepts. The results from three case study components have highlighted the applicability of the robotic automated disassembly approach in a variety of scenarios of different design complexity and recovery rate. The results also indicate that the adoption of this robotic disassembly enhances the pre-concentration of Strategically Important Materials (SIMs) and leads to minimisation of environmental impacts and increased material recovery value.

In summary, this research clearly highlights the importance of increased automation in the recycling of future complex products such as EVs. Experimentations have indicated that an average 95% of the materials and their associated recovery value could be achieved through the use of this robotic disassembly approach.

ABBREVIATIONS

AlTiN	:	Aluminium Titanium Nitride
BEVs	:	Battery Electric Vehicles
CAV	:	Compressed Air Vehicle
CBA	:	Cost-Benefit Analysis
CNG	:	Compressed Natural Gas
DC	:	Disassembly Complexity
DCRR	:	Disassembly Cost-Revenue Ratio
DEI	:	Disassembly Effort Index
DfD	:	Design for Disassembly
DfR	:	Design for Recycling
EBR	:	Environmental Benefit Rate
ECU	:	Electronic Control Unit
EEE	:	Electrical and Electronic Equipment
ELV	:	End-of-Life Vehicle
EMS	:	Engine Management System
EoL	:	End-of-Life
EPR	:	Extended Producer Responsibility
ETE	:	Environmental, Technological and Economic
EU	:	European Union
EVs	:	Electric Vehicles
FCEVs	:	Fuel Cell Electric Vehicles
FEVs	:	Fully Electric Vehicles
HEVs	:	Hybrid and Electric Vehicles
ICE	:	Internal Combustion Engine
KPI	:	Key Performance Indicator
LCA	:	Life Cycle Assessment

LCD	:	Liquid Crystal Display
LED	:	Light Emitting Diode
Ni-MH	:	Nickel–Metal Hydride
OECD	:	Organisation for Economic Co-operation and Development
PCB	:	Printed Circuit Board
PET	:	Polyethylene Terephthalate
PHEVs	:	Plug-in Hybrid Electric Vehicles
PMs	:	Precious Metals
PPP	:	Producer/Polluter Pays Principle
REEs	:	Rare Earth Elements
RFID	:	Radio Frequency Identification
RRR	:	Reusability/Recyclability/Recoverability
SIMs	:	Strategically Important Materials
TDT	:	Total Disassembly Time
UK	:	United Kingdom
WEEE	:	Waste Electronic and Electrical Equipment
XRF	:	X-Ray Fluorescence
XRT	:	X-Ray Transmission

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CHAPTER 1 INTRODUCTION

Rapid industrialisation has impacted the ecosystem and its ability to provide limitless resources to support human lifestyle. A series of problematic phenomena, such as air, water and soil pollution, acid rain, eutrophication, climate change, and resource depletion have drawn increasing attention. Increased awareness of the global environment has raised the need for "Sustainable Development" through innovation and sustainable engineering solutions. Recent engineering solutions have taken each stage of the product lifecycle into consideration. Stricter legislation has also helped to regulate industrial behaviour and provided guidelines.

Waste from End-of-Life Vehicles (ELVs) has been identified as one of the fastest growing sources of waste in Europe (Farel *et al.*, 2013). Automobiles are highly complex and innovative products. Both technological innovation and shortened life cycles are contributing to this rapid growth of ELVs. Every year in Europe, 9 million vehicles come to the end of their lives (Environment, 2014). Additionally, global car production is on the rise, with 23.2% of the world's cars produced in the EU (Huynh, 2013). It is estimated that an average lifespan of vehicles has decreased from 14 years to only 8.3 years in the worldwide (with variability among countries) (Zoboli et al., 2010; Bento et al., 2013; ACEA, 2012). Although current recycling solutions have met the requirement of the 2006 European ELV Directive targets (i.e. 85% recovery by weight in which 80% should be material recycling). This is far from the targets for 2015 (i.e. 95% recovery and 85% material recycling) in most cases. Furthermore, recent innovations in automotive design have also brought about complexity in the material composition and component configuration and these may contaminate the traditional waste stream.

The convenience of transportation has become a fundamental requirement for human society. Recent history has demonstrated that the increase in traditional vehicles with internal combustion engine (ICE) boosts the demands for fossil fuel and exacerbates impacts on the environment. In this context, Hybrid and Electric Vehicles (HEVs) have been developed to provide support for green transportation.

Although the principle of Electric Vehicles (EVs) has been understood since the end of the nineteenth century, the inability to mass produce rechargeable batteries has historically limited the take-up and use of EV (Larminie, 2012). In more recent decades, the drive to make the technology viable in a wider market has been the primary focus of development activities. Much of the motivation behind this drive for commercialisation has arisen from the environmental benefits anticipated from such vehicles.

Several types of HEVs have been developed, as summarised in Table 1.1. The main distinction between different vehicle types is primarily in the power source. This difference in turn has a direct impact on the vehicle structure and component/material characteristics. The most common type of such vehicles on the road nowadays is HEVs which is primarily a combination of traditional ICE vehicles and EVs. Figure 1.1 illustrates how an HEV works with a combination of power from ICE and electric battery. Typically, an HEV has a target operation lifetime of 15-20 years (Pistoia, 2010).

As shown in Figure 1 in Appendix A, the market share of HEVs has increased to 1% of all new registrations in the European countries; in Netherlands, HEVs account for 4.5% of the total sales. From the perspective of car models, over the last decade, the quantity of the HEV models has been significantly increased by a number of automotive manufacturers (see Figure 1.2). Therefore, it highlights a need to anticipate future impacts on sustainable development and management of these newly introduced vehicles.

Table 1.1 Summary of different HEV types (adapted from Ehsani *et al.*, 2009).

Type of HEV	**Power Source**		**Characteristics**
Hybrid electric vehicle	ICE		Hybrid electric vehicles can combine the benefits of ICE and electric motors to provide improved fuel economy; compressed air propulsion may be incorporated into hybrid systems, with battery electric propulsion
	Electric motor		
	Compressed air		
	Electric battery		
Battery Electric Vehicle	Plug-in charging		With no other energy source than the battery
	Battery		Energy mainly sourced from the battery for mobility assistance and partially sourced from the combustion engine for emergency purposes under specific circumstances.
Fuelled Electric Vehicles	Fuel cells	Hydrogen	The fundamental principle of it using fuel is much the same as the battery EV, but with a fuel cell or metal air battery replacing the rechargeable electric battery
		Natural gas	
		Proton exchange membrane	
	Metal-air battery	Zinc-air batteries	Metal-air batteries are a variant of fuel cells. They are refuelled by replacing the metal electrodes, which can be recycled. Zinc-air batteries are a particular promising battery in this class.

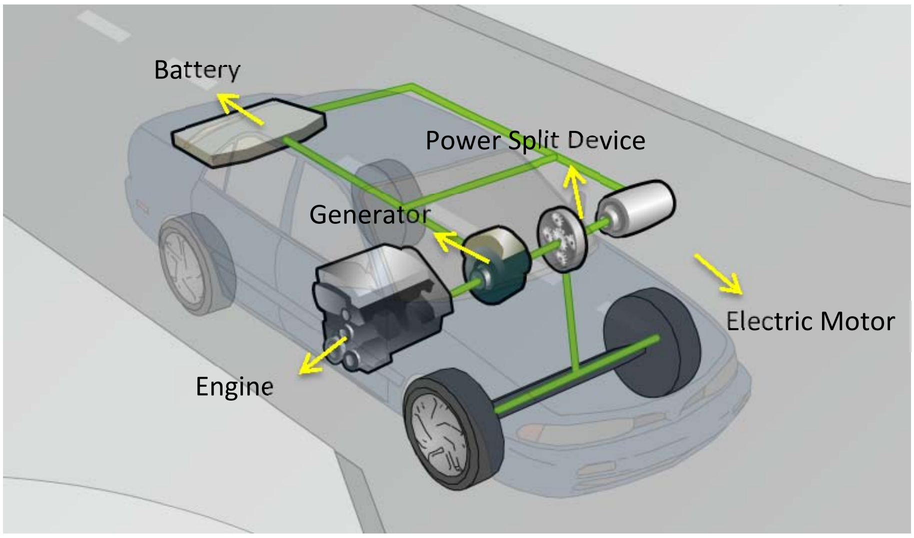


Figure 1.1 Schematic view of HEV.

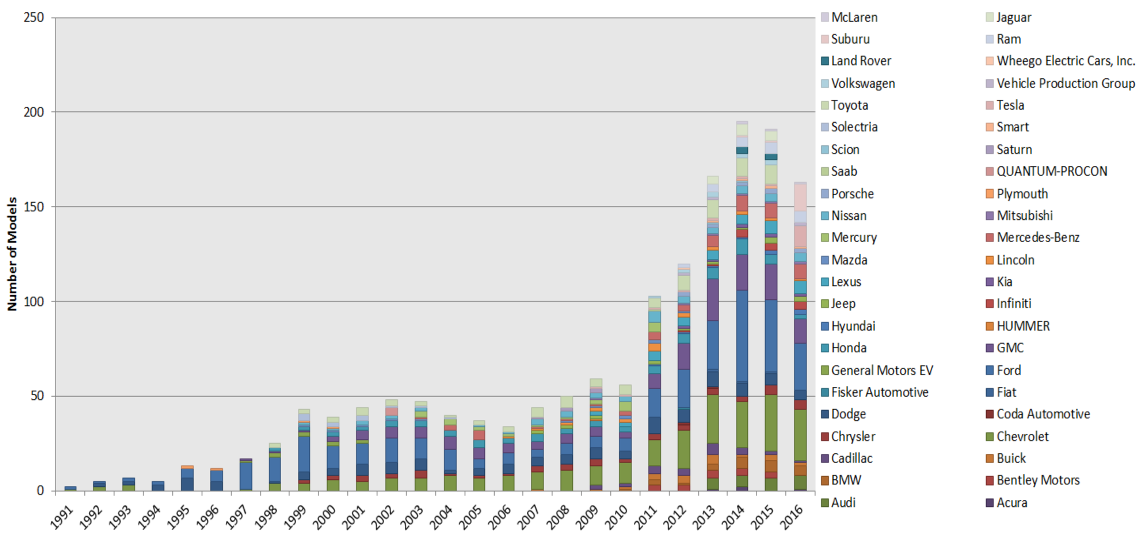


Figure 1.2 Growth of alternative fuel vehicles and HEVs models (AFDC, 2016a).

Since the first mass production of HEV was in 2001 (USDE, 2015), this indicates that around the year 2016 some HEVs will come to their end of life stage. Without any specific recycling approach, the End-of-Life (EoL) HEVs will be recycled with traditional vehicles which may result in loss of a significant amount of Strategically Important Materials (SIMs) and Precious Metals (PMs) that are represented in small quantities in such vehicles.

The European Extended Producer Responsibility (EPR) Directives have taken a proactive stance in placing responsibility for the management of EoL treatment. At EU level, four product groups have been targeted by EPR Directives on manufacturers, namely Packaging and Packaging Waste Directive 94/62/EC (European Parliament and Council, 1994), Batteries Directive 2006/66/EC (European Parliament and Council, 2006), End-of-Life Vehicle Directive 2000/53/EC (European Parliament and Council, 2000) and Waste Electrical and Electronic Equipment Directive 2012/19/EU (European Parliament and Council, 2003).

Consideration of EoL management requirements not only supports legislative compliance, and minimises environmental impacts, but also provides opportunities to control the life cycle cost and benefits. In some cases, extra costs may be introduced through the selection of costly and/or inappropriate EoL process methods. In the case of products containing valuable materials, the implementation of effective recycling processes may also result in the recovery of a proportion of original material costs, and the revenue from reclaimed materials for further use.

Nowadays, increasing attention has been paid to the waste from traditional ELVs. However, with the introduction of new vehicle types, EVs, novel recycling and recovery methods will be required due to their different material composition. The research assertion presented in this thesis is that EoL EVs introduce new challenges and opportunities which must be explored and investigated.

The research reported in this thesis, therefore, aims to investigate the next generation of vehicle recycling technologies and processes, specifically tailored for the new components and materials included within the EVs. This is to be achieved through:

1) Analysis of design of EV components in terms of their structural complexity and material content.
2) Undertaking of a number of robotic disassembly experiments to explore the feasibility of semi-automated processes.
3) Assessment of the viability of such semi-automated approaches for disassembly of various EV components.

An outline of this thesis structure is shown in Figure 1.3. The thesis can be considered in three sections, namely the research background and overview; theoretical research, experiments and case studies; and finally the research conclusions.

The research background and overview are made up of six chapters. Following the introduction, the research aim, objectives and scope are defined in Chapter 2. This definition of the research is supported by a literature review, which focuses on automobile design evolution in Chapter 3, and specific vehicle recycling technologies and processes in Chapter 4. Chapter 5 presents a review of the most relevant literature, such as the recycling approaches to electrical and electronic equipment and batteries. Chapter 6 provides a brief review of common research methodologies and outlines the methodological approach adopted within the thesis.

Figure 1.3 Thesis structure.

The second section of the thesis documents the theoretical research, experimental studies and case studies to address the research aims and objectives. In Chapter 7 a novel framework for EoL management of EVs is presented as well as the first stage of the framework, i.e. defining challenges in EoL management of EV. Chapter 8 illustrates the second stage of the framework, i.e. development of a three-step automated disassembly. The third stage of the framework is discussed in Chapter 9 that involves the development of a multi-criteria assessment of EV components disassembly processes. In Chapter 10 the applicability of the framework is demonstrated through a number of case study components.

The final section of the thesis presents the conclusions drawn from the research. Chapter 11 presents a discussion of the research findings and assesses the outcomes of the research against the stated objectives. This discussion is summarised in a number of final conclusions outlined in Chapter 12, in which opportunities for further development of the research are also presented. Additional data and detailed calculations to support the case studies are included in the appendices, along with two published conference papers and one journal paper, based on different aspects of the research reported within the thesis.

CHAPTER 2 RESEARCH AIM, OBJECTIVES AND SCOPE

2.1 Introduction

This chapter identifies the context of the research as well as the underlying research assertion. Several objectives are developed in support of the research aim, and for each of the objectives, the scope of the research is also described.

2.2 Research context and assertion

Economic development has come at the cost of severe impacts on the natural ecosystem. In order to achieve sustainable development in the manufacturing industry, one of the critical challenges is the shortage of raw materials and lack of ability to effectively recycle various products. Currently, driven by economic incentives, new recycling technologies are being developed for scarce materials.

The perceived environmental benefits of HEVs in comparison with conventional ICE vehicles have resulted in increasing growth in the market. As such, EV technologies and environmental performance have been the subject of academic interest. Various studies have endeavoured to investigate 1) the standards, policy, market, supply chain and manufacturing; 2) system architecture and battery charging; 3) energy storage technology and energy production; 4) power grid opportunities and infrastructure support, and 5) environmental impact arising during the use phase. The study by Boon *et al.* in 2003 demonstrated the impact of HEVs on environmental impact through vehicle recycling and recovery. Bandivadekar *et al.* (2004) studied the automotive life-cycle chain and analysed the impact of changing composition of vehicles. These results implied that the recycling of HEVs or other alternative fuel vehicles needs to be improved with new technologies and processes to maintain the economic viability of the existing recycling practices. Edwards *et al.* (2006) and Ferrão *et al.* (2006) both discussed the economics of recycling in view of the ELV Directive of the European Union (EU). Granovskii *et al.* (2006) focused on an economic and environmental comparison of various types of vehicles: conventional ICE vehicle, hybrid, and electric as well as hydrogen fuel cell vehicles. They reported that the added removal costs needed to be absorbed by improved material recovery. The Massachusetts Institute of Technology assessed the impact of the introduction of new automobile technologies on environmental performance (Weiss *et al.*, 2010). This research was based on life cycle analysis of the total system, including assessment of fuel, vehicle manufacture and distribution in addition to assessment of vehicle performance on the road. However, this study focused on the potential of new vehicles and fuel technologies to significantly reduce the emission of greenhouse gases which are widely believed to contribute to global warming. Kibira and Jain (2011) evaluated the impact of the increasing numbers of HEVs on the profitability of automotive recycling, particularly modelling the impact of large battery packs used in HEVs.

The literature review indicates the importance attached by several researchers to the issue of the economic viability of the automotive recycling activities of HEVs. Therefore increased attention to EVs and the absence of prior knowledge regarding EoL management of EV components provides the context, and supports, a base for the research reported in this thesis.

The material composition for EVs has changed dramatically compared to more traditional ICE vehicles. The current revenues in recycling ELV mainly result from the recycling of metallic materials, such as steel, aluminium and copper. EVs have a more sophisticated material mixture and components consisting of advanced materials (i.e. composite materials and complex polymers). In conventional vehicles, up to 80% of the total weight consists of metallic materials (Kibira and Jain, 2011; Burnham, 2012), which is valuable and easily recycled. The increased amount of plastic and composite materials found in newer vehicles, as well as in EVs, leads to a lighter weight and higher fuel efficiency. However, this creates problems with EoL management due to EVs having an increased material mix which has a low recycling value and is hard to separate. On the other hand, EVs contain many relatively high value materials including rare earth materials and PMs, but these exist in very low concentration within EVs, typically less than 5% of the overall weight, and are not recovered in typical recycling chains (Kibira and Jain, 2011). Therefore, the research assertion made in this thesis is that the application of current ELV recycling technologies and processes leads to the loss of valuable materials, thus highlighting a need for the development of new recovery and recycling technologies and processes.

2.3 Research questions

A review of the literature has shown a significant gap in the knowledge of recycling methods for EVs. In order to investigate this, the following questions must be considered:

1) Exactly what are the challenges and opportunities for recycling of EVs?
2) What are the existing recycling methods and tools for conventional vehicles that could

also be applied to EVs?

3) How can sustainability of EV recycling be improved using automation?

4) By what method can the economic feasibility and environmental benefits of such automated approaches for disassembly of various EV components be assessed?

2.4 Research aim and objectives

The overall aim of this research is to investigate the potential for next generation of vehicle recycling technologies and processes, specifically tailored for the new components and materials included within the EVs, using robotic semi-automated processes.

In order to achieve the research aim, the following objectives have been identified:

1. Review the evolution of the automobile industry and identify relevant EoL management requirements including those arising from legislation and published literature.
2. Explore and review the most relevant and recent research and studies in vehicle recycling, and recycling of similar electrical and electronic products.
3. Develop a framework for EoL management of EVs that supports identification, classification and evaluation of targeted materials and components contained in such vehicles.
4. Analyse the design of EV components in order to identify the optimal methods for improving their recycling and recovery.
5. Undertake a number of robotic disassembly experiments to investigate the feasibility of the semi-automated processes for EV component disassembly.
6. Assess the environmental, economic and technological feasibilities for robotic disassembly of EV components.
7. Test and validate the automated robotic approach for EV components recycling through a number of case study components.

2.5 Research scope

The scope of the research is in line with the objectives presented in Section 2.5 and is described in the following sections.

2.5.1 Review of the current status of EV technology

A review of automobile evolution will be conducted to identify the improving design concept and the current status of EV technology. Challenges and opportunities for the application of

EVs in sustainable transportation will be reviewed in order to develop an understanding of the potential scale of the EoL EVs waste stream.

2.5.2 Review of recycling technologies and processes for vehicles

In order to effectively place the research within the appropriate academic context, and to take advantage of existing knowledge, a review of reuse, recycling and disposal practices in the ELV recycling and recovery sector will be undertaken. This is to include an appraisal of literature considering present and future recovery technologies and processes. The results of this literature review will summarise the waste generation and what various recycling and recovery options are available for ELVs.

2.5.3 Review of relevant EoL management research

Studies relating to wider EoL management beyond the scope of pure vehicles but within the area of product recovery and waste management will be reviewed in order to ensure that the research considers all relevant aspects. In addition, the identification of legislative requirements will also be reviewed. Furthermore, an analysis of various studies and activities for other relevant EoL products and materials will be conducted.

2.5.4 Development of a framework for EoL management of EVs

A framework for EoL management of EVs will be developed to provide a structured approach to material and value recovery from EVs. A key challenge in the management of EoL EVs is to determine which components need to be dismantled from the vehicle to what extent those components must be disassembled; and which recycling processes should be applied; all whilst minimising the environmental impacts and increasing the economic benefits of EoL management.

2.5.5 Development of an automated robotic approach for EV components

The challenges and opportunities arising during EoL management are primarily defined by the design and material characteristics of the product. In order to classify and evaluate the characteristics of EV components, manual disassembly of components will be conducted. The level of required disassembly is identified by investigating the construction and material composition of the targeted components, and their potential recovery (hidden) value.

Consequently, an automated semi-destructive disassembly process will be investigated. The initial set of experiments aims to explore the feasibility of the automated robotic disassembly process through testing robot capabilities employing specially designed tools and modular fixturing system by varying numerous operational parameters, such as the feed speed, angle, length and depth of operations, etc. The second set of experiments will then be utilised for further validating all feasible automated robotic disassembly operations.

Finally, the validation and optimisation process will be explored to improve the efficiency and repeatability of the robotic disassembly processes, in order to improve its reliability and effectiveness. This stage concentrates on three main areas: 1) optimising the robotic set-up to reduce the overall time for re-positioning and re-fixturing components; 2) determining the optimum disassembly strategy with the most appropriate tool set-up; and 3) optimising the economic benefits of robotic disassembly through balancing the 'trade-off' between disassembly level and recovery value.

2.5.6 Assessment of environmental, technological and economic feasibility

The application of robotic disassembly for EV components needs to be evaluated regarding the environmental impact, economic performance and the technological feasibility. An assessment methodology will be used to evaluate the environmental impact of alternative EoL solutions, and model will be developed to demonstrate the various EoL scenarios in different cases. In addition, the technological feasibility evaluation will be developed to assess EV recycling alternatives. Similarly, a cost model will be proposed to allow estimation of the cost-benefit ratio for alternative EoL solutions for EV recycling.

2.5.7 Demonstration of the framework applicability through case studies

In order to assess the validity of the framework for EoL management of EVs, and the feasibility of the automated disassembly approach, the framework will be applied to three case study products. The results of the case studies, together with the observational outcomes during the experiments will be used to identify the benefits and limitations of the methods employed. Opportunities for improving the framework may be identified based on the implementation experience generated during the case studies, as well as the results obtained.

2.6 Chapter summary

In this chapter, the context of the research has been identified. Aim and objectives have been defined, and the research objectives have been used to generate the scope of research. The following three chapters address the initial research review objectives. Chapter 3 presents a review of EV technology, and Chapter 4 and Chapter 5 review the vehicle recycling sector and relevant literature with respect to EV recycling.

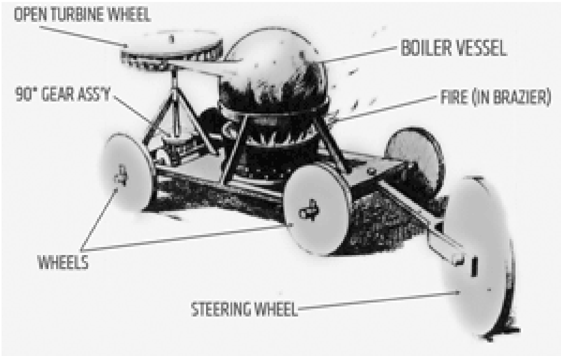
CHAPTER 3 A REVIEW OF ELECTRIC VEHICLE TECHNOLOGY

3.1 Introduction

This chapter provides an overview of the advancement in the development of automotive technology, to provide background to the research and to identify current knowledge regarding aspects of such technology most relevant to the research. The chapter begins with a review of evolution in transportation in relation to global emissions, fuel source, and related technology innovation. The chapter also provides a comprehensive overview of alternative fuel vehicles, among which EVs play significant role in future sustainable transportation.

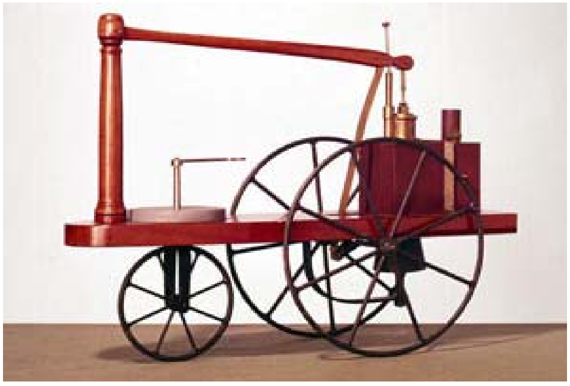
3.2 Evolution in the design of vehicles

An automobile or car refers to a wheeled motor vehicle that is used for transporting passengers or commodities. Based on the power source of the propulsion systems, the history of automotive can be broken down to different stages. As shown in Figure 3.1 (a), the history of vehicles goes back to as early as 1672 when Ferdinand Verbiest, a Jesuit missionary, mathematician and astronomer, was the first to build a steam-powered vehicle in the court of Kangxi in China. This vehicle was built on a small scale as a toy for the Chinese Emperor (Daempfle, 2013). Until the late 18th century, the first self-propelled vehicle powered by steam with sufficient space for passengers was first invented. As shown in Figure 3.1 (b), in 1769, Nicolas Joseph Cugnot created a steam engine powered automobile that was capable of transporting human passengers (Tipler, 2001). However, this machine needed to stop every 15 minutes to regenerate power, and its maximum speed was only two miles per hour. By 1784, in Great Britain, William Murdoch, a Scottish engineer and inventor developed a steam-powered vehicle (Kras, 2004). Seventeen years later (see Figure 3.1 (c)), Richard Trevithick was able to drive a full-sized vehicle on the road as shown in Figure 3.1 (d) (Wolf, 1996). Over the subsequent decades, a number of innovative technologies were developed, such as braking, transmissions and steering systems. Then in 1807, a primitive ICE was constructed and was powered by a mixture of hydrogen and oxygen, and was ignited by an electric spark, as shown in Figure 3.1 (e) (Eckemann, 2001). From 1832 to 1839, the first electric vehicle was invented by Robert Anderson that ran on a primitive non-rechargeable battery (see Figure 3.1 (f)) (Prior, 2005). In the late 19th century, George B. Selden filed a patent for the application of the engine and its use in a 4-wheeled car (Berger, 2001). Additionally, Karl Benz built the first car with gasoline ICE, and Cannstatt Daimler developed the four wheel drive concept based on the



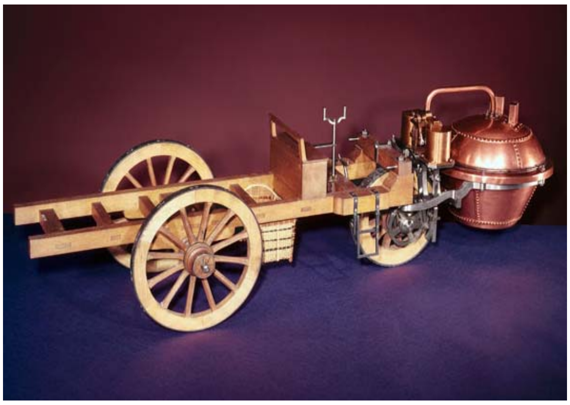
(a) 1672 – Ferdinand Verbiest

(b) 1769 – Nicolas Joseph Cugnot

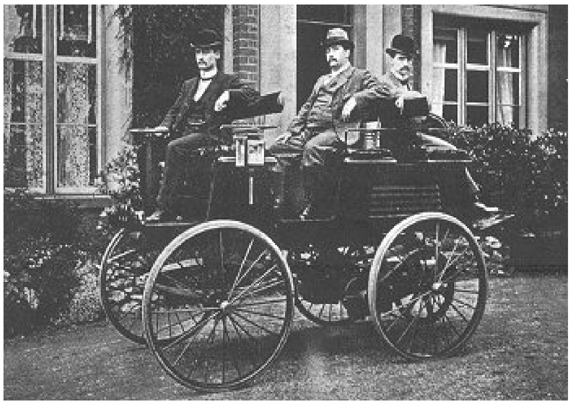


(c) 1784 – William Murdoch

(d) 1803 – Richard Trevithick



(e) 1807 – Francois Isaac de Rivaz



(f) 1839 – Robert Anderson

(g) 1885 – Karl Benz

(h) 1886 – Cannstatt Daimler

Figure 3.1 Automobiles in the 18th and 19th century.

ICE style of vehicle (Mercedes-Benz, 2010). By 1911, mass production of automobiles had begun in the United States and France, and by 1930 most of the basic automobile technology that we use today had been invented (Volti, 2006). In 1965, it was concluded and announced that harmful emissions were being produced from vehicles and safer devices regarding emissions, became mandatory (Glicksman *et al.*, 2007). Ten years later, the first antilock braking systems were developed for vehicles. Today the automotive industry manufactures a wide range of vehicles ranging from petrol and diesel engine vehicles, HEVs to EVs. Electric vehicles were first introduced in the late 19th century but were forgotten due to technical limitations of battery. However, its sustainable environmental performance brought it back to the market at the beginning of the 21st century.

3.2.1 The need for alternative power source for modern vehicles

A sustainable supply of renewable energy are becoming significantly important at present due to the depletion of non-renewable energy sources, as well as detrimental environmental impacts from generating and using non-renewable energy. In general, alternative fuel source vehicles are representatives that reduce energy consumption, dependence on fossil fuels and air pollution.

3.2.1.1 Energy saving and efficiency

Ghassemieh (2011) analysed the contribution of the energy consumption at each stage throughout the whole life cycle of typical vehicles. This work clearly highlighted that the 'use stage' of a vehicle is the most significant contributor in terms of energy consumption and overall environmental impacts. Therefore, the centre of innovation has been directed to material substitutions and development of advanced technologies, such as light-weight materials and low-emission powertrains. The results of a study by the Massachusetts Institute of Technology indicated that the environmental impact of the fuel consumption of HEVs and hydrogen gas vehicles are about 60% and 50% of the consumption of traditional ICE vehicles, respectively (Weiss *et al.*, 2010; Granovskii *et al.* 2006).

In addition, energy saving can accrue through improving the energy efficiency. The drivetrain of HEVs have a higher energy efficiency. In general, electric motors are more efficient in translating energy to rotary motion. It should be noted that since electricity is often not a primary energy source for HEVs, the production efficiency of the electricity varies in different cases. It is commonly reported that future vehicles offer an alternative energy conversion system that has several advantages over ICE vehicles (Fuhs, 2008). For example, fuel cell vehicles avoid high combustion-generated gas temperatures and, when fuelled with hydrogen, do not produce harmful gases or particulate emissions. The fuel cell itself operates at a higher efficiency than ICE vehicles. It is estimated that compared to traditional ICE vehicles, 30% of the energy can be reduced in a fuel cell vehicle with hydrogen on-board. For battery-driven electric vehicles, the life cycle energy consumption is 20% lower than ICE vehicles (Ghassemieh, 2011).

3.2.1.2 Improving energy security and fuel economy

Oil is a finite resource, and it is estimated that under current circumstances, global oil reserves could be depleted in 50 years (Khaligh, 2010). Nowadays, it is economically feasible to produce oil from coal. However the cost is around 10% more expensive, and coal is also a non-renewable resource. There is an increasing interest in designing alternative fuel vehicles that helps reduce the dependence on fossil fuels and improve environmental performance. In addition, due to the reason that the cost of electricity is relatively lower than conventional fuels; HEVs and EVs are more cost efficient than similar ICE vehicles (EERE, 2014).

3.2.1.3 Reducing pollution and mitigating global warming

Using of fossil fuels (i.e. petrol and diesel) results in increasingly detrimental environmental impacts, such as generating greenhouse gases and air pollutants to atmosphere and damaging the eco-systems (Sundar, 2013). In addition, vehicles can be powered by a number of fuel types, such as natural gas, liquefied petroleum gas, biofuel or electricity; and their emission and pollution are closely associated with the efficiency of fuel consumption. However at present, the use of all of these fuels creates various quantities of atmospheric pollution (EPA, 2005).

Pollution produced from a number of alternative fuel vehicles is expected to be much lower. For example, the electricity can be generated from chemical reactions in a fuel cell to power the electric motor. Therefore, water is the only resultant emission after the reaction in a combustion engine.

3.3 A vehicle classification based on their fuel source

As mentioned, alternative fuel vehicles provide the potential to contribute to improved energy efficiency, reduction in the dependence on fossil fuels, and mitigation of the environmental impacts, such as air pollution and global warming. The following section will review all relevant types of alternative fuel vehicles as shown in Figure 3.2.

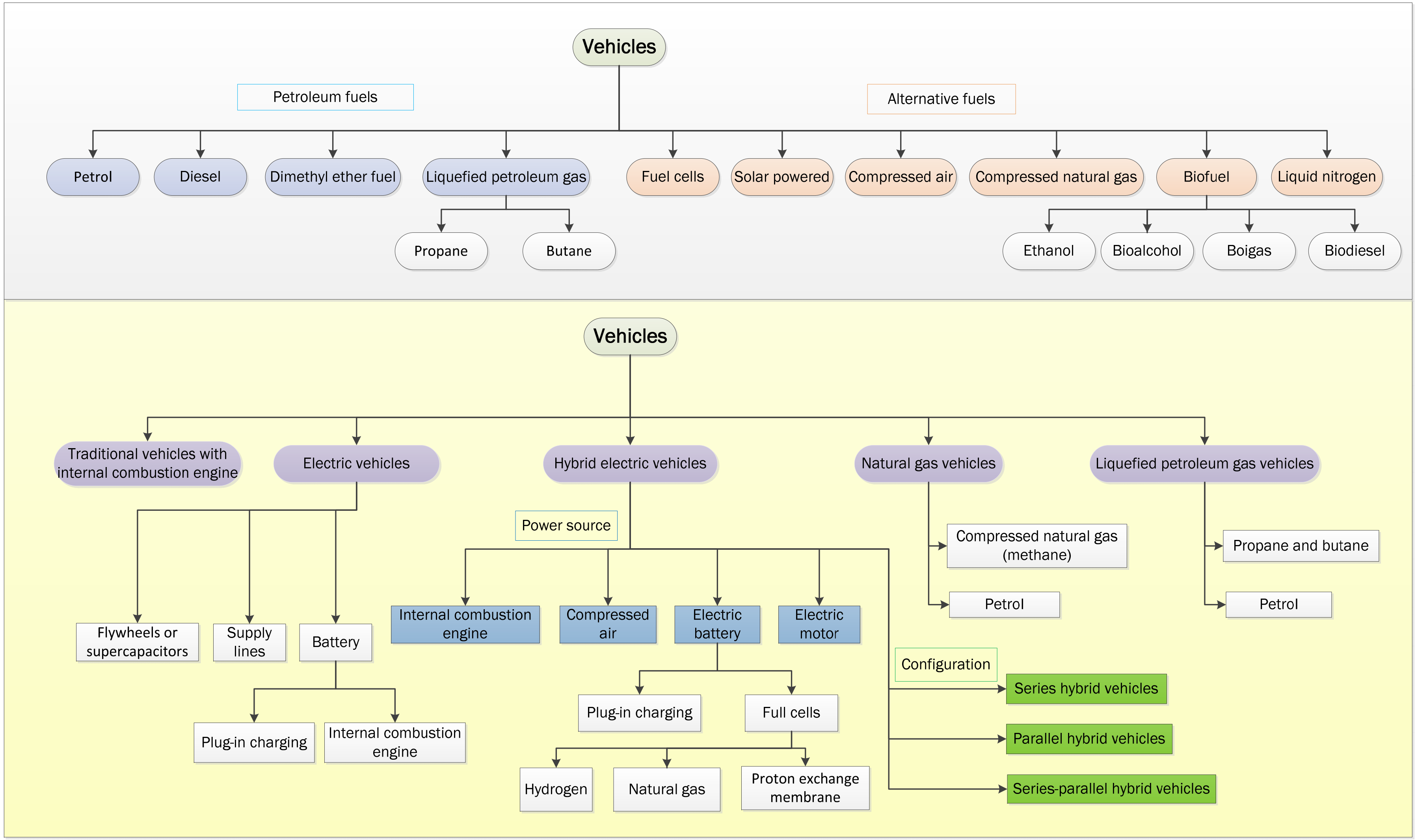


Figure 3.2 Vehicle classification.

3.3.1 Petroleum fuel vehicles

3.3.1.1 Petrol and diesel

Traditional fuels are produced from crude oil through a number of refining methods, such as petrol and diesel. In general, the refining process for diesel is simpler than to produce petrol while it contains more pollutants that must be extracted before it can achieve the same emission level as petrol. Compared to petrol engines, diesel engines offers better fuel economy due to the latter provides a higher volumetric energy density (ACEA, 2013). It is estimated that diesel combustion engines have 44% fuel burn efficiency, in comparison to around 25% - 30% in petrol engines (USDE, 2003).

3.3.1.2 Dimethyl ethyl fuel

Dimethyl Ethyl (DME) is an organic compound, which is a promising substitute as fuel in diesel and petrol engines (Semelsberger and Greece, 2006). The benefits of DME fuel vehicles include the acceleration of combustion, reduction of ignition delay and improved ecological characteristics, such as low emission of Nitrogen Oxide (NO_X), Carbon Oxide (CO), Sulphur Oxide (SO_X) and no smog. In addition, there are three modifications of engines available using varied fuels: a) only DME, b) a combination of diesel and DME, and c) dual fuels where DME and diesel supply are independent (Arcoumanis *et al.*, 2008).

3.3.1.3 Liquefied petroleum gas

Liquefied Petroleum Gas (LPG) can be used to fuel vehicles as a mixture of hydrocarbon gases. A typical mixture consisting of propane and butane allows the LPG to emit less carbon per joule than either of them individually (ESDE, 2014). Although commercially available LPG is produced from fossil fuels, it releases fewer greenhouse gases per unit of energy compared to petrol and diesel (ESDE, 2014). The disadvantages of LPG are the lack of its large scale availability in comparison to petrol and diesel, as well as it having lower fuel efficiency (ESDE, 2014). However, DME can be blended with LPG, which helps energy security and brings economic benefit. Increasing oil prices create demand for LPG alternatives that have similar properties and are economically viable. From the ecological perspective, the combustion of DME and LPG blends provides a reduction of 30% - 80% in CO2 emission, and reduction of 5% - 15% in NOx emission (IDA, 2010).

3.3.2 Alternative fuel vehicles

3.3.2.1 Solar power

The power of solar vehicles comes completely or mainly from solar energy. The basic principle is to store and use the energy in a battery after charging it using a solar panel (Wamborikar and Sinha, 2010) (see Figure 3.3). Solar-powered vehicles can only work effectively in areas with a large amount of sunshine; therefore it is unlikely to be a practical transportation for everyday use, in particular within the United Kingdom (UK). One of the solutions is to incorporate a conventional electrical charging socket that allows the solar power car to be charged from the power grid (BBC, 2014).

3.3.2.2 Fuel cell

Fuel Cell Electric Vehicles (FCEVs) fueled with hydrogen play a significant role in reducing emissions and dependency on fossil fuels (IEA, 2011). Instead of generating electricity from an engine or battery like other types of vehicles, hydrogen is used to provide power for FCEVs (NGC, 2013). No harmful emission but water vapour exhaust is generated from FCEVs that make them more environmentally friendly than traditional ICE vehicles (EERE, 2014). FCEVs are able to achieve much higher conversion efficiency than conventional engines, as they could achieve up to 60% fuel energy efficiency (Wipke et al., 2012). The technologically advanced components contained in an FCEV are shown in Figure 3.4 (EERE, 2016). It should be noted that most hydrogen is produced by steam with non-renewable resources, i.e. coal or natural gas. Therefore, pollution may occur during the production (Milbrandt and Mann, 2009). In addition, hydrogen gas has a relatively low volumetric density than other hydrocarbons which limits the store capacity of it on-board (Mori and Hirose, 2009).

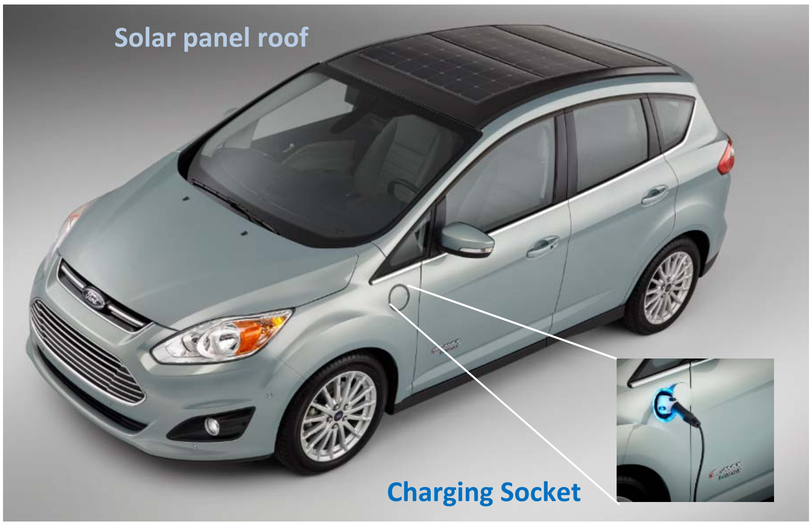


Figure 3.3 Solar-powered car concept by Ford.

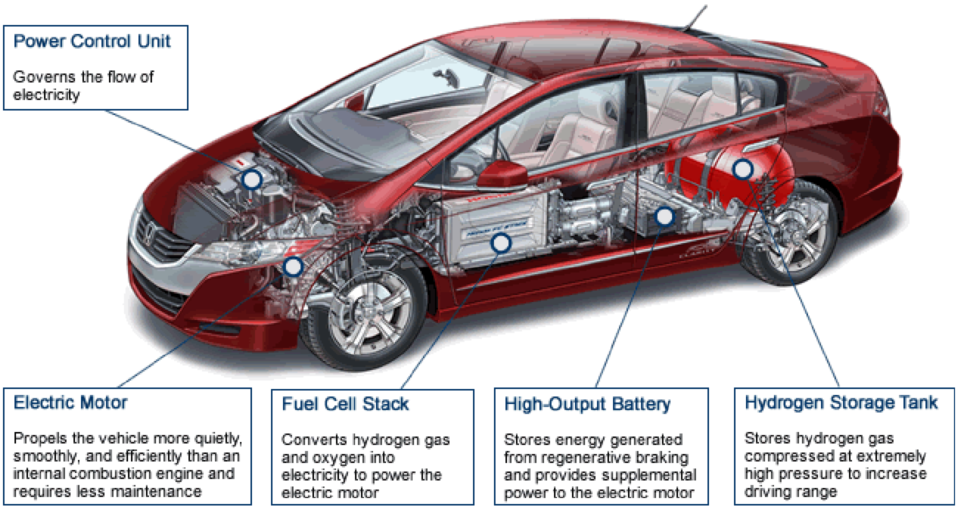


Figure 3.4 Schematic of a Fuel Cell Vehicle.

3.3.2.3 Compressed air

Compressed air is stored and used to power a Compressed Air Vehicle (CAV). A mixture of fuel and air is replaced with compressed air to drive the pistons of vehicles. It is claimed that the efficiency of use of compressed air is 90% (Hamilton, 2008). Compressed air propulsion can be utilised as one part of the hybrid systems (Patnaik, 2015). For example, the integrated system with both compressed air and battery electric propulsion is called hybrid-pneumatic electric propulsion (shown in Figure 3.5).

3.3.2.4 Compressed natural gas

Natural Gas Vehicles (NGV) are powered by natural gas (i.e. 95% methane) with adjusted engines (UNEP, 2009a). The condition to store natural gas in a fuel tank is a relatively high pressure ranging from 200 to 240 bars (UNEP, 2009a). Both petrol and diesel engines need slight adjustments to run on Compressed Natural Gas (CNG) (see Figure 3.6). For example, in a

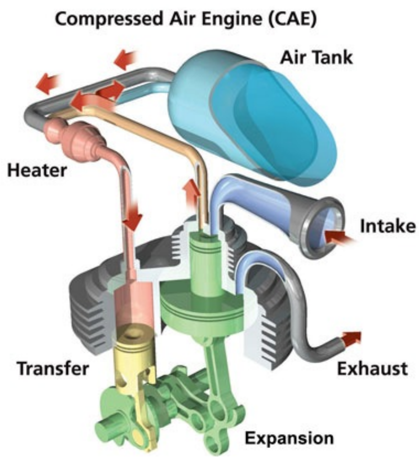
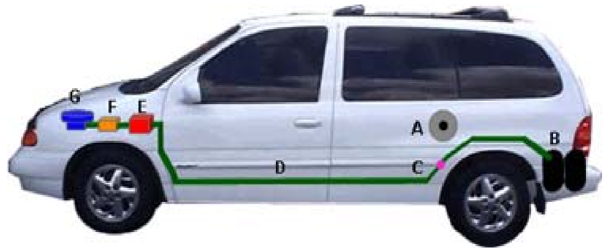


Figure 3.5 Schematic of compressed air engine (CAE).



A. Natural gas fill valve; B. High-pressure cylinders; C. Shut-off valve; D. Fuel line; E. regulator; F. Solenoid valve; G. Fuel-injection system

Figure 3.6 Schematic of natural gas fuelling system.

diesel engine, a small quantity of diesel is utilised as one part of the ignition system (UNEP, 2009b). Since the oil crisis in the 1970s, the CNG has been used as a fuel with sufficient supply. Additionally, the number of CNG vehicles have been gradually incresed in a number of developed and developing countries, such as Argentina, China, New Zealand and the Eastern European countries. In order to minimise the air pollutants generated from automobiles, a great effeort has been put on replaing traditaion diesel buses with CNG vehicles (UNEP, 2009b).

3.3.2.5 Bio-fuel

Different from fossil fuels that are generated by geological processes, biofuels are derived from organic matter through contemporary biological processes. Biofuels are estimated to provide 27% of the total transport fuel by 2050, as one of the potential alternatives to reduce the dependency on fossil fuels and contribute to the decarbonisation process (IEA, 2011). Conventional biodiesel is produced from vegetable oils, animal fats and used cooking oil that can be converted to biodiesel using methanol or ethanol. In most cases, biodiesel is used as a blend of biodiesel and regular diesel in normal diesel vehicles without engine modifications (AFDC, 2016b). The greenhouse gas emissions generated by biodiesel vehicles is less than half of the amount produced by regular diesel vehicles (NBD, 2016). It is estimated that more than 78% of the diesel vehicles in the market are approved of using biodiesel (NBD, 2016).

3.3.2.6 Liquid Nitrogen

Liquid nitrogen vehicles that operate on non-polluting liquid nitrogen instead of batteries have been developed in the United States and in Ukraine as shown in Figure 3.7 (Plummer et al., 2000; Turenko et al., 2005). The propulsion system of this type of vehicle consists of several modular: a pneumatic engine, a heat exchanger and a cryogenic tank for storage and primary evaporation (Nishane, 2014). The liquid nitrogen vehicles have less environmental impacts than other vehicles due to its exhaust gas is not harmful to the environment (Mulla, 2015). The constraints for these vehicles include two principal issues: 1) relatively low fuel economy, and 2) the generation of liquid nitrogen is an energy-intensive process (Bogomolov et al., 2004).

Figure 3.7 Experimental cryogenic vehicles operation on liquid nitrogen (from left to right: University of North Texas, Ukraine at Kharkov National Automobile and Highway University) (Traum et al., 2011).

3.3.3 Hybrid and electric vehicles

There are various configurations of electric vehicles that have been developed for different purposes. Currently, the major sources of the electricity utilised in hybrid and electric vehicles are drawn from energy stored in batteries, on-board charging system and off-board chargers (Monteiro, et al., 2012). The characteristics of these vehicles will be discussed in more detail in the following section.

3.3.3.1 Hybrid Electric Vehicles

Hybrid Electric Vehicles (HEVs) are powered by a combination of propulsion sources, inclduing ICEs, batteries, electric motors and energy produced from regenerative braking mechanism (EERE, 2013), as shown in Figure 3.8 (a). HEVs inherit the benefits of high fuel economy from conventional ICE vehicles and allow for a smaller engine to provided extra power by an electric motor. Furthermore, the power of the battery can be used for the auxiliary systems, i.e. sound system, headlights, and reducing the engine idling when stopped.

3.3.3.2 Plug-in hybrid electric vehicles

Plug-in Hybrid Electric Vehicles (PHEVs) have a battery-driven electric motor and petroleum or diesel powered ICE. In contrast to conventional vehicles, the utilisation of electricity from the grid helps reduce operating costs and petroleum consumption. As illustrated in Figure 3.8 (b), the propulsion sources of PHEVs come from either the batteries recharged by ICEs or standard grid. It should be noted that the overall environmental impacts of PHEVs largely depend on

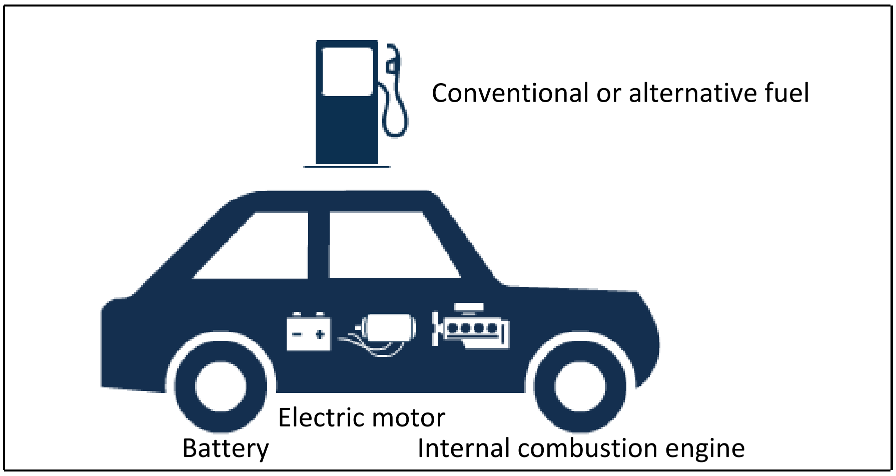


Figure 3.8 (a) Schematic of a hybrid electric vehicle.

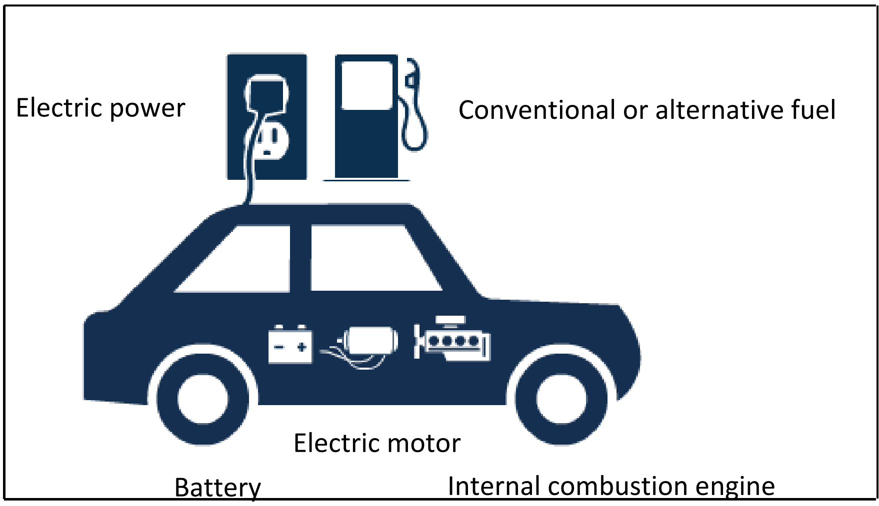


Figure 3.8 (b) Schematic of a plug-in hybrid electric vehicle.

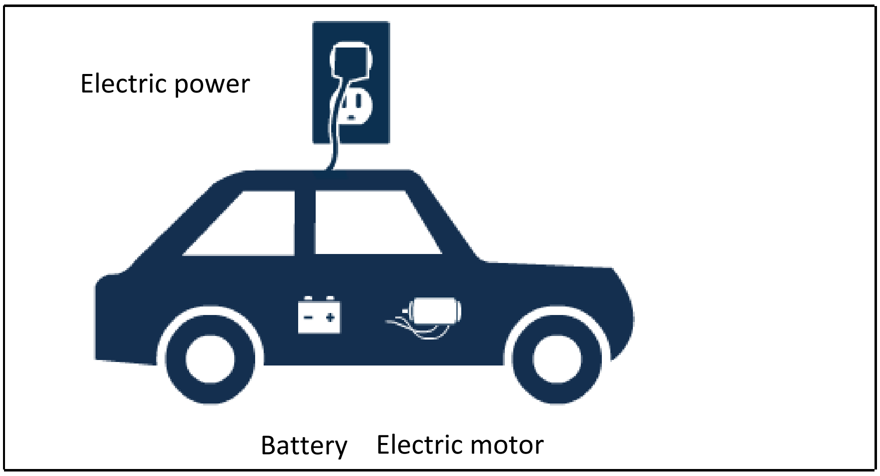


Figure 3.8 (c) Schematic of a fully electric vehicle.

sources and transition methods of the electricity (UNEP, 2009b). For example, the application of advanced grid technologies contributes to the increase in fuel efficiency. Utilising electricity can reduce the consumption of fossil fuels and associated air pollution; however the emission generated at the power station cannot be neglected.

3.3.3.3 Fully electric vehicles

In Fully Electric Vehicles (FEVs) or so-called Battery Electric Vehicles (BEVs), batteries play a significant role in propulsion using their stored electricity energy. As shown in Figure 3.8 (c), the batteries can be charged either through the regenerative braking system or by standard electrical outlets (UNEP, 2011). The feature of generating no air pollution from tailpipe makes these vehicles categorised as zero-emission vehicles by the U.S. Environmental Protection Agency (EERE, 2013). Since FEVs can be operated without using any fossil fuels, the market growth of these vehicles will result in reduced consumption of petroleum-based fuels and generation of emissions.

3.4 Specific design features in HEVs

There are a number of unique design features for EVs that influence the recycling of such vehicles. These are categorised in selection at technology, materials, and specific component design that are briefly outlined in the section below.

3.4.1 Technological advancements

3.4.1.1 Regenerative braking

Reuse of kinetic energy to regenerate electricity is another merit of HEVs. In general, when braking, friction occurs causing kinetic energy to be generated; this kinetic energy is discarded in standard braking systems. However, with the coordination between the traditional hydraulic brake operation and regenerative braking, the kinetic energy generated by friction heat can be collected and reused for driving in the future (TOYOTA, 2016).

3.4.1.2 Transmission system

Traditional ICE vehicles use an automatic transmission and, therefore, the transmission system consists of a torque converter, gearbox and controls. For HEVs, there is no torque converter contained in the transmission system (Burnham, 2012). A continuously variable transmission can be replaced with a set of planetary gears, or a single-ratio gearbox is used to extend the mileage of EVs and HEVs. In addition, replacing a sing-speed arrangement with a motor, the performances of the EVs and HEVs can be significantly improved (Burnham, 2012).

3.4.2 New material advancements

3.4.2.1 Light-weighting

The relationship between vehicle weights and fuel consumption makes weight reduction as a cost-effective method to improve automobiles' fuel efficiency and environmental performance (Ungureanu, 2007). Quantified results have indicated that every 10% of weight reduction contributes to an increase of 7% in fuel economy, and 20% reduction in vehicle weight results in a reduction of 25% in fuel consumption (Ghassemieh, 2011; Cheah et al., 2007). The majority approaches of the weight reduction consist of material substitution, redesign and downsizing of vehicles (Cheah et al., 2007). The technologies and processes of replacing steel with alternative materials (i.e. aluminium, magnesium and composite) have been investigated and developed (McWilliams, 2007). For example, it was identified that cast aluminium is an appropriate alternative material for cast iron products (Cheah et al., 2007). Vehicle structural and frame materials can be made of stamped aluminium and composite materials. It has been estimated that up to 20% weight reduction is achievable using currently available materials substitutes (Sperling and Cannon, 2008).

3.4.2.2 Material composition

Besides the reduction of total weight, vehicle material composition of HEVs and EVs has been changed dramatically. There is a high percentage of aluminium, plastic and advanced composites compared with conventional counterparts. The application of these materials provides an opportunity for weight reduction and design flexibility (Ghassemieh, 2011). An overview of material composition from different vehicle types has been developed, as shown in Figure 3.9 and 3.10 (Sears, 1997; Staudinger and Keoleian, 2001; Boon *et al.*, 2003; Kumar and Sutherland, 2008; Szeteiova, 2012; Kibira and Jain, 2011 and Burnham, 2012). For example, plastic materials used in automobiles is moving around 10% -15% of the total weight of the car. The percentage of steel has significantly decreased from 59% - 68% to 19% - 33%.

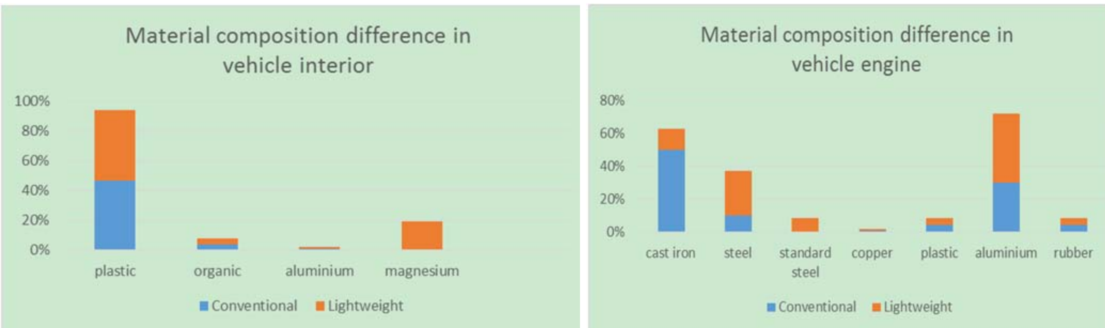


Figure 3.9 The material composition difference between traditional and lightweight vehicles (adapted from Burnham, 2012).

	Ce	La	Pt	Pd	Rh	Ce	Ga	Ag	Pr	Eu	Pr	Nd	Yt
Driventrain													
Batteries													
Catalyst													
Solar system													
UV absorbing glass													
LCD screen													
Electric motors													
Sensors													
LED headlights													

Figure 3.10 Vehicle components containing Rare Earth Elements (REEs) and PMs (adapted from Kitco, 2013).

3.4.3 Component design

In general, HEVs consist of major components that are specially designed for these vehicles. For example (see Figure 3.11), the main inverter (No.1) is used to drive the electric motor and support the regenerative braking mechanism to feed energy back to the battery. The DC/DC converter (No.2) converts the energy from high-voltage battery to traditional power supply system (Infineon, 2016). Auxiliaries components (i.e. heater, water pump and compressor) are powered by converted electricity using an inverter (No. 3) instead of being belt-driven (Infineon, 2016). Additionally, battery management system (No. 4) is responsible for battery state control while charging and discharging. An on-board charger (No.5) charges the battery with an AC/DC converter device, and the electricity can also be drawn from alternative charging methods, such as an off-board or inductive charging system (Infineon, 2016).

3.4.3.1 Engine

In the comparative study of traditional ICE vehicles, the HEVs are distinctly lighter in terms of their weights. It is revealed that in HEVs, a relatively small electric machine is mounted to the engine crankshaft. Some HEVs which have twin generators architecture also have downsized

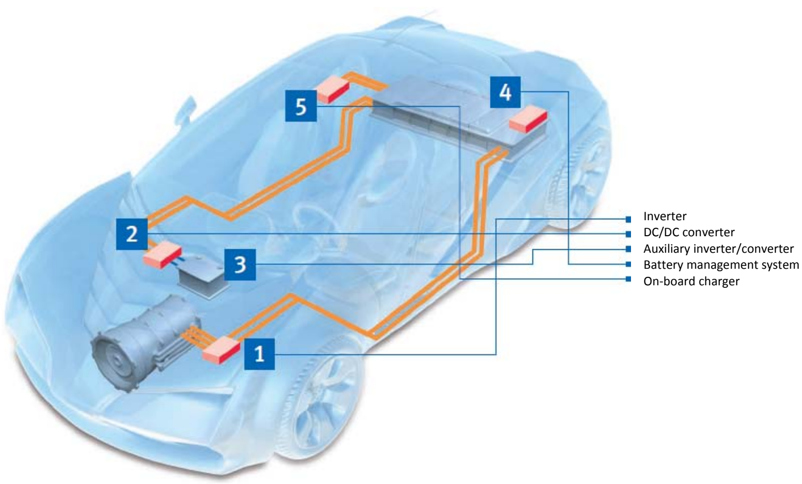


Figure 3.11 An overview of major components contained in HEVs (Infineon, 2016).

engines. In general, compared to traditional ICEs, the application of advanced hybrid system provides a more energy-efficient solution in driving mode (TOYOTA, 2016).

3.4.3.2 Electric motor and generator

Electric motors are employed to provide a compact packaging, lighter weight and a higher efficiency. With the assistance of innovative technologies of electric motors, it is feasible to adjust revolutions and torques to meet specific requirements (TOYOTA, 2016). All the characteristics are beneficial for smoother starting and acceleration operations.

3.4.3.3 Electronic equipment

A number for factors (i.e. megatrends, emission, urbanisation and fossil fuel usage) have increased the pressure on the automotive industry to develop more innovative and sustainable solutions to counter the detrimental effects. The electrification of the vehicle's drivetrain is one of the approaches to reduce energy consumption during its whole lifetime. Consequently, new components like an electric machine, power electronics and batteries need to be integrated into vehicles. On average of all traditional and alternative fuel vehicles, 15 electronic components are embedded in a modern standard medium-sized car, but this number can rise to 48 in a luxury car, including microcomputers and Electronic Control Units (ECUs) (Cucchiella et al., 2016; Kripli et al., 2010). It is also estimated that the value of the automotive electronic components account for 30% to 50% of the total cost of some vehicles (Wang and Chen, 2013).

3.4.3.4 Inverter and converter

The power control unit consists of an inverter and converters. The inverter is responsible for powering the electric motor, collecting energy generated from friction heat and feeding it back to the battery for later use (Infineon, 2016). This is a key component in the EVs, similar to the Engine Management System (EMS) of ICE vehicles. Regardless of the configuration of the motors (i.e. synchronous, asynchronous or a brushless direct current), one of the similarities of these motors is that they are all controlled by electronic control devices.

In HEVs, a number of electronic components are required to process different level of voltage in the electrical system. Converters increase the normal direct current supply voltage to a maximum voltage in order to feed the electric motor and the generator, and to step down the voltage for lower voltage electric devices and auxiliary systems.

3.4.3.5 Battery

The batteries of HEVs includes a standard vehicle lead acid (Pb-Ac) battery for the start-up and accessory load. For the HEVs, PHEVs, EVs, and FCVs, either a Nickel Metal Hydride (Ni-MH) or Lithium-Ion (Li-ion) battery are used in electric-drive systems. Further information about the battery types is discussed in section 5.3.3.

3.5 Impacts of specific design features on vehicle recycling

Typically, standard automotive recycling consists of removing reusable components for resale, followed by shredding the vehicle and then separating material for material recovery. The economic viability of recycling depends on the quantity and type of components for resale and the purity of the material recovered post-shredding. Because the material composition of HEVs and EVs differs from conventional vehicles as discussed in Section 3.4.2, their increased presence is expected to affect profitability and technologies required to recycle such vehicles. An example of this is that using increased quantity of lightweight materials could improve the fuel economy but may affect the recycling profitability by reducing the quality of the waste stream. Despite this, the increasing electrification of the automotive industry implies the demand for a holistic understanding of EoL management of EVs. Section 3.4.3 illustrates the advancements in vehicle components and highlights the economic incentives for an improvement on recycling these valuable electronic components. While numerous other studies already address the use phase of the EVs, this research focuses more on the EoL and recycling of EVs and their components. In addition, the composition of EVs has changed dramatically. On one hand, increased amount of lighter materials such as plastic and composite materials are embedded in vehicles to replace ferrous metals. On the other hand, SIMs such as REEs and PMs, are seen as the 'vitamins of modern industry' (Hurst, 2010). PMs and REEs are essential materials for components in HEVs and EVs such as engines, motors, generators, ECUs and batteries. The growth in use of PMs and REMs in automotive manufacturing between the years 2000 – 2009 is shown in Figure 3.12. In this context, the more complex design of EVs, the increased use of electronic parts, the new inclusion of lighter materials and PMs and SIMs all indicate a need for new approaches to recycling of EVs, which forms the main scope of the research reported in this thesis.

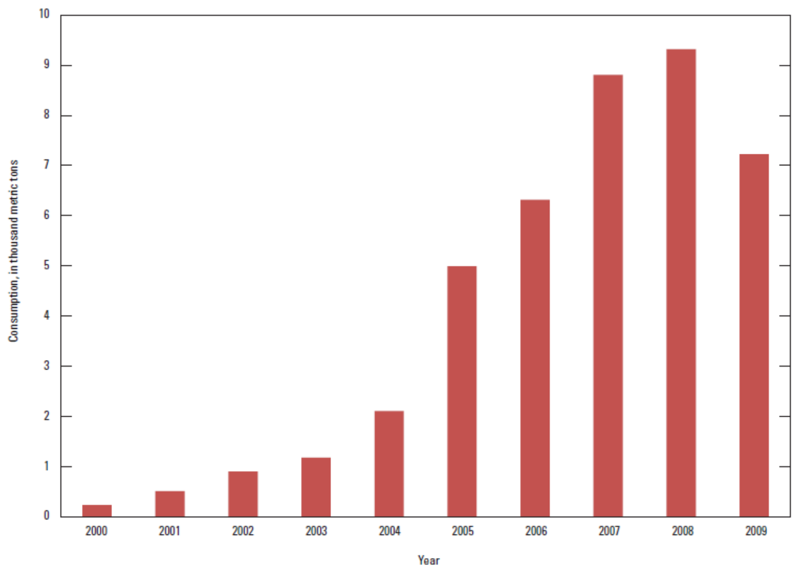


Figure 3.12 Demand for rare earth oxide associated within U.S. hybrid automobile sales from 2000 through 2009 (adapted from Bade, 2010; Goonan, 2011).

3.6 Chapter summary

The review of the automotive technology presented in this chapter provides important contextual information for the research undertaken within this thesis. Increasing concern about the fuel, resource consumption and global emissions has driven the transportation sector to consider a more sustainable path. Alternative fuel vehicles have become increasingly more important, and the market share of EVs increases dramatically annually. By analysing the EVs design characteristics, its impacts on ELV recycling can be identified.

CHAPTER 4 A REVIEW OF CONTEMPORARY VEHICLE RECYCLING TECHNOLOGIES AND PROCESSES

4.1 Introduction

This chapter provides a comprehensive overview of the current technologies and processes in the vehicle recovery and recycling sector and recent changes due to the requirement for the implementation of the ELV Directive. This chapter begins by describing the quantities of waste vehicles arising, and the prescriptive legislation that required manufacturers to improve the sustainability in the whole life cycle of vehicles. In the later section, it reviews the characteristics of current ELV recycling and recovery practices and provides a description of each technology and process. Finally, shortcomings and challenges in ELV recycling and recovery are discussed.

4.2 Waste arising and recovery practice for ELV

Sustainable transportation aims to consider both environmental and economic benefits of developing both fuel-efficient and cost-effective automobiles (Husain, 2010). The increasing consumption has resulted in a significant growth in the waste generation, in particular at EoL stage as shown in Figure 4.1. In fact, ELV has become one of the fastest growing waste streams in both developing and developed countries (Bourguignon, 2015). It is estimated that around 2.2 million in the UK and 12 million vehicles in North American reach the EoL stage each year

Figure 4.1 Waste from ELVs.

(Environmental Agency, 2014; GVD, 2014). Studies conducted in Europe estimated that each year, the lives of 8 million vehicles in Europe come to an end (ADEME, 2008). Waste electrical and electric equipment from vehicles have posed a problem because they contain different hazardous substances, such as lead, and cadmium in the Printed Circuit Boards (PCBs). Thus, ELV should not be destined for landfill or incinerated without any unsorted operations (ARA, 2012).

4.2.1 The European and international ELV Directive and legislation

The problems created by the waste generation from ELVs have been addressed by European Directive 2000/53/EC (refer to EU-ELV Directive). The EU-ELV Directive aims to minimise the waste generation, increase materials re-use, recycling and recovery throughout the life cycle of the vehicles (GHK, 2006; Li et al., 2014). The EU-ELV Directive impacts upon all automobile manufacturers that supply the European auto market. It imposes recycling and reuse targets on vehicles that will be and have been solved (European Parliament and the Council, 2000). In 2006, when the EU-ELV Directive was adopted, it had been estimated that there could be about 8 to 9 million tons of waste generated from ELV every year (Tuddenham *et al.*, 1996). However, according to the report from Andersen *et al.* (2008), this figure is likely to rise to 14 to 17 million tonnes in the year of 2015.

The targets on reuse, recycling and recovery of waste from vehicles set by EU-ELV Directive are:

- To reuse or recover at least 85% of the ELV weight by 2006 while recycling at least 80% of this;
- To reuse or recover at least 95% of the ELV weight by 2015 while recycling at least 90% of this.

The definition of reuse, recovery and recycling as per Directive 2000/53/EC is: 1) reuse refers to that the components of ELVs can be reused for the same function of their original design; 2) recovery indicates energy recovery i.e. incineration of combustible waste; or any of the applicable processes provided for in Annex IIB of the EU-ELV (Vermeulen et al., 2011); and 3) recycling refers to that the waste materials are reprocessed for the original or other functions, without the options of energy recovery.

In addition, EU-ELV Directive states that relevant key stakeholders in automotive industry should meet the following requirements (Zorpas and Inglezakis, 2012), including:

- Endeavour to minimise the utilisation of hazadous materials in the design of the vehicles

- Take 'Design for Recycling', 'Design for Disassembly' and 'Design for Remanufacturing' into consideration in the design and manufacuturing processes
- Increase the use of recycled materials in autobomible production
- Ensure that automotive components that placed on the market after 1 July 2003 do not contain specific materials (i.e. mercury, hexavalent chromium, cadmium or lead etc.)

Similar legislation on EoL vehicles has also already been implemented in Japan in 2004. It requires the majority of vehicle manufacturers to consider the design concept which is easy for recycling and ELVs treatment; and associated recycling and recovery targets have been increased from 50% by 2010 to 70% by 2015 (Saman, 2006).

In the U.S. automotive industry, the recycling rate is 95% without specific legislation for ELVs in the U.S. (Bandivadekar *et al.* 2004). It is stated that the high recycling and recovery rate is compelled by the revenue generated from recycling activities among the key players (i.e. recyclers, dismantlers). The profit margins of material recovery depend on the composition and condition of the ELV components, such as the value of the reusable sub-assemblies and the recovered materials. In addition, major automobile manufacturers have been working on programmes about recyclability improvement and waste reduction, such as Ford and General Motors. A similar situation also exists in Australia with no legislations on recycling ELVs. Most recycling management relates to the economic consideration, such as the cost of collection, storage and disposal of ELVs (Saman, 2006).

Therefore, such global strict recycling targets and economic benefits from vehicle recycling have highlighted the importance of recycling ELVs and the need for an optimisation of recycling systems.

4.3 An overview of the current recycling and recovery route for ELVs

Due to the financial incentives and legislative requirement in relation to the ELV Directive, there has been significant investment and improvement in vehicle recycling and systems. Although the exact processes may vary marginally in various countries, a typical flow diagram of the current recycling and recovery route for ELVs is illustrated in Figure 4.2. After the collection of ELVs, the first process is dismantling, and the de-pollution processing of hazardous materials such as batteries, fluids (oils, fuels), tyres and any other hazardous substance (Edward et al., 2006; Sakai et al., 2014). The removed components at this stage can be used for direct reuse, remanufacturing, recycling and energy recovery (Tian *et al.*, 2010). The high value salvageable components, such as engines, transmissions and airbags are reconditioned, remanufactured or resale (Sawyer-Beaulieu and Tam, 2015). The dismantling

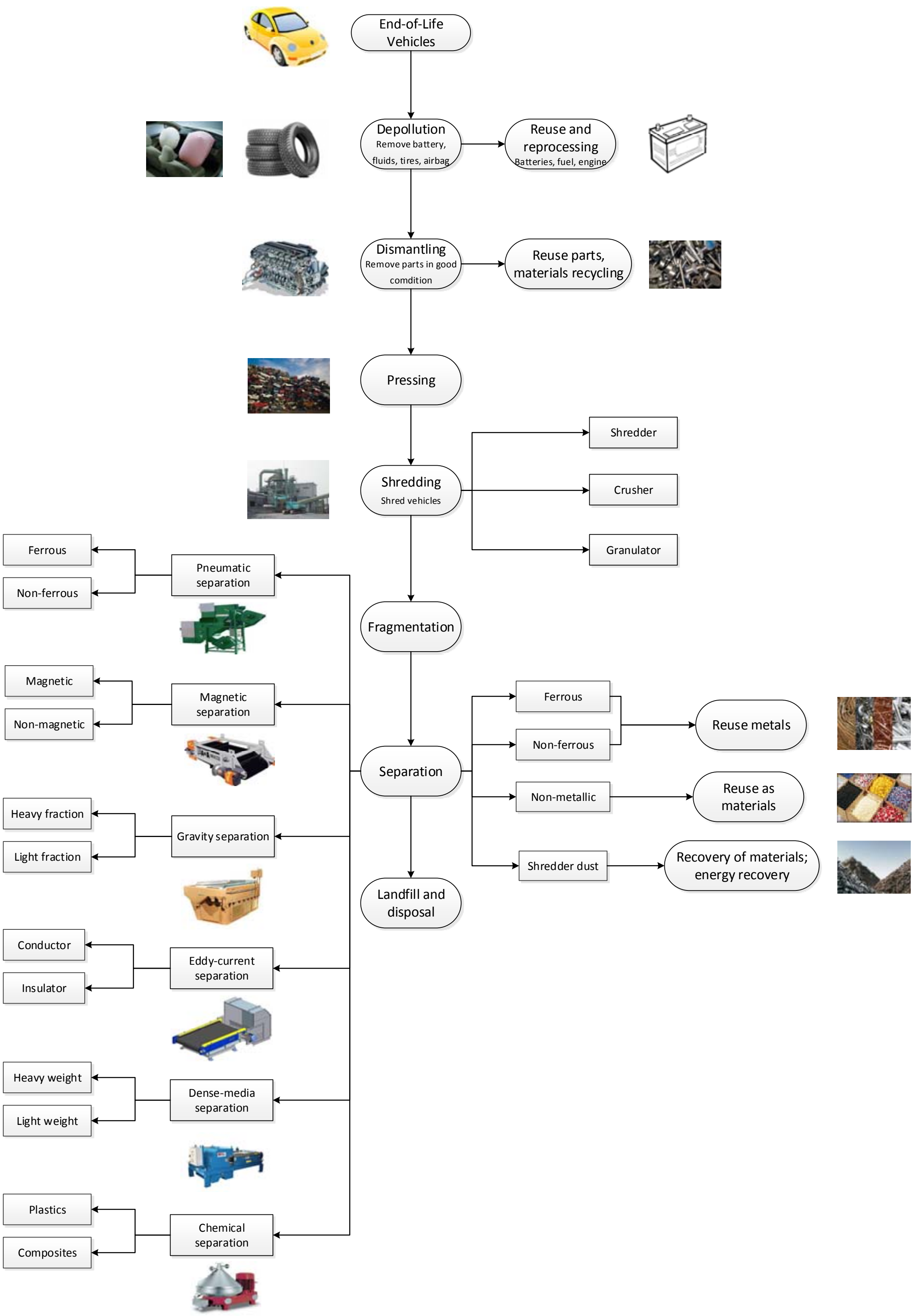


Figure 4.2 An overview of the current recycling and recovery route for ELVs (adapted from Sakai et al., 2014; Zarei et al., 2010; Smink, 2007; Edwards et al., 2006)

operation offers a low-cost replacement for repairs, for example, the body panels are used to repair vehicles damaged through road traffic accidents. The remaining hulk is typically flattened prior to shipment to the shredding infrastructure.

In the shredding process, the hulks and other material scraps that may come from consumer goods (such as white goods) are processed together. The shredders use huge hammers to crush hulks into pieces within a drum. A typical processing rate for shredders is 45 to 60 seconds per ELV (Reynaldo and Jurgen, 2009).

After the shredding process, materials are sorted and separated into different groups, such as ferrous, nonferrous metals and shredder residue. The initial process is the magnetic separation for liberating ferrous (all iron and steel, except stainless steel) from non-ferrous materials (which may include both metals and non-metals). The subsequent operation is to separate remaining non-ferrous metals from non-metallic materials, referred to as light Auto Shredder Residue (ASR) through eddy current separation, air separation and dense media separation. In the non-ferrous metal group, aluminium and steel can be separated by “light media” and “heavy media” properties. Copper and brass are separated using additional “image processing” approaches. The rest of the materials such as plastic, glass, paper/wood, fabric, rubber, and urethane foam are further processed using bespoke methods as required to liberate and recycle these materials. The remaining materials that cannot be separated are sent for energy recovery to landfill as ASR.

The recycling results generated by a study by Staudinger and Keoleian (2001) estimate that the ferrous metals (iron and steel) dominate 65% - 70% (by weight) the total waste stream; non-ferrous metals (stainless steel, aluminium, copper, brass, lead, magnesium, zinc and nickel) comprised 5% - 10%, while the ASR was 20% - 25% concentration of the composition. The separation approaches used in ELV treatment are further described in the following sections.

4.4 Material Separators used in post-shredder separation

4.4.1 Separation based on magnetic property

According to the magnetic properties, a suspension magnet, known as an over-band magnetic separator can remove ferrous metal from the conveyor. In the process, the magnet field and polarity are produced by rare earth magnets and a magnetic rotor. A conveyor belt drives a non-conducive drum; and through the induction of eddy current, a repelling force is generated.

Overall there is an electromagnetic swinging arm or more usually fixed as a static magnet aligned with the belt, as shown in Figure 4.3. Normally it is employed before the fragmentation process (Steinertglobal, 2015), but is also used post-fragmentation depending on the recycling line. In eddy current separators (see Figure 4.4), the non-ferrous metals can be separated from various sizes due to the differences between metal types of varying conductivity.

4.4.2 Separation based on electro-magnetic property

The electrostatic charge separator is applied to separate fine waste, usually in a drum as a dry process (see Figure 4.5). The principle is that through physical surface contact or triboelectric charging, there are electrical charger differences between various materials (Bittner et al., 2014), while the material with a higher electron affinity becomes negatively charged and the other becomes positively charged. Electron affinity depends on the chemical composition of the particle surface and leads to substantial charge differences among a mixture of materials. Electromagnet induction sorting systems measure the electrical and magnetic performance of the material, and they can be used as metal detectors. Once the metal type is detected, it can be removed by air jet as shown in Figure 4.6.

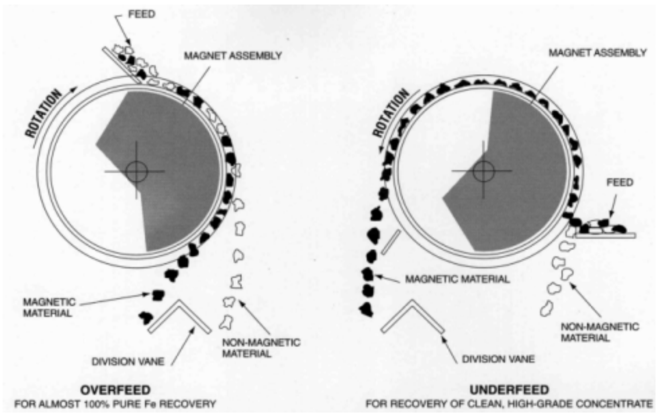


Figure 4.3 Magnetic separators.

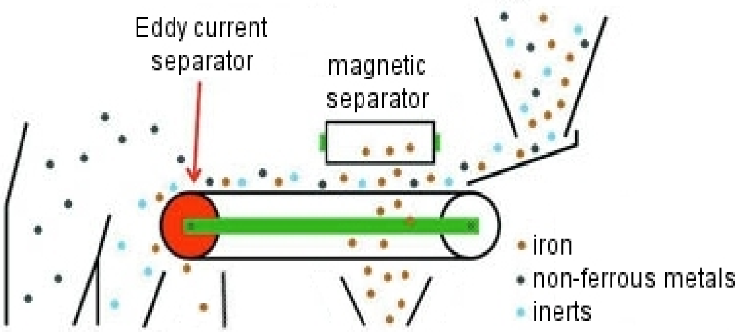


Figure 4. 4 Eddy current separators.

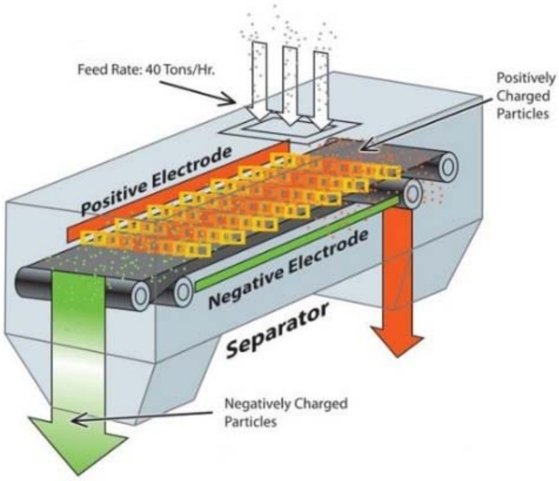


Figure 4.5 Electrostatic charge separator.

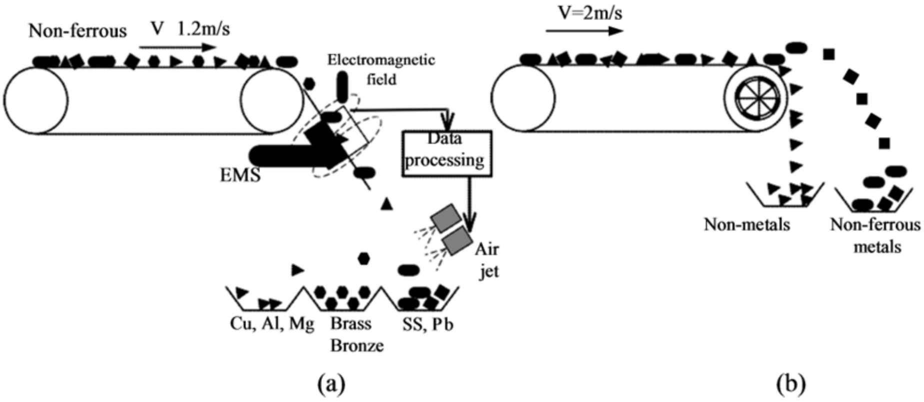


Figure 4.6 Electro-magnet induction separators.

4.4.3 Separation based on size and weight

According to the size of the gap on screening, vibrating sieving tables are useful in making the smaller objects fall through the screen. In addition, the air and vibration fluidisation from the air-table are resulting in the lighter granules to stratifying on top and sliding down the table while the heavier granules which are in contact with the table surface move up the table (Dodbiba *et al.*, 2005), as shown in Figure 4.7.

4.4.4 Separation based on density

According to the density difference, there are three types of separation: ballistic separators; sink/float (or called wet-water/chemicals) and sink/float (or called dry-medium-fluidised with air). In the category of density separation (dry) method, air-table separation fluidises the bed of materials using air and vibration. In the wet density separation method, the density of tank media can be increased by adding magnetite so lighter fractions such as PE (coloured bottle tops) float, whilst heavier (clear) Polyethylene Terephthalate (PET) sinks. The arrangement of

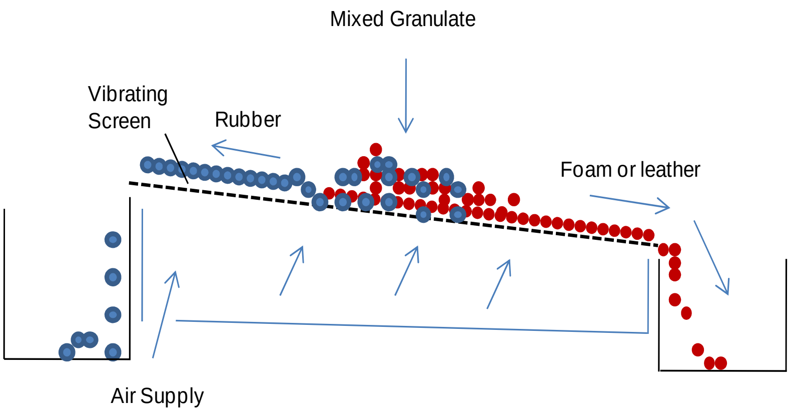


Figure 4.7 A air-table separation.

separation (wet) requires sink-float tanks, hydro-cyclone and centrifugal force-cyclone.

4.4.5 Separation based on sensor technology

Sensor sorting systems utilise sensors for detecting specific properties of materials, including physical, chemical or optical characteristics of individual materials. After recognition processes, in the central control centre, compressed air is used to eject target materials in the waste streams. This technology has been widely applied in food and chemical industries, as well as waste treatment processes.

4.4.6 Separation based on optical technology

A visible light recognition system is applied to sort products and packs with high-speed video and shape recognition software, as shown in Figure 4.8. Additionally, colour separation (CS) is used for large items but also smaller 'flake' separation. The RGB (red, green and blue) camera is accurate in delivering colour messages. In practice, a Spanish manufacturer of equipment and solutions PICVISE provides a system based on image processing to improve the detection of different materials for separation (PICVISA, 2013). X-ray sorting systems work like optical

Figure 4.8 A visible light separator.

systems but using X-rays for image processing, following by air jets to separate material and waste streams. There are two technologies in the X-ray category: X-ray fluorescence (XRF) and X-ray transmission (XRT). Using this optical technology, materials can be identified and sorted independently of their colour and level of contamination or pollution (TITECH, 2015).

4.5 Analysis of challenges in ELV recovery and recycling

The review of EoL EV recycling and recovery activities associated with various technologies and processes has highlighted that current practices in EoL EV management activities are presently driven mainly by economic factors. The following are a number of shortcomings in ELV recovery and recycling, identified by this research:

A. Reduction of metallic content in contemporary vehicles

Current ELV recycling and recovery activities primarily concentrate on the recovery of metallic materials due to their large proportion of existing vehicle mass. However, it is noted that in modern vehicles, the quantity of these materials has been dramatically reduced to meet specific requirements (i.e. light weighting and fuel economy). Thus, the profit margins of future EoL EVs recycling do not reply on the recycling and recovery of traditional metallic materials but precious materials (i.e. PMs and SIMs) contained in electrical and electronic components. These precious materials constitute a relatively small fraction of the overall weight which provides a challenge to achieve the economic viability of recycling and recovery of these materials.

B. Lack of available information and data to facilitate recycling and recovery

Chapter 3 illustrates that vehicle component structure and material composition are becoming more complex. It is noted that the information of the vehicle components is beneficial for decision-making on selecting the optimum recycling solution (Hauschild et al., 2008). Product information can be used as qualitative and quantitative data on product's characteristics, including the sub-assemblies' accessibility, material types and volumes, and joining methods (Shetty, 2015). Nevertheless currently, relevant information is not readily accessible, leading to difficulties in developing effective and consistent EoL recycling approaches (Lazarevic et al., 2010).

C. Lack of automated disassembly processes to support remanufacturing and recycling

Existing fragmentation and separation processes are not capable of extracting and liberating complex design and material mix products effectively, resulting in the loss of valuable materials in small quantities. Disassembly processes can be used for product remanufacturing and pre-concentration of target sub-assemblies and materials for value recovery. The disassembly for recycling has received significant attention both in academic community and industrial areas to extract and recovery pieces for reducing the environmental burden (Duflou et al., 2008). The disassembly is predominantly undertaken by manual operations over the past two decades while manual disassembly is time-consuming and labour-intensive (Schmitt et al., 2011). Thus, automated disassembly operations have been developed for a number of electronic products, such as personal computers, monitors, printed circuit boards (Knoth et al., 2001; Basdere and Seliger, 2003; Weigl-Seitz et al., 2006; Vongbunyong et al., 2013; Wegener et al., 2014; Wegener et al., 2015). Currently in the UK and Europe, there is no automated commercial process available, neither in the automotive industry (Cryan et al., 2010).

D. Impacts of lightweighting on recyclability of ELVs

The review in Chapter 3 illustrates that the introduction of EVs results in a decrease in the demand for steels and cast alloys while an increase in lightweight materials. However, there is a dilemma to strike the balance between achieving efficiency improvement through lightweighting (i.e. replacing ferrous and non-ferrous metals with plastic and composites) and improving recyclability of vehicles at the end of their lives (Hatayama et al., 2012). Whilst lightweight materials can reduce 'use phase' impacts, they can, however, be difficult to recycle, and with a more energy intensive production process (Lewis et al., 2014). An example of this can be seen in the case of aluminium and carbon fibres whose production process requires more energy than conventional materials, and the introduction of these materials increase difficulties in separation and recovery of the waste streams (Hopewell et al., 2009).

E. Inability to liberate valuable materials that are present in very small quantities

Typically alternative fuel vehicles, such as EVs, need to utilise valuable materials (such as PMs and SIMs) for their electrical and electronic components. However, the propositional weight of such valuable materials in current EVs is still very low (less than 5% by weight). This provides a new challenge in vehicle recycling as current methods are unable to liberate these valuable materials.

One possible solution includes improvement of the pre-concentration of these materials through dismantling and disassembly operations prior to the fragmentation process. However, dismantling is labour-intensive and in most cases not economically viable. Therefore, this research focuses on the enhancement of the dismantlability of ELVs and the recyclability of components using an automated robotic approach.

4.6 Chapter summary

This chapter has provided an overview of the current factors affecting EoL EV recycling and recovery activities. The legislative requirements surrounding the recovery industry provided a sound context to investigate appropriate recycling and recovery methods for ELVs. In addition, current shortcomings and challenges encountered within the recovery sector have been discussed. This has highlighted a need for introducing more automation prior to fragmentation and separation processes, which forms the main scope of research reported in Chapter 7-10.

CHAPTER 5 A REVIEW OF THE MOST RELEVANT LITERATURE RELATED TO END-OF-LIFE ELECTRIC VEHICLES

5.1 Introduction

This chapter aims to explore previous academic research and literature most relevant to the work reported in this thesis. This chapter begins by describing a background of evolving environmental concerns and associated environmentally conscious concepts. It continues with an overview of the most relevant literature, namely the publications on legislation, waste of electrical and electronic equipment management, and PMs, REEs, PCB recycling.

5.2 Overview of the relevant research areas

This chapter presents a review of the literature most relevant to the research of ELV, as shown in Figure 5.1. This research focuses on the automated disassembly approach for vehicle electronics, therefore, the review has been extended to other academic literature, including consideration of waste of electronic products and associated PCB recycling. Initially, other relevant legislation besides ELV Directive which was discussed in Chapter 4 is described. This is followed by the review of theoretical and practical approaches and practices for electronic waste (E-waste), PCB and battery recycling, and in particular the research about PMs and REEs recovery.

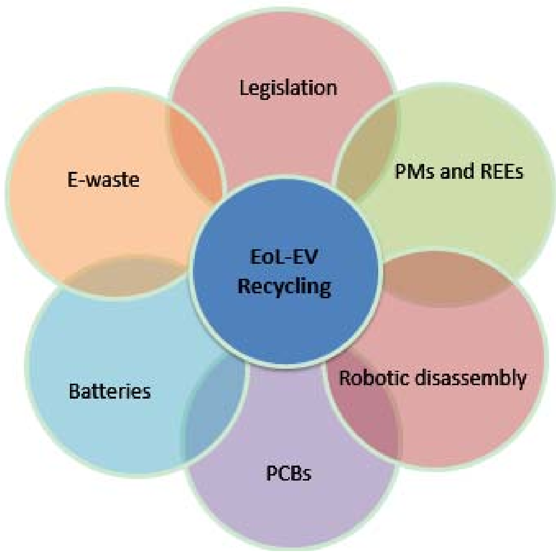


Figure 5.1 Overview of the relevant research considerations.

5.3 Policy principles, legislation and directives supporting EoL management

Based on the decades' effort on understanding of human impact on the environment, current environmental policies have been introduced in which the concept of EoL management has been developed. The First International Conference on the Human Environment, held in Stockholm in 1982, is a landmark event when the origins of modern environmental policy are taken into consideration (United Nations Environment Programme, 1972). Since then, there has been a series global efforts to address the increasingly detrimental impact on the environmental caused by human activities. In 1987, the concept of "sustainable development" was introduced by the World Commission on Environment and Development. Although the phrase can be interpreted in different context, the original definition (Hicks, 2006), "*…development that meets the needs of the present without compromising the ability of future generations to meet their own…"* (Brundtland, 1987), has become a dominant term in modern environmental research.

There has been a shift in the concentration of environmental policies in the past decades (Tukker, 2006). Early policy was reactionary to high-profile environmental crises; then aimed to minimise emissions and waste generation, and introduced the concept of "cleaner production"; and in the 1990s, policies were product-focused for achieving the environmental sustainability in a consumer-based society.

The Producer/Polluter Pays Principle (PPP) was adopted by Organisation for Economic Co-operation and Development (OECD) countries in 1972. A number of "guiding principles" were developed to minimise environmental impacts among member countries, and avoid the possible catastrophic consequences of industrial manufacturing processes, it states that:

"…prices of goods depending on the quality and/or quantity of environmental resources reflect more closely their relative scarcity and that economic agents concerned react accordingly." (OECD, 1975)

The PPP is not only the representative of environmental justice but also results in economic efficiency (Roy, 2006). This incorporated environmental cost makes recycling and recovery cost as one part of the normal cost of manufacturing products and providing services. Therefore, the natural resources would not be treated as free service but being tagged with price in a similar way to labour or capital costs.

Another variant of the PPP is the introduction of the EPR, which includes responsibility for collecting and recycling used products in the EoL stage. The definition provided by the OECD (2001) is widely used:

> *"An environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle. There are two related features of EPR policy: 1) the shifting of responsibility (physically and/or economically; fully or partially) upstream toward the producer and away from municipalities, and 2) to provide incentives to producers to incorporate environmental considerations in the design of their products."*

EPR is referred to as a policy tool that requires the polluter to be responsible for a series of EoL management processes, such as post-use collection, recycling, recovery and disposal of their products (Lifset, 1993). According to Lindhqvist (2000), EPR policies aim to encourage manufacturers of a product to minimise the environmental impacts across the entire lifecycle, promoting the total life cycle environmental improvement by extending their responsibility. In order to extend the responsibility of producers, EPR has been developed within environmental policy with the aim of incentivising product manufacturers to take proactive measures during the design process which will facilitate EoL management of their products; in such a way to facilitate resource efficient practices (e.g. reuse, remanufacturing, recycling and recovery). The concept has been embodied in a number of legislative and other instruments, in the EU and in other geographical regions (Tojo, 2004).

The first legislation incorporating an EPR approach was adopted with respect to packaging waste (European Parliament and Council, 1994), and more recently is illustrated by the ELV Directive (European Parliament and Council, 2000) and the Waste Electrical and Electronic Equipment Directive (European Parliament and Council, 2003). The evaluation of the implementation results of EPR for various product groups, ranging from packaging, small consumer batteries, ELV and Electrical and Electronic Equipment (EEE) has been undertaken by OECD (2001). The evaluation focuses on the aspects of the collection, reuse and recycling rates, stimulation of innovation, reduction of toxic substances and the cost of the implementation.

Directive 2000/53/EC on end-of-life vehicles (ELV Directive) aims to a) make ELV recycling and recovery activities with environmental conscious; b) to set quantifiable targets for reuse, recycling and recovery of automotive components; and c) to encourage the new design of vehicles with a view to their recyclability. Given that the responsibility for compliance falls with vehicle manufacturers, it is assumed that the directive will prompt innovative approaches to re-design and will encourage a reduction in the hazardous material used, an increase in the use of recyclable materials, and more emphasis on Design for Disassembly (DfD) (Crotty and Smith, 2006; Desai and Mital, 2005; Achillas et al., 2013). The detail about the Directive on ELV has been discussed in Chapter 4.

5.4 Directive on Waste Electrical and Electronic Equipment

Waste Electrical and Electronic Equipment (WEEE) refers to electrically powered devices that no longer satisfy the needs of their owners (Khetriwal *et al.*, 2009). Management of EoL electronics is one of the most challenging issues with its dramatically growth in the worldwide (Buekens and Yang, 2014). Mayer et al. (2012) pointed out that current implementation of EPR for WEEE has far failed. Thus, an alternative method for financing WEEE was provided with both effective and efficient framework to ensure the profitability of the EoL treatment.

EoL treatment of WEEE has aroused growing concern due to rapidly changing technologies and its dramatically growing volume. Similarly to the Directive of ELV, legislative requirements have been developed and imposed on WEEE, i.e EU Directives 2002/96/EC (European Commission, 2003). There are specific quantitative targets set as environmental obligations and constraint. For example, a reduced amount of hazardous materials and substances can be used in the electronic products (Barba-Gutierrez *et al.*, 2008).

The implementation of the WEEE Directive has set challenging recycling and recovery targets for manufacturers of EEE, and the anticipated results of the legislation are based on two underlying assumptions. The first assumption is that producers are provided with an economic incentive to revise designs in order to eliminate aspects which would prohibit reuse, recycling and recovery at the EoL phase. The second assumption is that an increase in use, recovery and recycling of materials from this waste stream will have a positive environmental effect (Mayers *et al.*, 2012).

Article 3 (a) of WEEE Directive has clarified the criteria for equipment considered to be covered by Directive 2002/96/EC (WEEE), “Equipment is dependent on electric current or electromagnetic fields in order to work properly, and equipment for the generation, transfer and measurement of such currents and fields.” WEEE Directive also states that “This Directive shall apply without the requirement to specific community waste management.” Therefore, it should be noted that the EEE devices like vehicle radios are not covered by the WEEE Directive. If the Electrical and Electronic (EE) component is not specifically designed to be used in a vehicle, that device should be covered by the WEEE Directive. But if the device is specially designed with the primary purpose to be used in vehicles, i.e. car radio and CD player, the ELV Directive applies instead (Day, 2005).

5.5 Review of the recycling of WEEE

5.5.1 Review on recycling of WEEE in different countries

At the early stage, the majority of the WEEE is generated in countries belonging to the Organisation for Economic Cooperation and Development (OECD) (Buekens and Yang, 2014). However, the faster growing EEE rates in both developed and developing countries have led to a large amount of e-waste now emerging globally, such as in USA (Kang and Schoenung, 2005), in China (Yu *et al.*, 2010), in Switzerland (Hischier and Gauglhofer, 2005), in Germany (Schebek, 2004), in Taiwan (Lee *et al.*, 2004) and in India (Seeman *et al.*, 2008).

Early EoL management of EEE was developed undertaken in European countries in which a number of institutions aimed to carry out voluntary take-back and EoL treatment activities (Buekens and Yang, 2014). Nowadays, in the worldwide, there are an increasing number of obligations and restrictions on WEEE management and treatment.

Japan has now become a major producer of electronic products since starting mass production in the 1950s and 1960s. The first initiative was introduced in the 1970s while the recycling and recovery were still not economic viable, thus this problem has initially emerged. However, at the beginning of the 20th century, recycling of WEEE was a legal requirement with a recycling rate of 80% - 90% by 2008 (Dimitrakakis *et al.*, 2009). In China, e-waste has now become a major environmental concern and its internal generation of e-waste has a large portion of the global WEEE generation (Yu *et al.*, 2010). In addition, operating in open burning sites and dumping from rough treatment of e-waste have resulted in serious environmental impacts, such as contamination soil and sediment (Xing *et al.*, 2009).

The USA still has the largest number of household WEEE (Buekens and Yang, 2014), without the introduction of any federal regulations on EoL treatment. Some American Corporations, such as Hewlet Packard have however pioneered responsible actions, such as the launch of the take-back systems and application of Design for Recycling (DfR) guidelines (Rossem *et al.*, 2006).

5.5.2 Review on recycling of various electronic products

The management of waste electronic components is difficult due to their rapidly increasing quantities of complex (Robinson, 2009). Electronic components contained both valuable and hazardous materials that need special treatment approach to mitigate its environmental impacts. Reusable, remanufactured parts and recovered materials can be extracted from the recycling processes (Herat and Agamuthu, 2012). This review aims to demonstrate the practices for a range of electronic components recycling.

5.5.2.1 LCD monitors

With the advanced technologies of liquid crystal display (LCD), it has become an alternative to cathode ray tube (Kim *et al.*, 2009). However, the increasing amount of LCD products is generated and disposed of which results in a challenge for both manufacturers and waste dealers. It is noted that a high-quality EoL management approach is required for LCD products recycling. In order to accommodate that need, a hybrid disassembly system has been designed and developed, incorporating both manual and automated disassembly operations. This work has been completed on a lab scale and is now in the process of being scaled up to a commercial scale (Kim *et al.*, 2009).

5.5.2.2 TV sets

An autonomous disassembly system for TV sets recycling has been developed at the University of Bremen in Germany. This set-up of the robotic cell includes disassembly and handling robots, intelligent vision system and various tools (Scholz-Reiter *et al.*, 1999). In addition, flat screen monitors were also utilised in a hybrid disassembly system proposed by Kernbaum *et al.* (2006) in which a 4-axis robot was capable of performing unscrewing and handling operations.

5.5.2.3 Cellular phones

Similar to other electronic products, cellular phones are made up of multiple parts and materials. After the collection, the batteries are extracted and recovered using a specific recycling path and the rest parts are being crushed without any prior disassembly (Geyer and Blass, 2010). In a specific study, a hybrid disassembly system was developed for the recycling of cellular phones (Kniebel et al., 2004). In this system, besides the removal of the main battery was operated manually, the rest of the operations were undertaken by a robot. In the case of disassembling a Nokia 5110 cellular phone, it is estimated that more than one-third of the processing time has been reduced (Duflou et al., 2008). Taking into account the high labour costs, improved disassembly efficiency and material recovery, there is great potential to increase automation in the future disassembly and recycling processes.

5.5.2.4 Personal computers

An automated disassembly for component recovery has been carried out on personal computers. In the research, a personal computer disassembly cell is presented. With the cell, a certain degree of automation was introduced in the non-destructive disassembly operations for the recycling of mass-produced electrical and electronic products (Torres *et al.*, 2004). Except the computer vision system that can recognise and localise the parts of the component, the disassembly system also has a modelling system which can be used to generate disassembly sequences and plan disassembly operations. Finally, those sub-systems cooperate with each other to achieve semi-automated disassembly. In addition, Li *et al.* (2013) developed a selective disassembly planning tool for WEEE. A multi-criteria decision-making tool was proposed for stakeholders to meet various WEEE treatment requirements.

5.6 Review on batteries

As demonstrated in the previous sections, batteries have been adopted in the vehicle energy storage system due to their characteristics concerning compact size, energy density and reliability, especially for electrically powered cars, such as HEVs, PHEV and EVs (Lukic et al., 2008). The technical aspects of the batteries are reviewed in the following sections.

5.6.1 Battery types and characteristics

In the automotive industry, most conventional vehicles have lead-acid batteries to power their electrical systems. It is estimated that 90% of lead production is supplied to the automobile industry as lead-acid vehicle batteries. More than 40,000 metric tons of lead is sent to landfill and wasted annually (Beliveau *et al.*, 2010). An overview of various battery types and environmental characteristics is illustrated in Table 5.1.

Ni-MH, or sodium-nickel- chloride batteries are widely used in BEVs for on-board supply. Li-ion batteries are now significantly developed and utilised in HEVs (Armand *et al.*, 2008). The major reasons for this increase are the favourable material characteristics of lithium, as it is a light metal and offers great electrochemical potential, which results in high power and energy density. In addition, lithium-ion batteries have been used as a power supply for a range of portable electronics in the market (Ward and Brownlee, 2000).

5.6.2 Battery recycling

The significantly increased price of oil results in the growing interest in renewable energy and the introduction of alternative fuel vehicles. Li-ion and NiMH batteries are widely utilised as effective energy storage devices in HEVs and EVs (Canis, 2013). Sulivan *et al.* (2011) have researched the role of recycling in the life-cycle of batteries. Additionally, Dunn *et al.* (2012) have worked on assessing the impact of recycling on cradle-to-grave energy consumption and greenhouse gas emission of automotive Li-ion batteries. Regarding EoL of lithium batteries,

Table 5.1 Overview of battery types and chemistries (adapted from Armand and Tarason, 2008).

Battery type	Features	Environmental impacts
Ni-MH (established)	Low voltage, moderate energy density, high power density Application: portable, large-scale	Nickel is toxic and difficult to extract, and limited recyclability
Lead-acid (established)	Low energy density, low cost, and moderate power rate Application: large scale, start-up power, stationary	High-temperature cyclability limited; lead is toxic, but recycling is efficient to 95%
Lithium-ion (established)	High energy density and high cost Application: portable, possibly large-scale	Lithium chemistry is relatively sustainable; recycling is feasible but with an extra energy cost
Zinc-air (established)	Medium energy density, high power density Application: large-scale	The smelting of Zinc is not sustainable
Lithium-organic (future)	High capacity, high energy density and limited power rate Applications: medium/ large-scale	Rechargeable and easy to recycle; Excellent carbon footprint
Lithium-air (future)	High energy density, limited energy efficiency Applications: large-scale, preferably stationary	Rechargeable and easy to recycle Excellent carbon footprint
Magnesium-sulphur (future)	Predicted: high energy density; power density unknown, cycle life unknown	Magnesium and sulphur are sustainable and recyclable Small carbon footprint
Al-CFx (future)	Predicted: moderate energy density, power density unknown	Aluminium and fluorine are sustainable but not recyclable
Proton battery (future)	Predicted: all organic, low voltage, moderate energy density, power density unknown	Sustainable, biodegradable

research work has been carried out looking into using organic acid as leaching reagents for the recovery of metals from spent Li-ion batteries (Li *et al.*, 2013).

5.7 Review on printed circuit boards

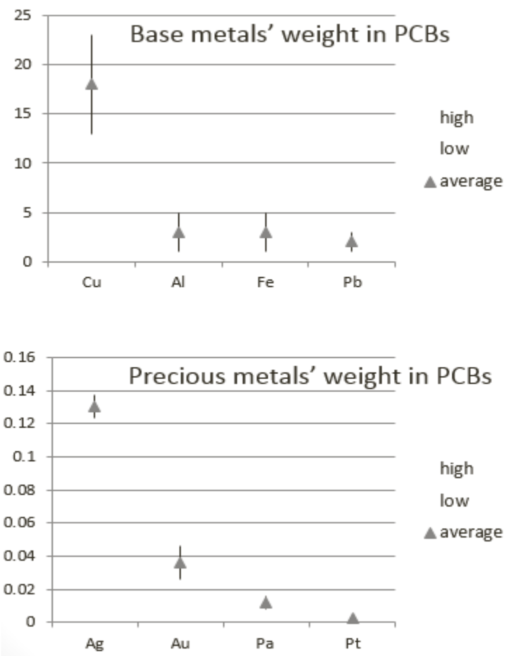
PCBs, as an integral part of most of the electronic systems, are commonly found in consumer electronics, military applications and medical equipment. As a core element in all electronic units, the proportion of waste PCBs is about 3% of electronic waste (Dalrymple *et al.*, 2007). PCBs consist of a diverse range of valuable materials (Leungl *et al.*, 2006; Wang and Gaustud, 2012). In the last decades, both physical and chemical technologies and processes have been applied for recycling waste PCB for material recovery (Rao, 2006).

5.7.1 Material composition of PCBs

A number of studies have been carried out on investigating PCB compositions (Das *et al.*, 2009; Guo *et al.*, 2011; Veita *et al.*, 2006; Park and Fray, 2009; Vasile *et al.*, 2008; Ogunniyi *et al.*, 2009, Wang and Gaustud, 2012). Based on the research results from the literature, the general PCB composition is shown in greater detail in Figure 5.2. More than twenty different materials are incorporated in PCBs, including PMs (i.e. gold, palladium, platinum, etc.), base metals (i.e. copper, aluminium, etc.), toxic metals (lead, cadmium, arsenic, mercury, etc.) as well as ceramics and plastics. Wang and Gaustad (2012) reported the representative composition based on PCBs from a variety of products and stated the great value of PMs in both informal and formal recycling and recovery processes.

5.7.1 Recycling and recovery methods of PCBs

Waste PCBs are one of the most arduous tasks to deal with because of its heterogeneity and high complexity due to the WEEE that they are encompassed by BIO Intelligence Service (2013). Key players in the recycling process include the PCB manufacturers, OEMs, end-users, disposal contractors, dismantlers and recyclers (Sohaili et al., 2012; Luda, 2011). The detailed relationship between those players is shown in Figure 5.3. Currently, there are two types of PCB recycling approaches regarding the types of material recovery process and methods as shown in Figure 5.4 (Mathieux et al., 2008; Chancerel et al., 2009; Luda, 2011).



Rare metals	Average
Ga (Gallium)	0.0035±0.001
Ta (Tantalum)	0.0172±0.001
Hazardous	**Average**
Pb (Lead)	2.0441±0.025
Zn (Zinc)	1.2213±0.05
Ni (Nickel)	1.2585±0.05
Sb (Antimony)	0.338±0.025
Mn (Manganese)	0.125±0.025
Mg (Magnesium)	0.1555±0.075
Bi (Bismuth)	0.0865±0.03
Cr (Chromium)	0.035±0.025
Cd (Cadmium)	0.0216±0.05
Ba (Barium)	0.02±0.001
As (Arsenic)	0.007±0.001
Be (Beryllium)	0.0038±0.005
Hg (Mercury)	0.0006±0.001

Figure 5.2 Metals' weight in PCBs (wt %) (adapted from Guo et al., 2011; Duan et al., 2011; He et al.,2006 ; Veit et.al., 2005; Goosey and Kellenr, 2002a; Park and Fray, 2009; Vasile et al., 2008; Ogunniyi et al., 2009; Wang and Gaustud, 2012).

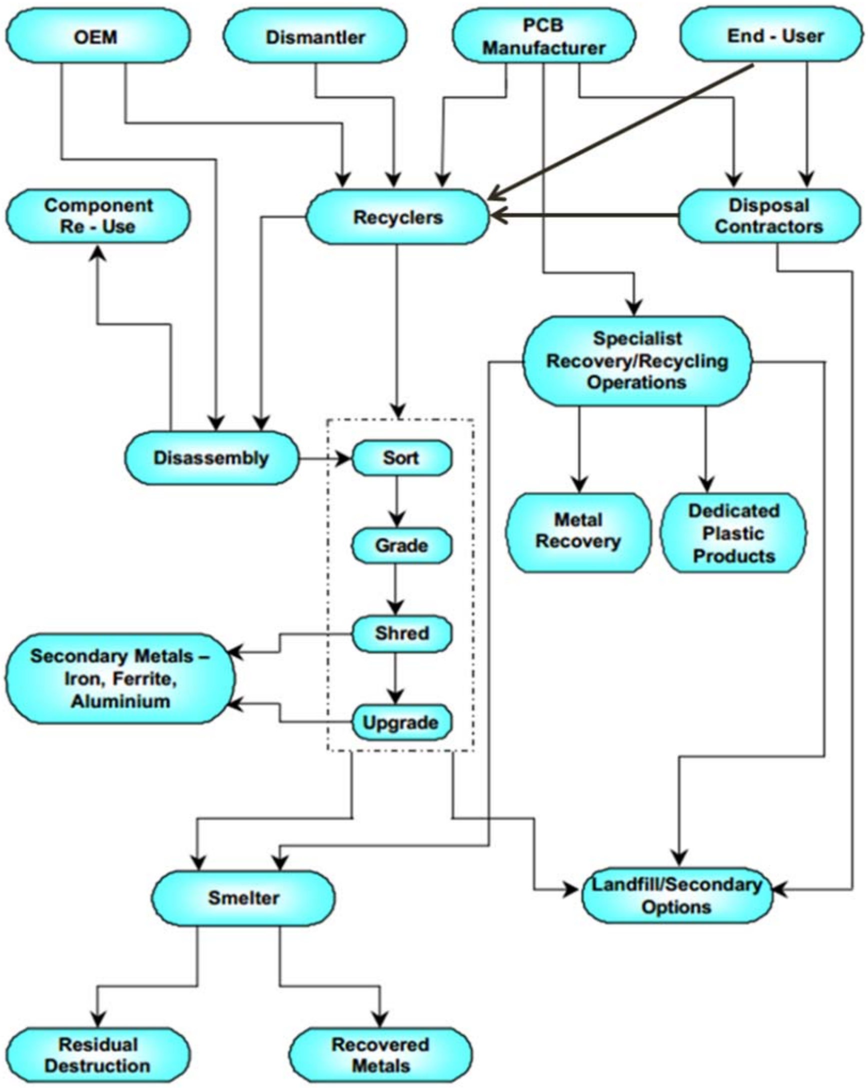


Figure 5.3 Recycling processes of PCBs (Goosey and Kellner, 2002b).

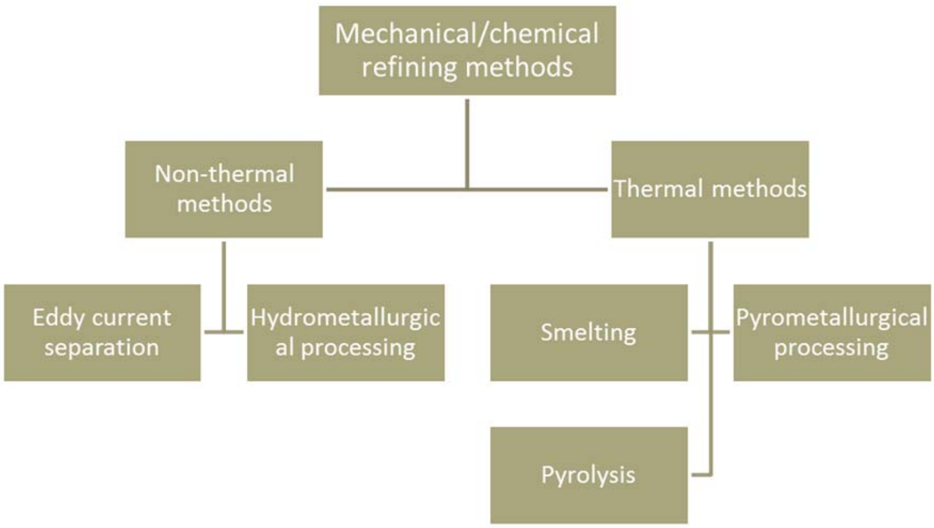


Figure 5.4 Recovery methods for PCBs (adapted from Mathieux et al., 2008; Chancerel et al., 2009; Luda, 2011).

5.7.2 Economic analysis of PCB recycling

In order to estimate the economic viability of EoL PCB recycling, there is a need to investigate the value of materials contained in PCBs. Materials prices can be collected from a range of organisations, including London Metals Exchange (LME), American Metal Market (AMM), United States Geological Survey (Goonan, 2011) and the Global Scrap, a scrap trading website (Wang and Gaustud, 2012). It should be noted that there is a tendency for metal prices to increase over time (sometimes due to the scarcity of materials) where recycling and recovery activities for processing these materials will be highly motivated. The metal contents and corresponding values in the PCBs are shown in Table 5.2. In addition, the measurement of material values is a highly liberal standpoint; therefore it involves a degree of uncertainty. Table 5.3 indicates the prices of the materials that are recovered from PCB waste (Cucchiella et al., 2015; Bizzo et al., 2014). Overall a better economic representation for the value of PCBs would be to investigate the secondary or recycled metals prices; however, this information is not readily available.

5.8 Review on rare earth materials and precious metals

Triggered by global economic growth and technology development, the demand for metals has increased drastically in recent times. Furthermore, the exclusive use of specific, low quantity

Table 5.2 Metal contents and intrinsic values in PCBs (Flandinet *et al.*, 2012)

Metals	Composition (g/Kg)	Metal value* (€/Kg)	Intrinsic value
Ni	2.17	16.38	0.04
Cu	255	6.50	1.66
Au	0.632	33020.52	20.87
Ag	0.306	672.04	0.21
Fe	2.61	0.11	0.003

* Metal values are based on 2010 Market Values.

Table 5.3 Materials market price (€/kg) (Cucchiella et al., 2015; Bizzo et al., 2014).

Materials	€/kg		Materials	€/kg		Materials	€/kg	
	σ	μ		σ	μ		σ	μ
Aluminium	1.5	0.2	Gallium	180	12	Selenium	42	17
Antimony	7.6	0.4	Glass	0.05	0.01	Silicon	1.7	0.3
Arsenic	1.4	0.4	Gold	34,070	4665	Silver	514	58
Barium	550	95	Indium	550	84	Steel/Iron	0.12	0.02
Beryllium	864	201	Lanthanum	7.8	0.5	Tantalum	156	27
Cadmium	1.5	0.2	Lead	1.7	0.3	Tellurium	90	15
Cerium	8.6	2.9	Mercury	90	8.5	Terbium	641	29
Chromium	1.7	0.2	Molybdenum	21	3	Tin	17	2.3
Cobalt	25	0.2	Neodymium	72	4.8	Titanium	11	2.9
Copper	5.2	1.3	Nickel	14	1.3	Tungsten	71	29
Dysprosium	266	147	Palladium	23,214	4806	Vanadium	20	3.4
Europium	781	237	Plastics	1.2	0.08	Yttrium	47	5.6
Ferrite	0.12	0.02	Platinum	37,607	4343	Zinc	1.7	0.1
Gadolinium	104	5.4	Praseodymium	117	19			

σ=average value; μ=standard deviation.

resources may lead to the critical situation of significantly reduced the availability of raw materials. Thus, the serious concerns about the so-called ‘critical metals’ have begun to emerge.

Due to the unique mechanical, chemical, electrical, magnetic and luminescent characteristics of SIMs they have become critical elements in modern age technological applications. In addition, emerging technologies have often resulted in the increased demand for critical raw materials, such as those in the fields of advanced, green and military technologies. Most application fields of rare earth materials are the green technologies. The concept of ‘green technologies’ indicates these technologies contributing to environmental protection in terms of the utilisation of renewable energy, the reduction of energy consumption and control of air emissions. The major applications of rare earth materials are typically magnets, catalysts, polishing, glass, ceramics and lighting (see Table 5.4).

Table 5.4 Rare earth materials and their applications (adapted from U.S. DOE, 2011; EPA, 2012).

Rare Earth Element	Common applications
Scandium (Sc)	Metal alloys for the aerospace industry.
Yttrium (Y)	Ceramics; metal alloys; lasers; fuel efficiency; microwave communication for satellite industries; colour televisions; computer monitors; temperature sensors.
Lanthanum (La)	Batteries; catalysts for petroleum refining; electric car batteries; high-tech digital cameras; video cameras; laptop batteries; X-ray films; lasers.
Cerium (Ce)	Catalysts; Light Emitting Diode (LED); metal alloys; lens polishes (for glass, television faceplates, mirrors, optical glass, silicon microprocessors, and disk drives).
Praseodymium (Pr)	Ni-MH batteries; fibre-optic cables; improved magnet corrosion resistance; pigment; searchlights; airport signal lenses; photographic filters.
Neodymium (Nd)	Colour glass; high-power magnets for laptops, lasers, fluid-fracking catalysts.
Promethium (Pm)	Beta radiation source, fluid-fracking catalysts.
Samarium (Sm)	High-temperature magnets, reactor control rods.
Europium (Eu)	LCDs, fluorescent lighting, and glass additives.
Gadolinium (Gd)	Magnetic resonance imaging contrast agent, glass additives.
Terbium (Tb)	Phosphors for lighting and display.
Dysprosium (Dy)	High-power magnets, lasers.
Holmium (Ho)	Highest power magnets.
Erbium (Er)	Lasers, glass colourant.
Thulium (Tm)	High-power magnets.
Ytterbium (Yb)	Fibre-optic technology, solar panels, alloys (stainless steel), lasers, a radiation source for portable X-ray units.
Lutetium (Lu)	X-ray phosphors

Another group of important materials are widely used as catalysts in various industries due to their specific physical and chemical properties (Ramesh *et al.*, 2008). Due to the high value of precious metals, they provide economic incentives for recycling activities (Hagelüken and Meskers, 2010). Most PMs are applied in 'green tech' or 'clean tech' products with increased demand growth, however, they are also often used in general EEE worldwide. They are viewed as critical metals because of their supply security, high value and greater exclusive properties than other materials. However, the minor concentration in complex and multi-metal products is one of the largest difficulties in the recycling process of these materials. Common applications of PMs are illustrated in Table 5.5.

5.8.1 Materials in magnets

According to the research results carried out by Zhong *et al.* (2010), about 20% - 30% of rare earth magnets are scrapped in production processes. Because rare earth magnets are fragile and brittle, they can fracture easily (EPOW, 2011; Oakdene Hollins, 2010). The high value of rare earth materials makes the recovery economically attractive from both pre-consumer and post-consumer scrap (Dent, 2012). The possible recycling approaches for these scrapped materials are summarised by Oakdene Hollins (2010), with the first involving a re-melting and recovery process; this, however, has relatively low output levels. Essentially the rare earth in the state of oxide can be recovered, but this brings about a lower embedded value.

In terms of chemical approaches, applying magnesium chloride as an extracting agent is useful to selectively extract Nd and Dy from the mixture scrap (Shirayama and Okabe, 2009). In addition, the recovery of Nd oxide alone is also possible; it can be achieved through using Na_2SO_4 double-salt precipitation and oxalate secondary precipitation (Tang *et al.*, 2009)

Table 5.5 Common applications of PMs (Hagelüken and Meskers, 2010; Ad-hoc Working Group, 2010).

Precious metals	**Common applications**
Ruthenium(Ru)	Electronics (hard disk drives) and process catalysts/ electrochemistry, pharmaceuticals, super-alloys, photovoltaic
Rhodium(Rh)	Auto catalysts, fuel cells, electronics, glass, ceramics and pigments
Palladium(Pd)	Auto catalysts, medical/dentistry, electronics, glass, ceramics and pigments
Silver(Ag)	Electronics, industrial applications (catalysts, batteries, glass/mirrors) and jewelry, Radio Frequency Identification (RFID), lead-free soft solder
Osmium(Os)	Catalyst, minor industrial applications
Iridium(Ir)	Electrochemistry, crucible (for mono-crystal growing) and spark plugs
Platinum(Pt)	Auto catalysts, pharmaceuticals, medical/dentistry, fuel cell, electronic, glass, ceramics and pigments
Gold(Au)	Most in jewelry and some in electronics

Separation processes can also be based on electrical reduction (Zhang *et al.*, 2010), milling and re-sintering (Zakotnik *et al.*, 2009) and pyrometallurgical and hydrometallurgical methods. It has been claimed by Hitachi Ltd. that they have developed a machine to extract the rare earth materials from discarded electric devices (Clenfield and Shiraki, 2010).

5.8.2 Materials in lighting and luminescence

An overview of the recycling and recovery approaches has been carried out by Mei *et al.* (2009). They noticed that Otto and Wojtalewicz-Kasorzak (2009) developed a method to recycle yttrium and europium from fluorescent lamps in six steps. Also, that TV tubes and computer monitors can be the raw resources from the extraction and recovery of yttrium and europium (Rabah, 2008; Resende and Morais, 2010).

5.8.3 Materials in battery

According to the research by Japanese JOGMEC's Metals Mining Technology Group (2013), the technology of recovery mixed metal, nickel and cobalt are developed for the waste Ni-MH batteries in the hybrid electric vehicles. Also, as pre-separation, the possible extraction of the rare earth materials can be achieved through smelting operations, pyrometallurgical treatments or leaching with sulphuric acid (Gao, 2010).

5.8.4 Materials in catalysts and other applications

There is uncertainty in the economic feasibility of recycling of REEs (mostly lanthanum) from Fluid Catalytic Cracking (FCC) catalysts. The reclaiming of rare earth materials such as neodymium and dysprosium is conducted by the Japanese company Kosaka Smelting and Refining (Sekiya, 2010).

In summary, it is known that most recycling technologies for REE and many other critical materials are in lab scale, and rare in larger industrial practices. It results from the drawbacks of high cost and relatively low output during the initial recycling activities. In theory, the recovery activity is an energy intensive process and involves a mixture of chemical and mechanical treatments. In order to achieve the economic viability, several constraints need to be taken into account. In addition, there is a difficulty in transportation processes over large distances due to the magnetic property interfering with the aircraft instruments. The possibilities of export to other countries may block the implementation of urban mining. Most of the recycling activities involved in the separation and dismantling processes are energy intensive and expensive. Another issue during the recycling of REE is that due to their minor proportions in the products, when they are initially mechanically treated i.e. shredder, they may become significantly entangled with other material causing the REE not to be efficiently extracted and therefore lost.

5.9 Other considerations in line with EoL vehicle recycling

5.9.1 Economic considerations

With the introduction of relevant legislations and directives relating to vehicle recycling and recovery, there is an increasing need to have a sound understanding of the recycling and recovery chain and associated economics to support decisions on investment and selection of appropriate recycling and recovery processes (Coates and Rahimifard, 2008). The study by Coates and Rahimifard (2008) provided an overview of the stakeholders, their roles in the UK ELV recovery chain, and developed an EoL vehicle costing framework to facilitate increased value recovery. A holistic ELV cost model was developed to support both high and low level recycling and recovery decisions. It was stated that as a catalyst for sustainable development in ELV recycling, legislative requirement promotes the key stakeholders to make an investment in ELV industry but it not sufficient to achieve a long-term sustainable development. Therefore, the study indicated the importance of identifying economic rewards of ELV recycling for substantial environmental improvement within the sector.

In addition, a model has been developed by Farel *et al.* (2013) to undertake an economic analysis of ELV glazing recycling for individual value chain stakeholder and the whole network. A dynamics approach was proposed to model the economic performance of the recycling system under different scenarios. It is concluded that the application of the recycling system contributed to a significant increase in the profits and cost savings.

In order to estimate the economic benefit of the disassembly process, relevant studies have been carried out. Coulter *et al.* (1996) state that the separation is only economically viable in the case that the separation is time-efficient, or the value removal rate is high. Essentially, the value removal rate should be greater than the operation cost for a profit to be achieved.

Furthermore, another study carried out by Das *et al.* (2000), introduced a methodology to support and facilitate the economic analysis of disassembly operations. A multi-factor model was proposed to generate disassembly effort index (DEI) scores. This DEI scoring model can be utilised as an effective and efficient tool for the estimation of the disassembly effort and cost.

5.9.2 The application of automation

The modern assembly system is requested to be flexible and adaptive to increasing number and variety of products and changing demand volume. With the trend of automation, the automated disassembly is expected to increase the economic efficiency and profitability. However, automated disassembly is not as easy as the reverse of the assembly process. Unforeseen uncertainties and difficulties during automated disassembly can occur (Scharke, 2002). Currently, the most important factors in the application of automation are:

- Differences within product lines, automated disassembly systems have to deal with a great variety of different 'style' of the same products;
- Varying design and construction of products in general that due to the rapid development of new product types, material mixes and features, the design and construction vary considerably;
- Difference in product states: the unpredictable product conditions after the usage phase causes most of the uncertainties;
- The inadequacy of disassembly tools: usually the disassembly tools used to separate components are traditional standard assembly tools, in some cases; specially designed tools for disassembly operations are needed.

Reap and Bras (2002) have investigated the value of robotic semi-destructive disassembly for remanufacturing and recycling. The work carried out by Weigl-Seitz *et al.* (2006) gave an overview of re-usable, valuable modules from electronic devices using automated disassembly operations. A number of case study products were selected to demonstrate the applicability of the disassembly line.

An automatic cooperative disassembly robotic system has been developed to distribute tasks among robots (Torres *et al.*, 2009). Based on decision trees, the work cell can take the work area of each robot and its characteristics into consideration. Therefore, this automated work cell is capable of coordinating multiple robotic manipulators to undertake concurrent tasks.

In the past three decades, disassembly processes have gradually been applied in PCB recycling for material value recovery (Iji and Yokoyama, 1997; Kopacek and kopacek, 2002; Mou *et al.*, 2004). In addition, the initial application of automation was used in the removal of electronic parts in the PCB with thermal and mechanical treatments (Li et al., 2010). The semi-automated PCB disassembly system developed by Kopacek and Kopacek (2002) has the ability to disassemble different boards with only a few software modifications of the systems, it required a low investment cost and allowed for the extraction of some components without damage in an economic way.

A number of researchers have investigated a range of automated approaches for disassembly and improved concentration of valuable materials, prior to final recycling and refining processes. Duflou *et al.* (2008) have reviewed various disassembly practices and highlighted the importance of automation techniques as well as tooling and fixturing systems for flexibility and robustness of disassembly processes. In relation to this, research projects have also been proposed in employing robotic systems in the disassembly of electronic products. Knoth *et al.* (2001) have developed an intelligent robotic disassembly process which utilises a vision system to identify components for extraction and to remove the components based on simple robotic processes. Basdere and Seliger (2003) have explored the use of robots within a flexible disassembly and recovery line for large and small size electrical consumer devices. Vongbunyong *et al.* (2013) have also proposed the concept of 'cognitive robotics' for disassembly of LCD screens and TVs, utilising a vision system, and have highlighted further flexibility and configurability challenges to deal with multi-product designs. Wegener *et al.* (2015) have focused on disassembly of the batteries in hybrid vehicles and have proposed as their future work, the investigation into the use of robots in this application.

5.10 Critical assessment of relevant research

The review in Chapter 3 has identified that alternative fuel vehicles are seen as the one of the answers to the transport sectors problems of diminishing material resources and global environmental impacts. Studies have shown the range of potential benefits of alternative fuel vehicles compared to traditional ICE vehicles; including potential fuel saving, fuel economy, reduction of emission as discussed in Section 3.2.1. Additionally, the material composition and design of the automobile continues to change. Increasing numbers of electrical and electronic components and growing amount of SIMs and PMs have been contained in alternative fuel vehicles as detailed in Section 3.4.2 and Section 3.4.3. But those components and materials were not in the original design of traditional vehicles. Thus, the introduction of those alternative fuel vehicles brings recycling challenges in the future ELV recycling and recovery activities.

The review has also stated that the electrical and electronic components have brought efficiency and reliability to the components. However, the quantity and material compositions of these electronic components have changed to achieve the functional performance and met environmental requirements (as discussed in Section 3.4.3.3). Beside base metals, PMs and

SIMs are contained in these electronic components. It was clear that those new materials are distinguished from basic materials and normally valuable, rare and costly with very limited supply, as discussed in Section 5.8. In addition, these valuable materials are often presented in small quantities in the components and complexly linked to other materials. Therefore, there is a need to develop a new recycling technology and process for effective recycling and recovery of these materials.

An overview of current ELV recycling technologies and processes has been presented in detail in Chapter 4. The chapter identified a critical gap in current ELVs recycling processes, highlighting that automated disassembly can be a part of the recycling processes in order to maximise profitability and improve environmental performance. The expensive manual operations have limited the dismantling and disassembly processes in the recycling while automated dismantling and disassembly have been applied in other recycling practices to increase the operating efficiency and economic benefits, a number of case studies have been presented in Section 5.5.2 and Section 5.9.2. Thus, increasing automation could be a trend in future automotive recycling and recovery activities.

Currently, ELV recycling and recovery have been driven by the value recovery from used components and material recovery (discussed in detail in Section 5.9.1). It is clear that there is little to be gained by developing a new approach that will improve the recovery of specific targeted valuable materials unless that process is economically viable and technologically feasible. Therefore, technological feasibility evaluation also needs to be taken into consideration, and economic assessment for future EVs recycling processes is also required for the visualisation of the effect of various processes and their parameters that influence operational cost and revenues of the activities involved.

5.11 Chapter summary

The review carried out in this chapter has explored the relevant research associated with EoL management. It is clear that EoL management has a close link to design and manufacturing processes, and shows that environmental legislation and directives have placed emphasis on EoL management of products so that manufacturers are under pressure to meet stipulated recycling and recovery targets. However, the hidden economic impacts of EoL management should be identified and made use of in a better manner, such as understanding more clearly the value of carrying out recovery of PMs and REEs contained in electronic components using automated systems. Overall the complexity of the issues identified with relation to EoL management justifies the requirement for a framework to support further exploration of developing EoL management approaches for EV components. This framework is developed in Chapter 7, following an overview in Chapter 6 of the methodology adopted in carrying out the research reported in the thesis.

CHAPTER 6 RESEARCH METHODOLOGY

6.1 Introduction

This chapter details the research methodology adopted to conduct the research reported in this thesis. The chapter begins with a brief description of various approaches to research and a discussion of the key features and characteristics of those types. The second section outlines the methodology applied within this thesis. It begins by discussing the initial context of the research that helps generate the original research assertion. Once the scope and goal of the research have been identified, the framework is designed and developed. Then a detailed description of each stage is laid out.

6.2 Overview of research methodologies

Research is defined as "a careful, systematic investigation in some field of knowledge, undertaken to establish facts or principles or to find answers to a problem" (Grinnell and Unrau, 2010) and it has been stated that the purpose of the research is to use a systematic controlled, empirical and critical approach to investigate the propositions about the presumed relationships about various phenomenon (Kerlinger, 1986). Research activities can be classified in terms of five principal attributes that are represented in Figure 6.1 (Kumar, 2010; Kothari and Grag, 2014).

In terms of application, research can be classified in a number of ways, including as fundamental or applied research. Fundamental research may be concerned with an intellectual hypothesis or a formulated theory that may lack practical application at the present or in the near future. Also, fundamental research focuses on the development of an existing techniques, methods, theories or procedures through adding information to the existing organised body of scientific knowledge. In the case of applied research, the principal aim is to discover and identify a solution for some pressing practical problems in a specific situation. Following the definition of the research aim and objective in Chapter 2, it has been identified that the thesis will incorporate mainly applied research, since it collates information about a specific problem (namely EoL management of EVs), with an element of fundamental research, since it involves the development and refinement of the methodology which incorporates both existing procedure and novel techniques and tools.

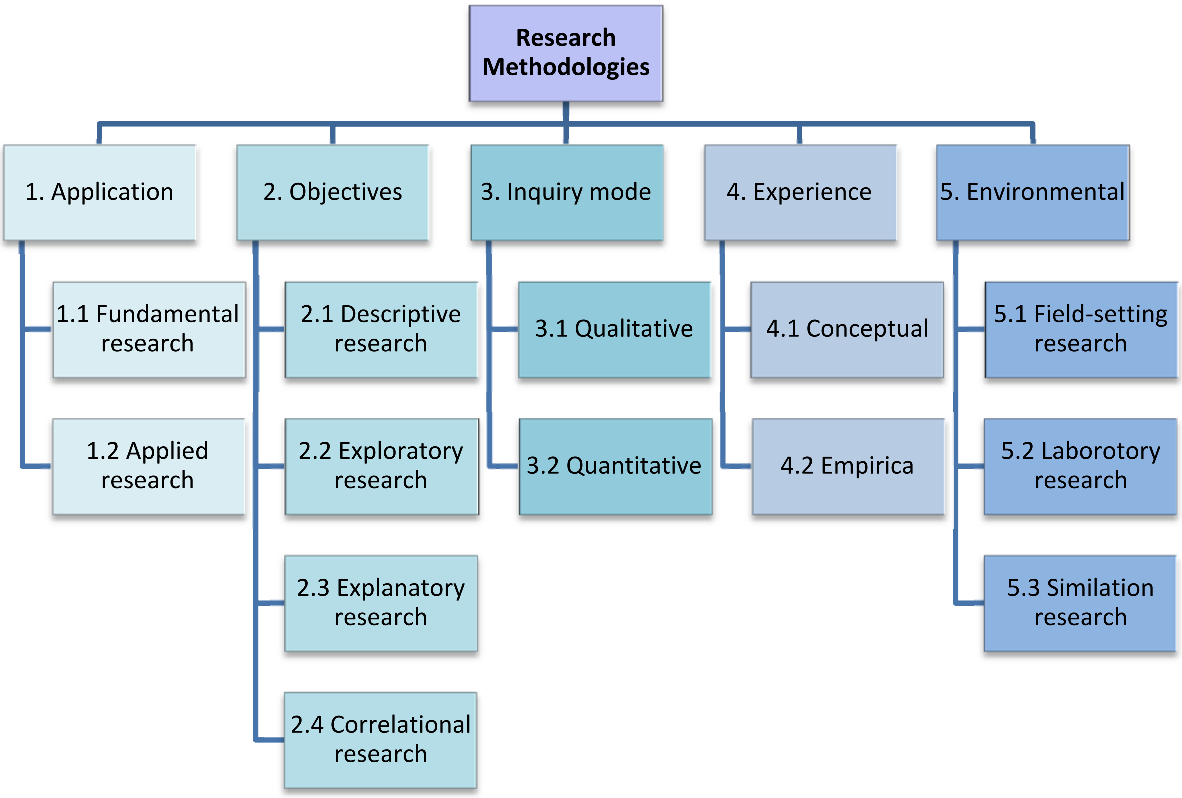


Figure 6.1 Overview of different research types (adapted form Kumar, 2010; Kothari and Garg 2014).

According to the attribute objectives, Kumar (2010) defines descriptive research as the research aims to systematically collect information to "describe what is prevalent". Exploratory research identifies the objectives' priority of testing for the refinement of existing procedures and tools. Additionally, explanatory research focuses on the explanation of how an association between two or more aspects of the situation being studied exists, while correlation research aims to prove or disprove the existence of the association.

Within the thesis, it is necessary to employ a research methodology encompassing a range of approaches, in order to address the objectives defined in Chapter 2. Descriptive research is required in order to develop a thorough understanding of the nature of EoL waste arising from EVs, relevant legislative requirements and existing recycling techniques for ELV management. Exploratory research is used in the definition of the research aims and scope, and it is also employed in the stage of validation and optimization of automated disassembly. Correlational and exploratory research is required in terms of the association between automation and disassembly, pre-concentration and recycling processes.

With regard to inquiry mode, qualitative research is concerned with the analysis of the variation in a qualitative phenomenon, situation or attitude under clear methodological principals. In addition, quantitative research, based on quantitative measurement, is applicable to phenomena that can be expressed in terms of quantities. Within the thesis, the emphasis is primarily on quantitative methods, such as the estimation of disassembly time, material concentration, and economic assessment, which are data based. Qualitative method is also required to analyse various factors when the quantitative measurement is not feasible or reliable.

Kothari and Grag (2014) further classify research type by experience. Conceptual research is concerned with some abstract ideas or theory, generally employed for new concept development and existing theory reinterpretation. Where research hypothesis is given, and research is based on experiments, observation and empirical studies, it is defined as empirical research. Within the thesis, empirical method is appropriate when proof of association of variables can be sought through experiments. Finally, another classification method is based on the environment in which the research is to be carried out. Research can be field-setting research or laboratory-based research or simulation research. And within the thesis, the research involves laboratory activities, such as manual disassembly and automated disassembly using robot arm.

Effective integration of these different types of research into a coherent methodology will provide a systematic approach to addressing the research aim and objectives defined in Chapter 2. This research methodology is described in Section 6.3.

6.3 Research methodology

This research is a hybrid integration of qualitative and quantitative methods. The experimentation of the disassembly is primarily quantitative methods, which are data driven. Qualitative methods will also be employed to evaluate environmental benefits, technological feasibility and economic impacts. The qualitative approaches are useful in supporting the development of the research in areas where data are unavailable.

In this context, the research methodology adopted in this thesis consists of four distinct stages: review and background, modelling and framework development, testing and validation of the research concept along with the research conclusion. These stages together with a series of steps and actions that are necessary to carry out the research in an effective way are illustrated in Figure 6.2.

It begins with the initial exploration involved with setting the research assertions and hypothesis, and the refinement of the hypothesis into specific aims and objectives. These were

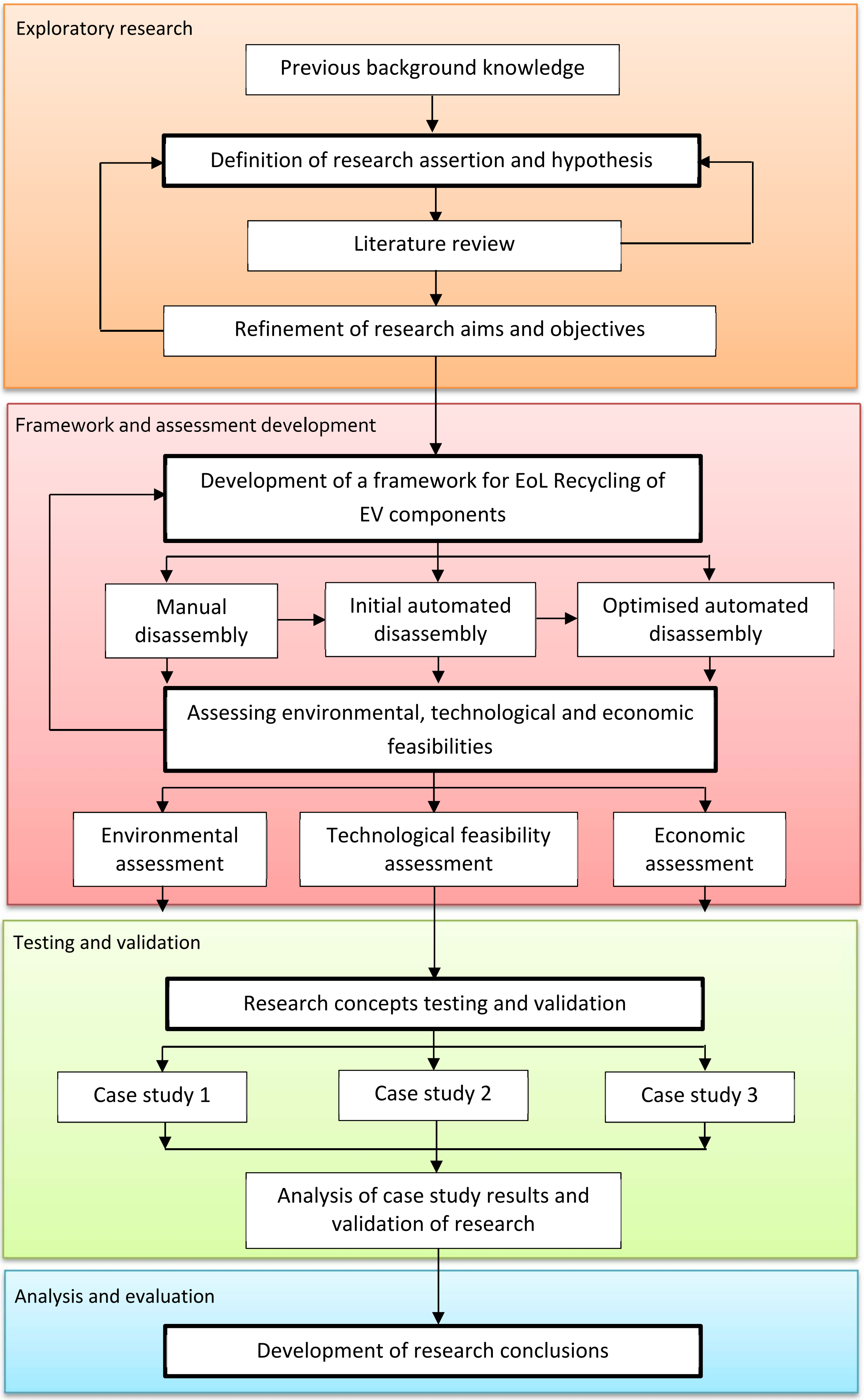


Figure 6.2 Research methodology applied within the thesis.

formulated using the author's prior knowledge in the subject area, and further developed and refined through reviews of the related literature. To this end, a comprehensive literature review was conducted utilising literature research to understand vehicle evolution, EVs, automotive recycling and recovery technologies and processes, and relevant recycling studies. This investigation aided in understanding the shortcomings and challenges found with existing vehicle recycling approaches, as well as the opportunities for developing new future vehicle recycling technologies and processes, which provided the information on which the research work was developed. The additional knowledge gained from continuing literature review activities and practical experience informs the refinement of research assertion, specific aims and objectives.

Once the research assertion had been developed, the information gathered from the literature review was used to direct the work of the next development stage. The following stage focussed on further theoretical research in which framework and model for EoL EV recycling were developed. The first step of this stage was to develop concepts for the framework using the findings from literature review and objectives laid out. Based on the research objectives and review findings, robotic automation is embedded into the research as a flexible approach to extract and pre-concentrate materials from components or subassemblies. A three-stage automated approach was designed and developed. It involves an initially manual disassembly that is performed in order to explore component design and material content and to identify an initial process plan for robotic disassembly procedures. The second stage utilises this initial plan to disassemble the component, using the robotic cell, and to identify the operating limits of the robotic arm during the disassembly process. The information and knowledge from this second stage was used in the final stage to validate and optimise the robotic disassembly operations.

This phase of research also required the consideration of sustainability in assessing EoL management option for EV components in which technological feasibility replaced social impacts. Therefore, environmental, technological and economic aspects are employed as key factors in this multi-criteria consideration. This Environmental, Technological and Economic (ETE) feasibility assessment is valuable for assessing individual performance characteristic while the potential benefits of a methodology for amalgamating these three individual assessment results are identified in supporting decision-making in a user-friendly manner. Additionally, the comparison of ETE feasibility assessment of different EV components can be achieved by combining the normalised results from the individual evaluation method into a single representation of overall performance.

The third testing and validation phase of the research involves testing and refining of the framework for EoL EV framework using three case studies. The case study products were selected to test three different applications of the framework, and companies with different component constructions and material recovery values. The first demonstrates simple construction and a low value component. The second explores a component with medium complex construction and high recovery value. The third one focussed on a component with relatively low potential value but complex construction. These case studies were conducted using a systematic application of the framework approach.

The final and fourth stage is the evaluation phase of the research reported in this thesis, involving the analysis of results and findings from the research activities and case studies, to draw concluding discussion and overall conclusions, identifying areas for further research and development in future vehicle component recycling practices.

Although the methodology presented in Figure 6.2 suggests a linear progression through the four stages defined in this section, it is acknowledged and understood that the research has many other facets, thus feedback loops across each stage have been implemented to develop and further refine the research as it was carried forward.

6.4 Chapter summary

This chapter discussed various types of research and identified the research methodology utilised in this thesis to address the research aim and objectives identified in Chapter 2. Following the general overview, four main stages of research have been illustrated in chronological and schematic order, although due to the iterative nature of the research, some specific aspects may need revisiting and refinement. The research supported by the first phase of the methodology is reported in the earlier part of the thesis, in Chapters 1 - 6. The following sections of the thesis will address the framework and assessment development, testing & validation, and evaluation phases throughout Chapter 7 - 9. The final sections will detail the case studies in Chapter 10, and the concluding discussions and conclusions & further work in Chapter 11 and Chapter 12, respectively.

CHAPTER 7 A FRAMEWORK FOR END-OF-LIFE MANAGEMENT OF ELECTRIC VEHICLES

7.1 Introduction

In this chapter, a three-stage framework for EoL management of EVs is presented. An overview of this framework and its relationship to the waste management hierarchy, pre-concentration and automation are discussed in the initial section. The later sections of this chapter described the specific considerations in the first stage of the framework. The second and third stages of the framework are discussed in Chapter 8 and Chapter 9 respectively.

7.2 The specific requirements for a structured approach to recycling of electric vehicles

Current innovative technologies and processes of ELVs management are primarily motivated by economic benefits, based on the capabilities and availability of the technologies and facilities. Nowadays, the introduction of new vehicle types, EVs, requires novel recycling and recovery methods due to their different components and material constitution. Increasing amounts of electronic products and components are embedded in EVs which would change the composition of existing material streams in both ecological and economic aspects. The reclamation of the PMs and SIMs that are represented in small quantities may generate new economic incentives for automotive recyclers. Furthermore, hazardous materials used in PCBs may pollute the material stream that influences the economic viability of recycling and recovery activities. Thus, there is a need to evaluate the EVs components through collecting and analysing information that is required for the development of further recycling methods.

Both driven by the legislative requirements and economic incentives, there is a need to improve the material value recovery and minimise the environmental impact in the EoL management of EV components. Based on the previous review, automated disassembly has been proposed as a novel approach for future EVs recycling and recovery. The dismantling process has seen a terminal decline as components have become electronically integrated, making them difficult to remove and replace. Moreover, the profit margins of separating material streams are dependent on material purity and contamination levels. However, it is noted that the automated robotic disassembly of components has never been attempted by the majority of EoL vehicle recycling and recovery activities. This research, therefore, aims to improve the pre-concentration process through robotic disassembly processes to reduce disassembly time and cost, and improve recycled material purity.

The EoL management solution for EVs is developed in the context of the waste management hierarchy, aiming to reduce waste at source, improve the feasibility of reuse and conduct recovery and recycling in a more efficient way (to achieve the maximum economic benefits from products and generate the minimum amount of waste). Figure 7.1 illustrates a schematic of the waste management hierarchy developed within the research, which addresses the connection with the EoL management solution.

The minimisation of the EoL waste is influenced by the design that determines the product characteristics and material selection. The general ELV recycling flow has been discussed in Chapter 4. The de-pollution aims to remove hazardous substances, such as fluids and airbag. Then recyclable and valuable components are dismantled for reuse as secondary products, reconditioning or remanufacturing, such as engines, EV batteries and other mandatory parts. Both of these two options require the consideration of the efficiency of the disassembly operations. Disassembly operations provides the potential of achieving a higher quantity and quality of material recovered prior to the downstream material recovery process, thus, the amount of associated residual waste can be reduced. Recycling and recovery activities consist of the segregation and purification processes, which aim to liberate different materials contained in the EoL products for further downstream processes. When the recovered material is resupplied for use in the original application, the process is called a close-loop scenario. Otherwise, the recovered material is supplied for a new application, which refers to an open-loop scenario. The last choice is the disposal of any non-recyclable fraction. At this stage, the separation of hazardous substances from a non-hazardous waste stream should be conducted before the shipment to the landfill from both ecological and economic perspectives.

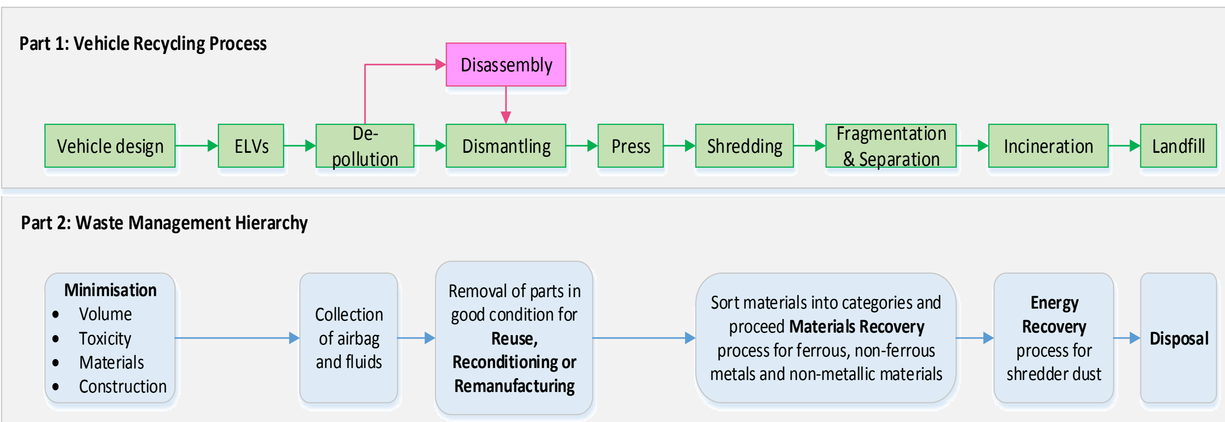


Figure 7.1 Relationship between waste management hierarchy and EoL management.

The above discussion highlights the need for a systematic approach for EoL management for EVs. They are included in a series of stages of a recycling process framework, which is developed in this research and are described in the following sections.

7.3 A framework of EoL management of electric vehicles

An overview of the framework developed to support EoL management of EVs, referred to hereafter as the EoL-EV framework is illustrated in Figure 7.2. The EoL-EV framework has been established in a four-stage procedure with a modular structure. It should be noted that the dismantling of the EV components is not within the scope of this research. Dismantling refers to the process of removal of components from the vehicle prior to disassembly.

The initial stage is **defining challenges** in EoL management of EVs, involving the identification of the EoL characteristics of the product stream, the analysis of the existing recycling technologies and relevant legislations. To support this, components of interest are identified and then classified into different groups according to their physical structure and recovery value.

A three-step **disassembly approach** is developed in the second stage of the framework, which consists of non-destructive manual disassembly, initial automated disassembly and the validation and optimisation process. The EV components are undertaken through this three-step disassembly process.

In the third stage of the framework, three factors are combined as a multi-criteria **decision support** tool for future EV recycling, taking environmental, technological and economic performance of robotic disassembly into consideration. The individual stages of the framework are described in more detail in the following sub-sections: the remaining of Chapter 7 details Stage 1 of this EoL-EV framework, while Stage 2 and Stage 3 will be outlined and discussed in Chapter 8 and Chapter 9, respectively.

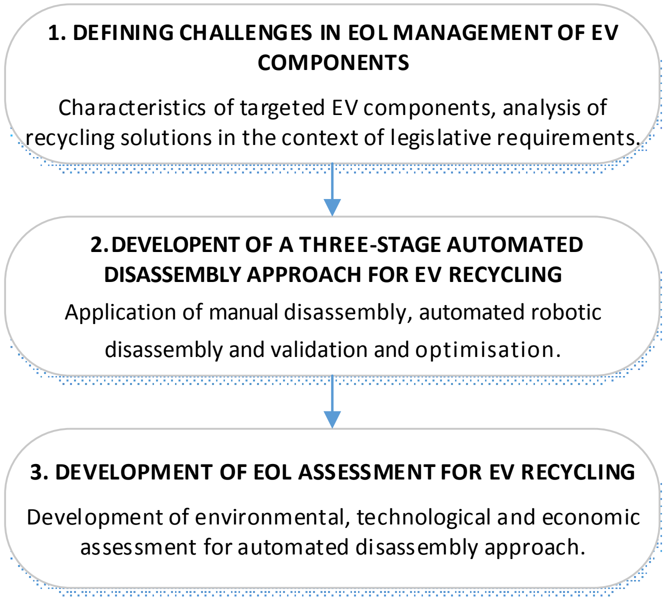


Figure 7.2 The three stages in the EoL-EV framework.

7.3.1 Stage 1: Defining challenges in EoL-EV framework

The first stage of the framework is all about gathering information. In this stage, research and analysis are undertaken on a range of topics relevant to EoL management of EVs (see Figure 7.3). Characterisation of EoL EV components (i.e. design features and material composition) are considered relevant to the development and evaluation of EoL options. In addition, based on review results, the feasibility of existing EoL vehicle recycling technologies and processes is assessed for EoL management of EV components. After analysing the target components and recycling techniques, relevant legislative constraints and requirements are investigated. Finally, in order to achieve the economic viability of the EoL EV recycling, there is a need to understand the economic performance of the EoL recycling scenarios and processes.

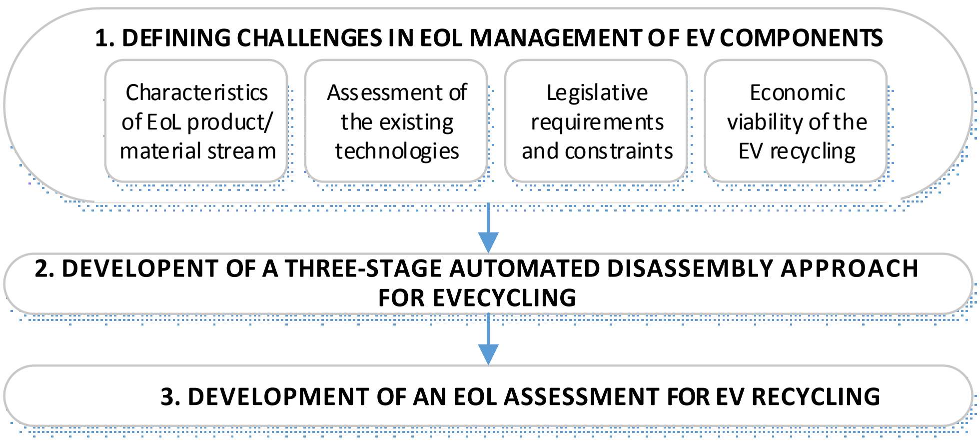


Figure 7.3 Stage 1 of the EoL-EV framework showing the definition of the problem.

7.3.2 Stage 2: Development of a three-step automated disassembly approach for EV recycling

In order to develop an EoL solution for EVs, an automated robotic approach for EVs recycling is proposed at this stage, as shown in Figure 7.4. Since EoL management of EVs is a largely unknown field, the second stage of the framework incorporates a significant portion of the research novelty of the thesis. Stage 2 is described in more detail in Chapter 8 within the thesis. As shown in Figure 7.5, non-destructive manual disassembly aims to analyse EV components, providing an understanding of the design and material characteristics, and identification of the disassembly depth and feasible disassembly methods required. Compared to costly, inefficient and time-consuming manual disassembly operations, semi-automated robotic disassembly is

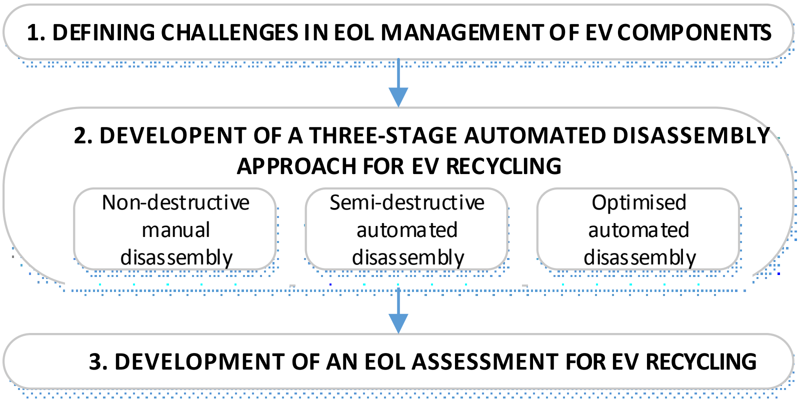


Figure 7.4 Stage 2 – Development of a three-step automated disassembly approach for EV recycling.

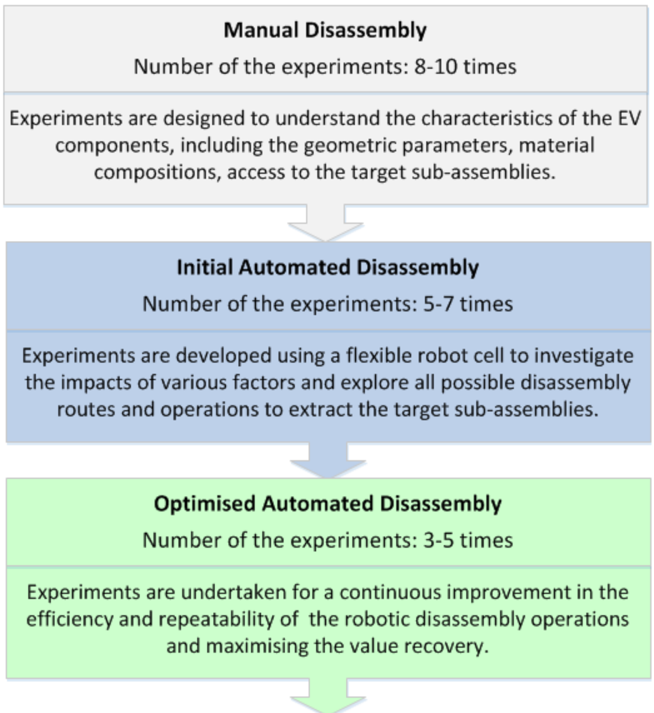


Figure 7.5 Visualisation of the steps in Stage 2.

developed and examined in this research. Based on a flexible work cell, an initial set of experiments aim to explore technical difficulties of automated robotic disassembly processes; investigating feasible disassembly strategies and plans, and evaluating the capability of the robot, tools and fixtures. Following the identification of all potential EoL scenarios, the framework requires the most promising scenario for each EV component to undertake validation and optimisation of automated disassembly processes. In the final step, feasible automated disassembly approaches are evaluated and optimised to achieve the optimal performance in terms of the cost-effectiveness, time, reliability and repeatability.

7.3.3 Stage 3: Development of an EoL assessment for EV recycling

In the final stage of the framework, the requirements of EoL management solution are based on ecological and economic performance, as well as the technological feasibility, as shown in Figure 7.6. These three aspects are evaluated individually before being integrated into one variable as a decision support tool for EV components recycling.

In this EoL-EV framework, ecological assessment is based on environmental impacts stemming from specific materials. The Reusability/Recyclability/Recoverability (RRR) method proposed by the European Commission Joint Research Centre has been adapted and applied in this research as a quantitative evaluation approach (Ardente and Mathieux, 2012). In addition, a simplified technological feasibility assessment has been carried out by comparing additional PMs recovery yield from disassembly processes to a shredding-based scenario. Disassembly data (i.e. disassembly time and cost) is utilised to assess different recycling scenarios for various EoL EV components. Furthermore, to ensure economic profit, a cost-benefit model is utilised to quantify the cost of implementing proposed disassembly processes and the recovery revenues generated from recovering valuable materials. Detailed information of its application in the EoL-EV framework is discussed in Chapter 9.

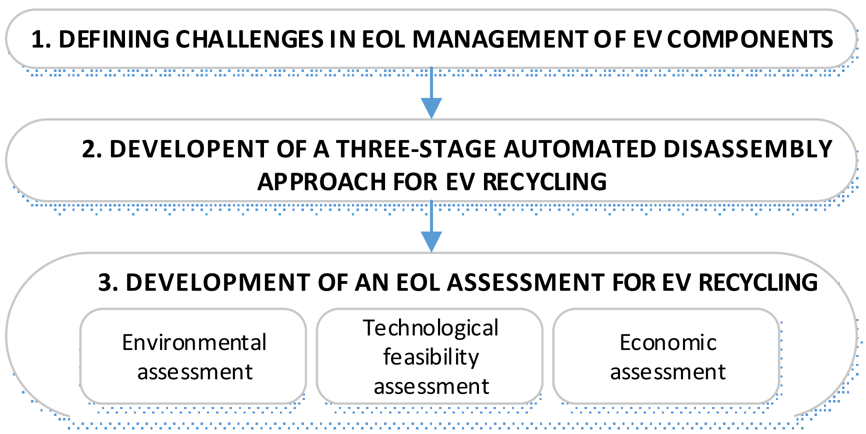


Figure 7.6 Stage 3 – Development of an EoL assessment for EV components recycling.

7.4 Overall interactions within the framework in detail

The determination of environmentally friendly, technologically feasible, and economically viable recycling methods for EoL EVs is a complex problem. It involves concurrent consideration of products and materials related EoL issues. Detailed illustration of the interconnection between sections is shown in Figure 7.7.

This research has identified the importance of product information in conducting appropriate recycling activities. Therefore, access to design information can facilitate product and material recycling for recyclers. The initial task concerns the development of a detailed definition of EoL management problem. This requires characterising EoL product design and associated material composition. According to specific product requirements, typical product design process turns conceptual ideas into tangible inventions and products. From this aspect, general information associated with product and materials contained is useful for EoL management, however, access to initial product design is often not known and this absence of available information is one of the biggest obstacles in adopting and developing effective EoL management solutions. In ELV recycling and recovery sector, the most mature approaches are currently designed and

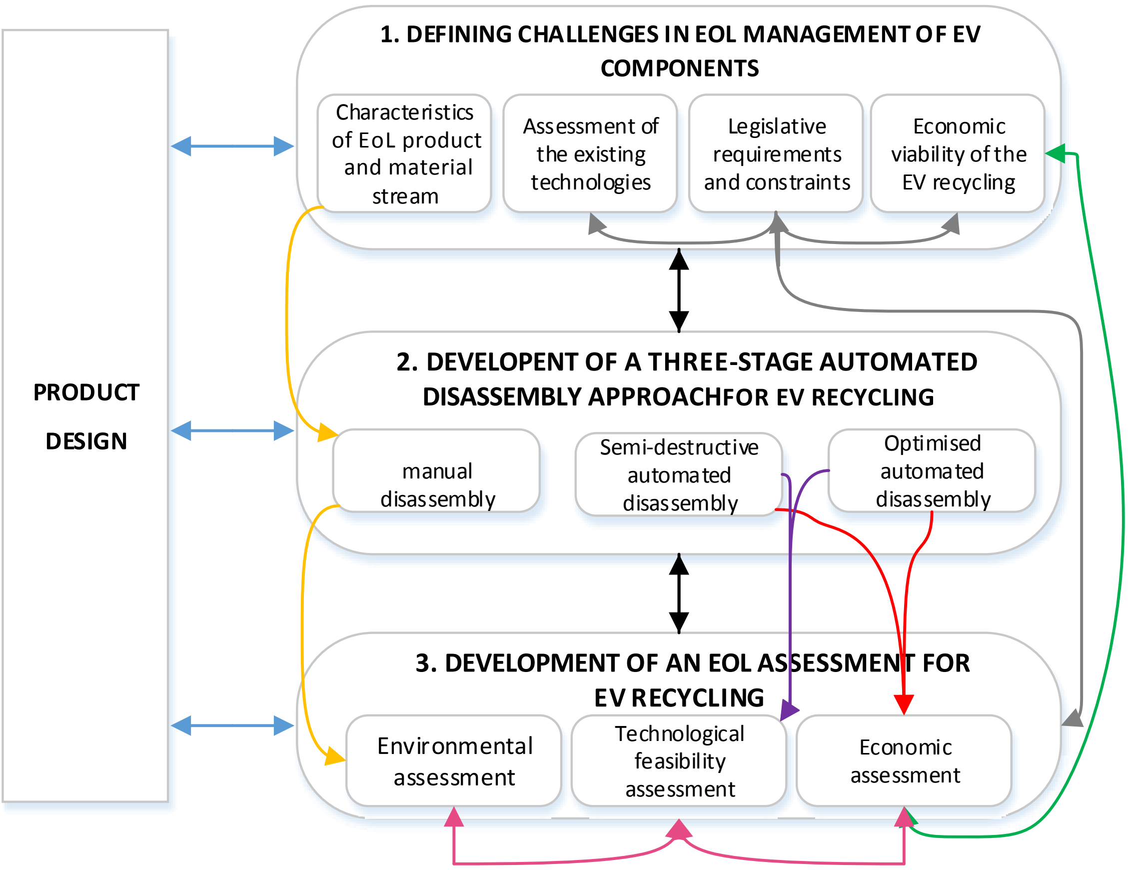


Figure 7.7 The interaction between various stages of EoL-EV framework.

developed for traditional ICE vehicles, without consideration of new EV components and materials and other emerging automotive technologies. Thus, understanding the differences between traditional ICE vehicles and EVs is useful through manual non-destructive disassembly processes. Conversely, the output from manual disassembly processes is valuable to identify and understand of EoL product and materials streams from EVs, which can be further used in design and development of semi-automated robotic disassembly processes for EV components.

In addition, the existing technologies and facilities used in current vehicle recycling processes have been discussed in Chapter 4. Within this research, the multi-critieria assessment sets a research boundary and fills in a research gap. The environmental benefits, technological feasibility and economic viability are the major concern for the EoL EVs recycling. In EVs, specific components that cannot use traditional recycling methods are identified and classified according to their design and recovery value.

Although general requirements can be defined from knowledge of environmental legislation, specific requirements are determined in relation to the characterised EoL stream. In some cases, legislation may forbid certain actions and set specific targets in EoL management processes; in other cases legislation may influence associated economic cost and benefits. Furthermore, the performance of EoL solutions in respect of environmental impacts needs to be taken into consideration in developing EV recycling approaches.

In terms of the automated robotic approach, the first stage involving manual disassembly of valuable parts and contaminating materials from EV components. These manual operations are beneficial for understanding product design concepts and the characterisation of the EoL products. Relevant information, such as disassembly sequence, disassembly time, material composition and tools used are collected and analysed. Based on the knowledge gained from the first step, the semi-destructive robotic disassembly is undertaken, which involves experimental set-up and investigating numerous operational parameters. After the exploration and development of all feasible automated robotic disassembly plans, the final stage is the validation and optimisation process. Different robotic disassembly plans, various accessing routes are explored and investigated for achieving the optimal performance, i.e. efficiency, reliability and repeatability.

Following the identification of feasible EoL disassembly processes, the framework requires these processes to be defined in sufficient detail for the multi-criteria evaluation. Three most commonly used parameters are selected to assess the overall performance, including environmental assessment, technological feasibility assessment and economic assessment. It is believed that specific legislative constraints and requirements motivate the development of innovative technologies in vehicle recycling and recovery processes. However, the economic benefit is often the greatest incentive to undertake ELVs recycling operations. In terms of EVs, as mentioned in Chapter 3 and Chapter 4, the new components and materials contained in EVs may change the environmental and economic performance of recycling activities. Therefore, there is a need to reconsider the existing vehicle recycling methods and develop most appropriate recycling and recovery option for EV components.

The environmental assessment is used to obtain a quantitative evaluation of environmental impacts in different EoL cases. Furthermore, one of the greatest interests of this research is the evaluation of technological feasibility, including their efficiency, repeatability and reliability. Additionally, a cost-benefit model is developed to quantify the cost of implementing robotic disassembly and associated revenues generated from the recovery of valuable materials. There are interconnections between these parameters, for example, in order to be compliant with legislation to protect the environment, investment is required to develop new recycling techniques and processes. Conversely, the implement of advanced recycling technologies can minimise the environmental impacts and increase the economic revenue from recycling and recovery activities.

7.5 Defining challenges in EoL management of EV components

The first stage of the EoL-EV framework is to define the challenges in EoL management of EV components as described in Section 7.3.1. This is achieved by focusing on four specific considerations which are illustrated in Figure 7.8 and discussed in following sections.

7.5.1 Characteristics of EoL product and material stream

The EoL stream can be defined in terms of the macroscopic and microscopic features. Macroscopic characteristics refer to the product design itself, such as the construction, while the microscopic characteristics relate to the fundamental constitution of the product, such as material composition.

The increasing electrification in automotive industry implicates the demand of understanding EV components. The increased use of integrated electronics within the components, and the increasing sophisticated techniques using electronic parts make the vehicle recycling more complicated. Further complications for vehicle recycling arise due to the material composition

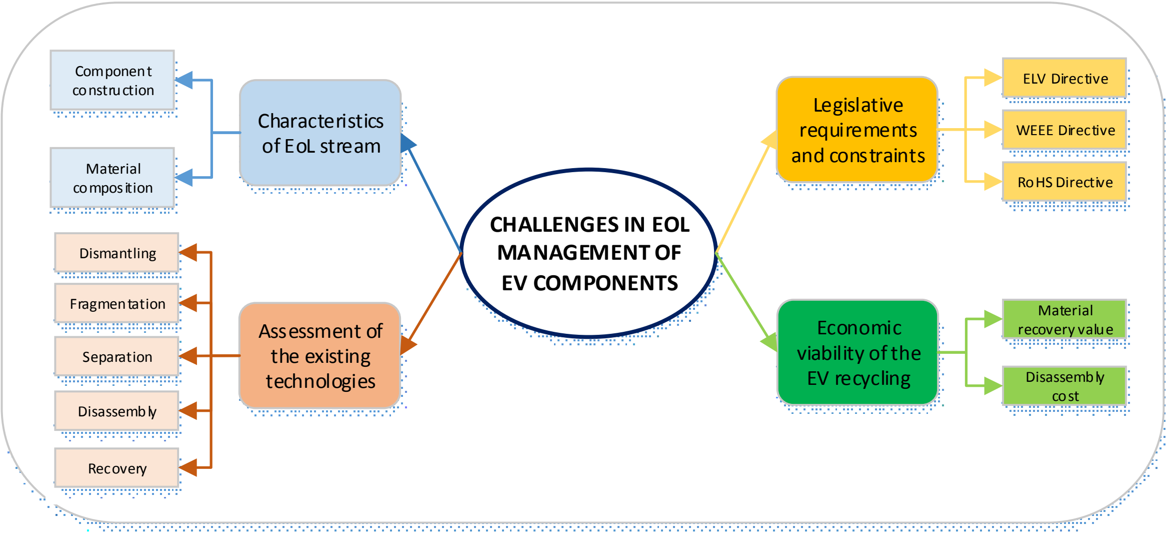


Figure 7.8 Stage 1: Defining the challenges in EoL-EV framework in detail.

changes for weight reduction or other specific functionality requirements, and vehicle component changes for better performance and driving experience. Therefore, there is a need to investigate the knowledge and identify the targeted EV components and materials, especially when they reach the EoL stage.

Within the first stage of the EoL-EV framework, the following specific aspects are discussed:

a) Component construction

- Identifying of the target components of EVs
- Classifying of component construction

b) Material composition

- Identifying and quantify material presented in the target components
- Identifying of valuable and hazardous materials that may be of particular interest at the EoL stage

7.5.2 Assessment of the suitability of existing technologies and tools for EV recycling

The definition of the EoL solution for EVs requires the understanding of existing ELVs recycling techniques. Chapter 4 provides an overview of current ELV recycling technologies and processes with the analysis of their advantages and disadvantages. Despite the economic and sustainable advantages of current recovery and recycling activities in automotive industry, studies would suggest that existing component dismantling cannot make substantial headway into improving the recycling and recovery targets laid down by the ELV directive, as the majority of extracted and recovered materials are metallic and are currently counted within the assumed recycled fraction processes. Hence, this research has argued that future of EoL EV recycling should concentrate on the pre-concentration process through robotic disassembly, and the development of new technologies for post-fragmentation. The consideration for improvement in material recovery through post-fragmentation, however, is beyond the scope of this research. Therefore, this research focuses on making the disassembly process economically viable and technologically feasible, and increasing value gained from EoL EVs recycling. In this case, it is a necessity not only to determine when and if EV component disassembly becomes economically feasible, but also to consider the selection of components and the development of disassembly methods for target sub-assemblies and materials.

7.5.3 Specification of legislative requirements and constraints

The legislative requirements for EoL management solution are defined after the characteristics of the EoL stream and the assessment of the existing vehicle recycling techniques. The consideration consists of general requirements (i.e. general legislation regarding waste and landfill management), and more specific constraints on recycling vehicles (ELV Directive), electrical and electronic equipment (WEEE Directive) and hazardous materials (RoHS Directive).

7.5.4 Economic viability of the EV recycling

Typically, the recycling consists of removing reusable components, shredding and separating remaining materials for material recovery. Profitability depends on the quantity and type of components and materials recovered. Because the components and materials difference between the EVs and traditional vehicles, the profitability may be affected. Therefore, there is a need to understand the technologies for the EV components that cannot use traditional vehicle recycling methods and its economic impact. In order to achieve a long-term sustainability of the EoL solution in automotive industry, the economic implications need to be understood and must not be prohibitive to the profitability of ELV recycling and recovery.

Based on the data available in the current research, following the classification of the targeted components, the framework requires economic consideration for the EV recycling. The targeted EV components are classified into different categories based on permutation of its construction (simple, medium and complex) and recovery value (low, medium and high). This classification provides a comparison mechanism for further development and assessment of the automated robotic approach. An economic model will be developed to quantify the cost implementing a proposed EoL automated approach and revenues generated from the recovery of valuable materials from the disassembly processes.

7.6 Application of the EoL-EV framework

Case studies explored the application of the framework in different situations. In this application, the framework is employed to evaluate the effects of automation in disassembly processes. Additionally, specific EoL solutions of target components are differentiated not only by the material and construction characteristics but also by the capability and efficiency of the automated robotic disassembly operations.

As a flexible tool, the framework supports the evaluation of various EoL scenarios, and identification of preferred solutions, based on the three considerations: environmental, economic and technological aspects. Case studies explore three categories of components, in terms of different constructions and values: they are 1) simple, low value component; medium, high value component; and complex, low value component. In these modes of applications, the framework is used to evaluate the effects of automation in robotic disassembly processes under different component designs.

7.7 Chapter summary

In this chapter, the EoL-EV framework has been presented and each of the stages in the framework described in detail. Chapter 1 and 2 provide the research context and identify the research aim and objectives. Chapter 3 – 5 present a holistic review regarding the most relevant literature to support the definition of research. Methodological approaches adopted within the research are outlined in Chapter 6. The overview of the EoL-EV framework is presented in the earlier part of Chapter 7, and the first stage of the framework is reported in the rest of Chapter 7. The second stage of the framework, the development of an automated robotic disassembly approach for EV recycling, is explored in detail in Chapter 8. Chapter 9 continues by reporting the research supporting the third stage of the framework, namely the development of an EoL assessment for EV recycling. Finally, the application of the complete EoL-EV framework is demonstrated through case studies documented in Chapter 10.

CHAPTER 8 AN AUTOMATED ROBOTIC APPROACH FOR DISASSEMBLY OF EV COMPONENTS

8.1 Introduction

This chapter provides a more detailed description of the second stage of the EoL-EV framework in which three specific steps are defined, namely: ***manual disassembly*** to assess and develop a comprehensive understanding of product design, initial ***automated disassembly*** to test and examine process capability, and ***optimisation and validation*** to improve speed, repeatability and overall efficiency of automated robotic disassembly processes. These three steps and their interdependency are described in this chapter.

8.2 Justification of robotic systems for automated disassembly

Industrial robots have been widely used in different areas of automated recycling as discussed in Chapter 5. The application of automation in industries leads to a number of benefits, including increased productivity, reduced failure rate, more resource-efficient operations, improved product quality and working environment. Disassembly can be automated to be more productive and reduce cost. The integration of automated robots in recycling systems should be considered for the following reasons:

8.2.1 Quality improvement

Industrial automated robots are capable of significantly improving the quality of processes (Asfahl, 1992). Automated operations can provide high precision and quality work all the time, while this level of consistency is difficult to achieve through manual operations (BARA, 2016). In some cases when high repeatability, reliability and positioning precision are needed, human work may not be able to compete with ones produced by the robots since robotic operations provide high accuracy without experiencing deviation due to fatigue (BARA, 2016). The use of robots has shown significant quality improvement in the manufacturing industry and therefore should be transferrable to the recycling industry.

8.2.2 Improvement of production efficiency and increased productivity

The increased and constant operational speed through the application of robots has a positive impact on production efficiency (Probst et al., 2013). This is because an automated robot is capable of working at a constant speed without pausing for breaks (Kabra et al., 2011). Reduction of disassembly time is one of the major advantages of robotic operations. In general, payback is usually quicker when the product is complex and of high value which takes a long time to disassemble manually. Regarding low value products, the economic benefit can be easily lost by high labour costs, thereby making automation essential (Nof, 2009).

8.2.3 Safety, improvement of working environment

Worker safety is one of the important reasons for automating an operation (Probst et al., 2013). It is noted that the misuse of human body may lead to short-term fatigue and long-term injury. Automation is one of the solutions to avoid expediting susceptible fatigue and injury. Additionally, in recycling activities, processes may take place in an environment that is not suitable for human body to stay long. Workers may be exposed to contaminated environments (e.g. toxic and harmful substances). In this case, the safety of working environment can be improved by reducing human contact with these hazardous substances, meaning workers can be moved to supervisory roles while high-risk applications are undertaken by robots (Kabra et al., 2011).

8.2.4 Savings and better cost effectiveness

Cost-effectiveness of robots is not always straightforward to calculate. Most of the cost regarding high capital expenditure on initial investment, including the robot, tooling and installation costs. However, in comparison to manual operations, the benefits of employing robots include the cost reduction in wages and improved environment control for safety and health issues. Therefore automation would, first of all, improve worker safety results concerning long-term financial savings, because there would be fewer healthcare and insurance concerns for employers (Garetz and Michaels, 2015). Secondly, automated robots also offer consistent performance which eliminates the delays during the operations. Robotic operations are always accurate, minimising material waste and increasing the outputs. In other cases, the impact on quality may be the justification in itself, particularly when high precision, repeatability and reliability are required.

Therefore, the application of automated robot in the disassembly process can yield substantial opportunities in this research. The robot can relieve humans from repetitive, hazardous and unpleasant environments, and potentially provide economic growth.

8.3 An automated robotic approach for disassembly of EV components

In the second stage of EoL-EV framework, the possibility for undertaking the automated robotic approach to disassemble EV components is investigated. To be able to identify the feasibility of the automated robotic approach, there is a need to fully understand the design features of targeted EV components (i.e. joint method, sub-assemblies relations). Where this data are available via component suppliers, they can be used for further automated robotic disassembly processes. But in cases where this information is not available, the only way to obtain this data is via manual disassembly. Therefore, an automated approach for EV recycling developed in this research consists of three steps, as depicted in Figure 8.1 and outlined below:

a) Manual non-destructive disassembly aims at identifying disassembly level required and provides information such as tools used, time consumption and component design information (e.g. construction and material composition).
b) Initial semi-destructive automated disassembly utilises the information generated in the first step to define a series of automated processes to disassemble the EV components. This step also produces information on how to optimise these processes for increased efficiency.
c) Validation and optimisation step aims to validate and optimise automated robotic disassembly processes to improve performance, such as operation speed, operation time, repeatability and reliability.

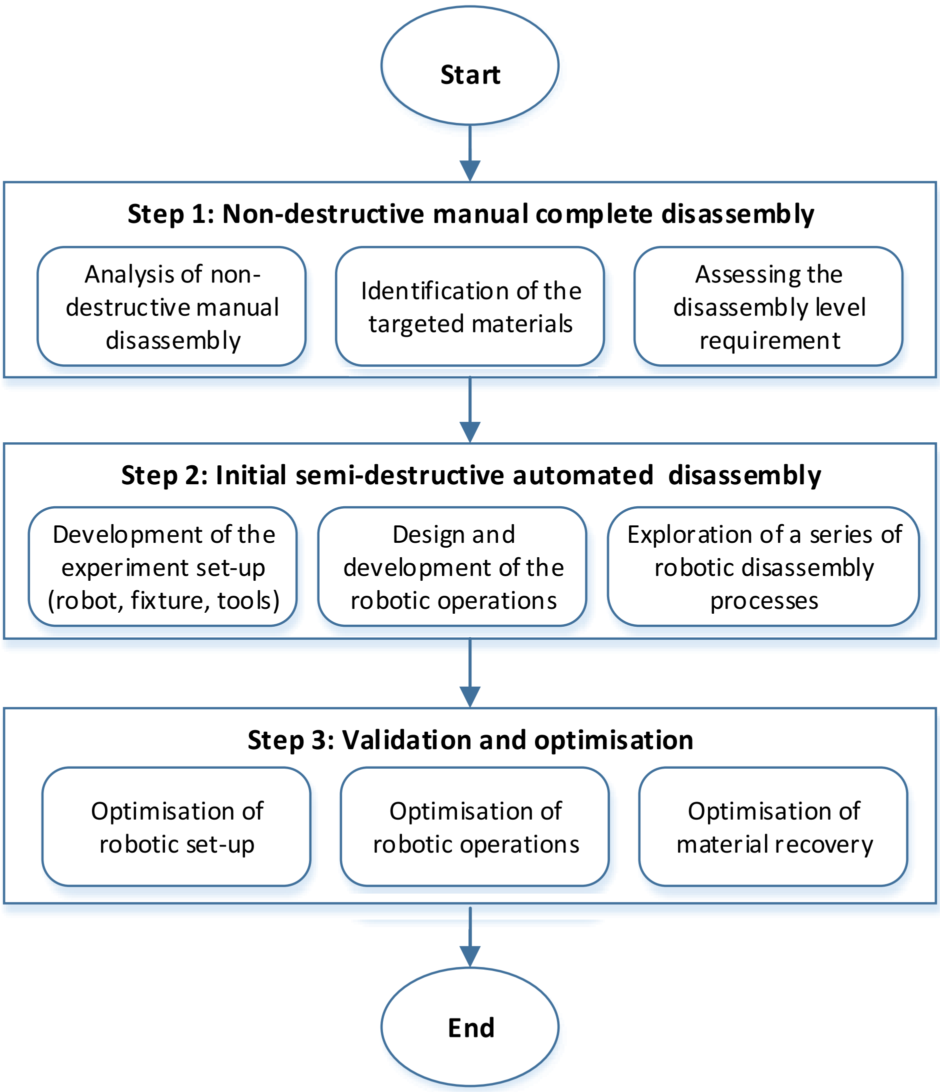


Figure 8.1 A three-step automated approach for EV recycling.

8.4 Step 1: Non-destructive manual disassembly

This step aims to generate information and knowledge required prior to disassembly planning. The non-destructive manual disassembly attempts to identify general understanding the characteristics of EV components, regarding the design construction and material composition. This investigation provides relevant information for automated robotic disassembly processes in the following stage.

8.4.1 Analysis of non-destructive manual disassembly

It is commonly reported that the majority of the environmental impact of a product is decided during the design stage. During EoL management, particularly important aspects of design are the selection of materials and configuration of parts. These two factors are based on the functionality, manufacturing feasibility, aesthetics and cost. As one aspect of design, the component configuration affects EoL management from the perspectives of size, mass, and its structure, thus defining the quantity of waste generating from each EoL unit. The accessibility of valuable materials within the components design may allow the disassembly process to be economical sustainable because a high-value material fraction can be extracted, recycled and recovered.

Therefore, the development of an automated approach for EV components is founded upon a clear understanding of relevant design and material characteristics. Challenges and opportunities for minimising environmental impacts, maximising economic benefits and improving the technological feasibility in a compliant manner are explored.

In the framework presented in Chapter 7, an automated approach for EV recycling is defined. Disassembly is considered to be one of the critical elements in product recovery due to the fact that it allows selective separation of desired parts and materials in a systematic way. Thus, the first step, manual disassembly process will address several questions in the context of the disassembly output, inspiring by DfD guidelines (Reap and Bras, 2002; Go et al., 2011) such as:

i) How long it takes to achieve the full, non-destructive disassembly?
ii) What are the components' status, design characteristics, and materials constitution?
iii) Where are the locations of the targeted parts and materials?
iv) What is the quantity of the target parts and materials?
v) What tools are used in the manual disassembly process?
vi) Is it economic to disassemble a sub-assembly further as to increase purity?

Step 1 aims to understand how components were constructed before developing a disassembly strategy. According to the disassembly results, each target component is classified into one of the specific categories based on permutation of its construction (simple, medium and complex) and value (low, medium and high). In terms of the component construction, as one of the indicators, it is closely related to disassembly processes. It can affect the accessibility and recognisability issue that allows quick and easy disassembly and the requirement numbers of tools and operations that facilitate the disassembly. Additionally, the revenue from the recycling is derived from the extraction and recovery of the valuable parts and materials. Therefore, potential recovery value of targeted components is another indicator for this research that needs to be taken into consideration.

8.4.2 Identification of the targeted materials

Typically, the first stage of disassembly aims to improve the accessibility to different parts of components. In the second step, valuable parts or sub-assemblies are reclaimed. Finally, the last step is attempting to facilitate downstream material recovery process with a higher grade of purity for further processing. The targeted materials, PMs and SIMs, are mainly contained in the PCBs. Thus, manual disassembly needs to focus on the identification and extraction of the PCBs.

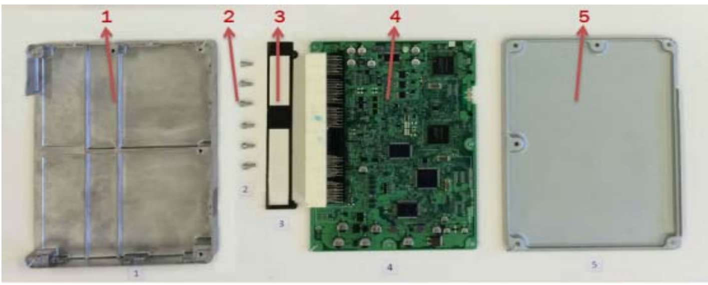
8.4.3 Assessing the disassembly level required

A feasible disassembly sequence for each EV component is also needed. Because in some cases, some steps cannot be performed until their predecessor steps have been completed. Therefore, a suitable sequence is not only beneficial to minimise the total number of tool exchanges, fixture set-up and the total idle time; but is also helpful for attempting to remove target parts and materials as early as possible.

It is acknowledged that the disassembly cost is proportional to the time required by the operations of disassembly and to the percentage of valuable components removed. Thus, sometimes the complete disassembly is not economically feasible due to the imposition of external constraints such as time. In this research, the application of selective disassembly is feasible since the removal of valuable parts and materials is essential, but also the reduction of time and required effort of the automated process makes economic sense.

8.4.4 An illustration of manual disassembly

In order to give an example to illustrate the process, a simple ECU for power management has been utilised in this chapter. As shown in Figure 8.2, a power management ECU is a device to manage different power requirements from a motor vehicle and directly connected to the battery to control the electrical system. A power management ECU consists of five fundamental parts a lid, a number of screws, a sticky tag, a PCB, and a rear casing. Table 8.1 provides an overview of the results of manual disassembly, discussed in previous review chapter, in



No.	Items
1	Rear casing
2	Screws
3	Sticky tag
4	Printed circuit board
5	Lid

Figure 8.2 A breakdown of the power management ECU.

Table 8.1 Disassembly datasheet for power management ECU.

Name of the components		Power management ECU	
Total weight (g)		723	
Total time (minutes)		2.5	
Weights for each parts (g)			
No.	Items	Weight (g)	Material
1	Rear casing	292	Steel
2	Screws	9	Steel
3	Sticky tag	3	Polymer
4	Printed circuit board	229	Multi- Material
5	Lid	190	Aluminium
Manual disassembly processes			
No.	Disassembly steps	Tools used	Time (seconds)
a	Fixturing	human force	10
b	Tear off the sticky tag	human force	5
c	Unscrews 6 screws on the lid	screwdriver	84
d	Lift off the lid	human force	5
e	Get the PCB out	human force	3
f	Tool exchange and handling	human force	40

this research, the sub-assemblies that contained PMs and SIMs are selected as targeted parts. The detailed material composition is shown in Table 8.2 in which the targeted materials are highlighted.

As shown in Figure 8.3, partial and complete disassembly has been undertaken. Therefore, regarding the power management ECU, valuable parts are the chuck of PCB and metallic casings; therefore once the metallic casings have been removed, and PCB has been extracted, the disassembly process has reached completion. In addition, the sticky black tag provides a practical challenge for getting access to the PCB as it holds the front and rear casings in place. Thus, in the further disassembly process, it needs to be removed manually at the beginning.

There are important remarks from the manual disassembly process. The EV components were in various conditions at their EoL, such as wear and geometric damage. For example, the bent metallic casing makes the fixturing and disassembly operations most difficult when compared to the components in standardised condition. It is also noted that variations occur within the components,

Table 8.2 Material composition of power management ECU.

Component Name: Power management ECU			
Material		Unit: g/part	Price (£/g)
Ag	Silver	0.1008	0.37
Au	Gold	0.01896	28.2
Pd	Palladium	0.00044	16.82
Cu	Copper	55.075	0.0041
Ni	Nickle	0.801	0.00142
Pb	Lead	0.137	0.00121
Sb	Antimony	0.054	0.0059
Sn	Tin	4.358	0.01278
Zn	Zink	5.146	0.00143
MgO	Magnesium oxide	0.508	-
Al2O3	Aluminium oxide	22.747	-
CaO	Calcium oxide	11.510	-
SiO2	Silicon oxide	37.442	-
Fe	Iron	6.902	0.00026
Mn	Manganese	0.146	0.0018
TiO2	Titanium dioxide	0.745	-
BaO	Barium oxide	2.168	-
*Source: http://www.metalprices.com			

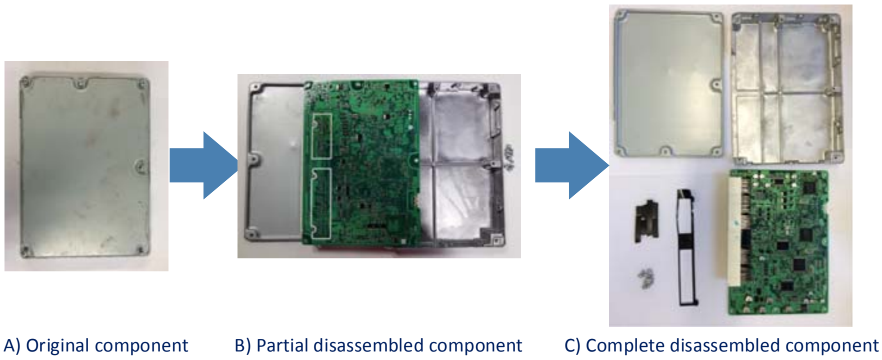


Figure 8.3 Different disassembly levels of power management ECU.

i.e. brackets, and wires attached to the casings. Therefore, the variation of the components would lead to a significant challenge in developing standardised automated operations.

8.5 Step 2: Initial semi-destructive automated robotic disassembly

8.5.1 Development of the experimental set-up

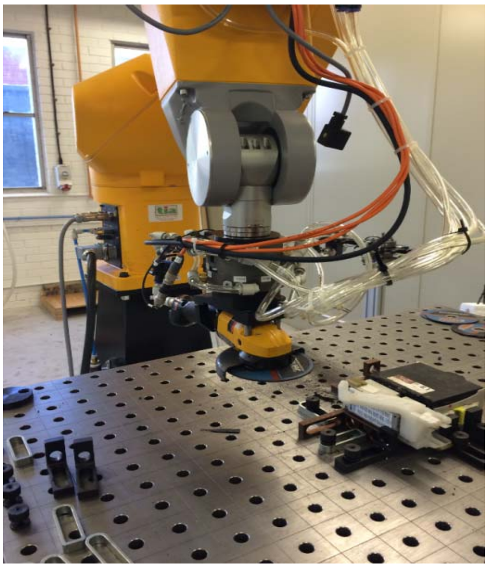
A flexible robotic cell has been developed and utilised for undertaking semi-destructive robotic disassembly operations (see Figure 8.4). This robotic cell consists of four modular: 1) a standard six-axis industrial robot; 2) a standard modular fixture with a set of fixturing accessories; and 3) a number of specially designs tools for disassembly operations (i.e. milling, cutting and gripping).

Based on this set-up, this step aims to investigate the feasibility of robotic disassembly operations for EV components. Therefore, a number of various experiments were designed and carried out to assess the capability of the robot arm, tools and fixturing system. The findings from this step will be used to support and facilitate the validation and optimisation process in Step 3.

Figure 8.4 Robotic disassembly cell.

8.5.1.1 Selection of robot for the automated disassembly cell

The robot used in the laboratory experiment is the Stäubli RX 160 industrial robot. The RX160 series of medium payload robots features a highly precise articulated arm with 6 degrees of freedom for optimum flexibility, as shown in Figure 8.5. There are two modes to operate the robot, the manual mode and the automatic mode. Additionally, in manual mode, maximum speed is about 10% of the maximum speed in automatic mode.



Model	RX160	Features
Degrees of freedom	6	Enclosed structure
Nominal load capacity	20 kg	Rigid structure
Maximum load capacity*	30 kg	Multiple mounting configurations
Reach	1710 mm	Stäubli patented reduction gear systems
Repeatability-ISO 9283	±0.05 mm	Large work envelope
Protection class (*wrist)	IP65 (*IP67)	
Attachment methods	Floor or ceiling	
Stäubli CS8 series controller	CS8C	

Figure 8.5 RX 160 6-axis robot and specifiction.

8.5.1.2 Selection of tools for the automated robotic disassembly cell

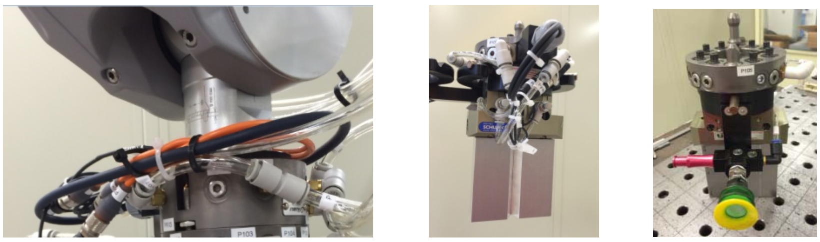
Tools include all electromechanical equipment plus associated handling devices that are needed to undertake disassembly operations (shown in Figure 8.6).

a) *Tool changer*: the compact automatic tool changer increases the productivity levels and reduces the overall size of the tools. It is held in a place with quick-release clips for short changeover times. Proximity switches and sensors are applied to monitor the status.

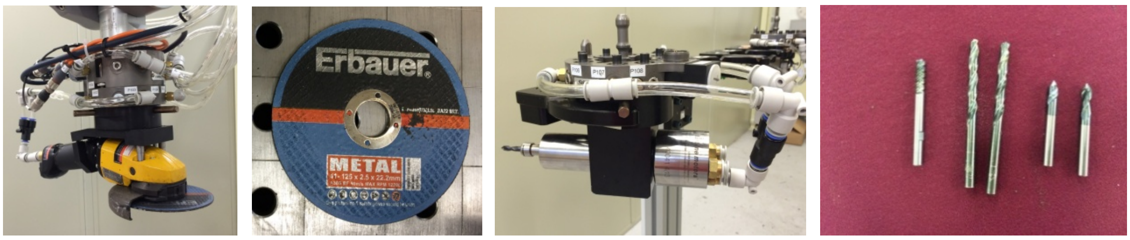
b) *Gripper*: the two-finger parallel gripper has a large gripping force and high maximum movements. With a sufficient supply of air pressure, the vacuum gripper is well capable of providing a high vacuum for grasping objects, but it has only one surface for gripping the objects.

c) *Cutting tool:* the angle grinder is designed for removing material using abrasives. It works under the air pressure of 6.3 bars (90 psig), and its maximum free spin speed is 1200r/min. Currently, the circular saw blades that were used in the laboratory experiment are Erbauer Metal Cutting Discs (125 x 2.5 x 22.23 mm).

d) *Milling tool:* the milling tool includes a patented double turbine 740XP series, ER 11 (6 mm) collet system, and a 6 mm milling bit. The double turbine keeps the tool at a high speed and low vibration. For example, three types of milling bits were used for the experiments: 1) spiral-shape milling bit; 2) 6 mm standard milling bit, and 3) 6 mm Diameter 90° Point Aluminium Titanium Nitride (AlTiN) Coated Carbide milling bit.



(a) Tool changer **(b) Two-finger gripper** **(c) Vacuum gripper**



(d.1) Cutting tool **(d.2) Saw blade** **(e.1) Milling tool** **(e.2) Milling bits**

Figure 8.6 Robotic disassembly tools.

8.5.1.3 Selection of fixture for the automated robotic disassembly cell

The fixture is the part that is needed to facilitate, or even make feasible, the disassembly activity. The fixture applied in the laboratory experiment is the Divano 16 series (1.2m X 0.8m), it has a 50 mm grid pattern of 16 mm holes on the table top (shown in Figure 8.7). The thickness of the surface is 12 mm, and it is manufactured with high-quality ENS 355J2+N (St. 52/3 Steel). The grid lines in a distance of 50 mm help to arrange and position the components. All components can be positioned, fastened and clamped by the appropriate clamping accessories using clamping bolts.

a) Ball lock bolts: connect element for all system parts on table; 3 polygon shaped expansion elements of bolts realise precise self-centring, force-fit all-over, and self-locking functions;

b) Stops: displacement stops are adjustable by using a bilateral scale, and providing a large surface contact area for both locating and clamping;

c) Right angle brackets: the angle squares hold components at 90°. The holes and slots combination allow for adjustments in fixturing;

d) Clamps: have adjustment ring for height fix and enable the clamp to swirl 360° and be positioned at any point.

8.5.2 Design and development of the robotic operations

The first set of experiments is used to investigate the capability of various units of the robotic cell, including the specially designed tools for the robot arm and the modular fixturing system. Varying parameters (i.e. operating speeds, depths, lengths, angles) are designed and tested. The second set

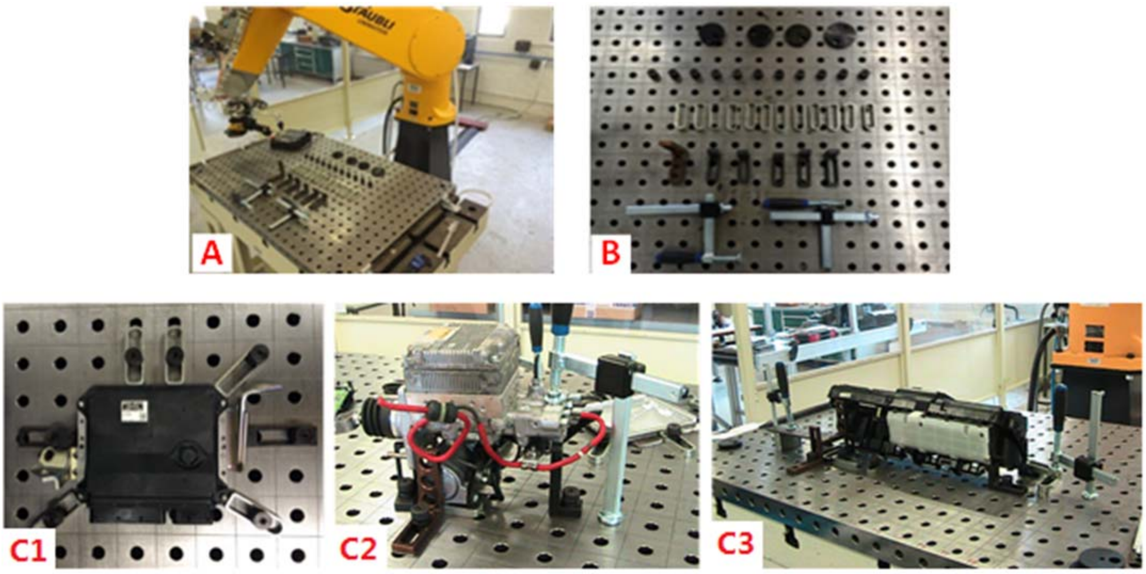


Figure 8.7 Fixturing: A) Fixture table, B) Fixture accessories and C) Exemplified applications.

of experiments aims to generate the optimum automated robotic disassembly operations with high reliability and repeatability.

The robot was controlled in a manual mode, ensuring the exploration of the approaching methods and various movements in a relatively slow speed (10% of the speed of the automated mode). All technologically feasible disassembly approaches are explored. Different scenarios are considered, including various approach methods, disassembly depths, operation speeds, and fixture mechanism. It is a learning process where the trials enhance the understanding of robotic disassembly operations.

8.5.3 Exploration of a series of robotic disassembly processes

The overall objective of this phase is to complete a continuous improvement of robotic disassembly processes that is achieved by a gradual approach. A number of trails are undertaken to investigate the impacts from various factors, i.e. tools, fixtures, operational parameters. Every trial provides a better understanding of the tools and potential improvement on the fixtures, as shown in Figure 8.8. Appendix B provides a detailed illustration of the application of this process.

8.5.4 An illustration of semi-automated robotic disassembly

The power management ECU was again selected for demonstrating the semi-automated disassembly process. The learning from manual, complete, non-destructive disassembly includes:

1) The power management ECU's construction is simple, consisting of five parts; and it is in a regular shape that facilitates fixturing;
2) Valuable elements contained in the power management ECU are 1) PCB, which contains precious metals; 2) casings, which are made of metallic materials, aluminium and steel;
3) The disassembly depth is the stage that the PCB is removed from the casing, considering the environmental and economic impacts, and technological difficulties.

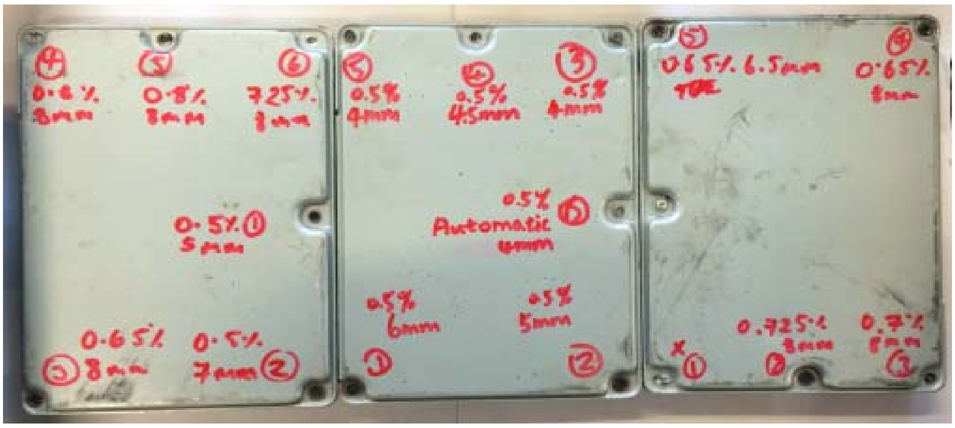


Figure 8.8 An example of exploration of a series of the robotic disassembly processes.

The major problems involved in this case are:

- Taking off the sticky tag on the side, which required a specially designed tool;
- Milling screws on the lid to remove the lid and approach the PCB, where the feasibility of various types of milling bits needed to be tested;
- Get the PCB out of the casing, where the capability of the grippers needed to be tested.

8.5.4.1 Fixturing methods in the initial robotic disassembly processes

The relatively low depth of the component requires that the fixture accessories should have a similar or even lower depth on sides. Otherwise, the accessories may hinder the movement of the robot. Therefore, the initial fixture mechanism for the power management ECU consists of a right angle bracket, stops and ball lock bolts (as shown in Figure 8.9). In terms of the fixture mechanism, different accessories can be used to achieve the same function, such as replace the right angle bracket with the straight edge stops that lower the height of the fixture and minimising the possibility of collision with the tool. It should be noted that, at the beginning of the automated disassembly process, the sticky tag was removed manually, and then the power management ECU was fixed on the fixturing table.

8.5.4.2 Design of the automated operations

The automated operations include using the milling tool to mill off the screws on the lid, using the vacuum gripper to lift the lid and then extract the PCB. It is identified that the PCB is located inside the casings (see Figure 8.10 A). However, this board is held in place using a sticky tag which provides a practical challenge for its removal using the robot gripping tool. Therefore, the solution is to remove manually the sticky tag as the first operation before the milling process. It should also be noted that in regards to the approaching method, another method instead of milling screws on the lid existed; using an angle grinder to cut the aluminium lid, which is another solution to get access to the PCB (shown in Figure 8.10 B). In this case, it is necessary to consider the capability of the sawing

(a) Fixture plan A (b) Fixture plan B

Figure 8.9 Fixture mechanism.

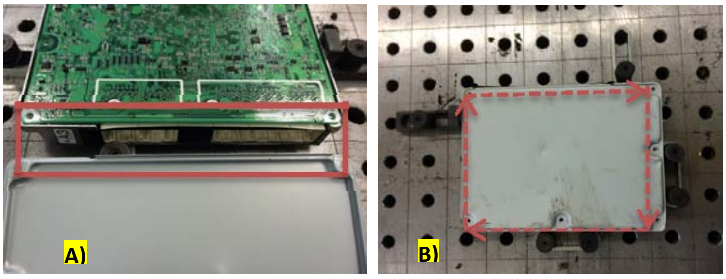


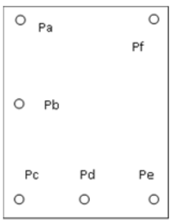
Figure 8.10 A) Sticky tag issue; B) An alternative approach method.

blade, whether it is hard and tough enough to cut metallic materials; in addition, the time efficiency and the material recovery both need to be taken into consideration. However, it took three times longer compared to the milling process and accelerated tool wear of the blade. Therefore, the lid-cutting approach was discarded in the automated disassembly process for this product.

8.5.4.3 Tool capability test

In the automated disassembly process, the milling tool and gripping tool were used for releasing the lid and extracting the PCB. Therefore, the capability of these tools needs to be tested in different cases as shown in Figure 8.11. Regarding operational parameter, i.e. milling depth and speed, the test results are illustrated in Table 8.3. If the milling speed is too high, large amounts of heat are generated with sparks, and sometimes there was insufficient torque to mill through the screw, correspondingly. When the milling speed is set too low, the time efficiency is significantly reduced. In addition, the milling depth plays a role in milling operations. It turned out the best combination of depth and speed setups were 6.5 mm and 0.65% for this product.

In addition, because the collet size of the milling tool was 6 mm and the size of the screws and washers on the lid is 8 mm when using a 6 mm mill bit, the washers were left on the product after the milling took place (shown in Figure 8.12 a). This affects the efficiency of the operation due to the residue on the milling bit head hinders the following operations i.e. removal of the lid and PCB. The possible solutions includes: a) the use of a gradual changing size milling bit, whose head is 8 mm and another end is 6 mm for the collet; and b) the application of a U-shape mechanism, this would be an extra operation which is developed to get rid of the residue after every milling initial milling operation (shown in Figure 8.12 b).



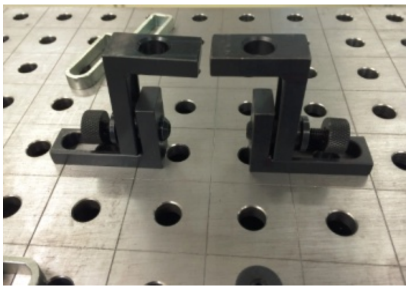
Point	Milling bit	at
Pa	used standard milling bit	lab
Pb	point locator milling bit	lab
Pc	point locator milling bit	workshop
Pd	standard milling bit	lab
Pe	standard milling bit	works
Pf	point locator milling bit	lab

Figure 8.11 Milling bits test.

Table 8.3 Milling depth and speed test result.

Depth (mm)	Speed (%)	Time (second)	Result	Notes
6	0.2%	30	√	At constant relatively low speed
5	0.5%	10	√	Worked
4	0.5%	7	x	Failed, mill through half of the screw
4.5	0.5%	7	√	Worked
4	0.5%	5	x	Repeat test to see whether 4 mm depth is enough to drill through
5	0.5%	10	x	Milling time was too short
5	0.5%	7	x	New miller bit
7	0.5%	9	√	Worked
8	0.65%	8.5	√	Overshooting
8	0.8%	6.5	x	Failed, the fixture was not stable, slippery
8	0.8%	8.5	x	The tool stopped at the end
8	725%	-	x	Wrong setting about the speed
8	0.725%	9	x	Not central
8	0.725%	10	x	Tool stopped
8	0.7%	11	x	Tool stopped
8	0.65%	11.5	x	Tool stopped
6.5	0.65%	11	√	Worked

(a) Milling residue



(b) An U-shape mechanism for milling residue issue

Figure 8.12 Problem of milling residue.

Additionally, three more different milling bits had been tested for milling off the screws, which are spiral-shape milling bit, standard milling bit and point AlTiN coated carbide milling bit, and the range of the head size is from 6 mm to 10 mm. The experiment results indicate that a standard milling bit and point milling bit were workable for milling operations, and a point milling bit had better performance with less heat generation and faster operation. In addition the 8 mm head size can mill off the screw head and the washer that solved the problem of the milling residue.

It is noted that lateral error (horizontal error) may occur by influences from a combination of factors, such as the stability of the fixturing table during operation. In practice, milling depth should be set to 5 mm to ensure the screws were removed; while the tool wear should be monitored as it affects the performance. There is a balance between the milling speeds and their performance. For example, if the speed was set too high, in theory the milling time could be reduced; however, the milling process was failed due to the lack of sufficient processing time and the trembling of the tool and components, which was caused by the vibrations from the tool forcing its way through the screw head.

As discussed in the tool description, the vacuum gripper is designed to work on even and smooth surfaces, while there is undulation on the surface of the PCB, which may be a challenge for the vacuum gripper. Therefore, various gripping locations on the PCB were tested as shown in Figure 8.13.

8.6 Step 3: Validation and optimisation of automated robotic disassembly

Based on the previous experiments in Step 2, Step 3 aims to validate the existing robotic disassembly processes and generate the optimum one with consistent repeatability and reliability and maximised value recovery. Three tasks are included: 1) optimising the robotic set-up to reduce the overall time spent on on re-positioning and re-fixturing components; 2) determining the optimum disassembly strategy with the most appropriate tool set-up for EV components; and 3) optimising the economic benefits of robotic disassembly through balancing the ‘trade-off’ between disassembly level and recovery value.

8.6.1 Optimisation of robotic set-up

This step aims to minimise the number of the part set-up and tool exchange. It is preferred that the automatic operations can be conducted from one direction without changing the fixture of the component. In addition, it is also beneficial to optimise the sequence of tool use and minimise the tool exchange numbers.

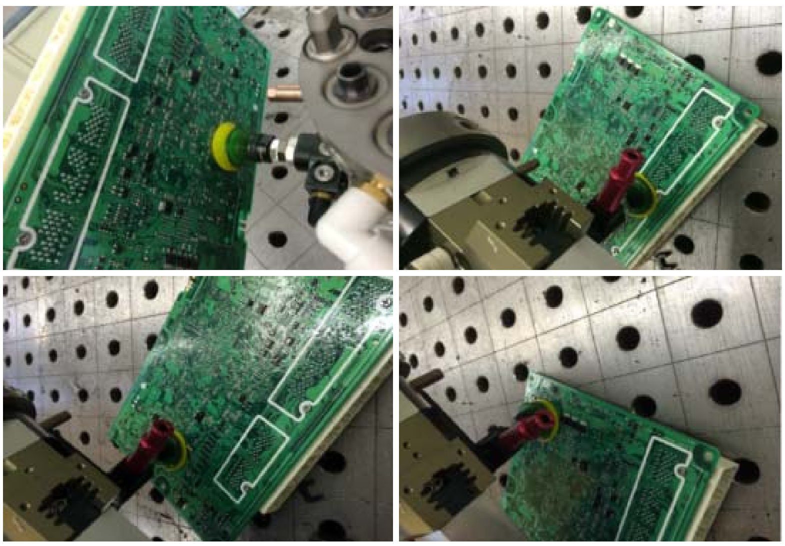


Figure 8.13 Operational parameters test: Gripping point test.

8.6.1.1 Two-finger parallel gripper

The robot gripper includes a two-finger parallel gripper and a vacuum gripper. In terms of the two-finger parallel gripper, there is a limit on the parallel gripping domain between the two fingers and the possibility of gripping components of irregular shapes is difficult. One suggestion is to provide a different construction of the gripper fingers (see Figure 8.14). Another way to improve the tool performance is to replace the two-finger parallel gripper with a more versatile gripper. Versatile grippers range from the common two jaws parallel gripper (provided that its stroke is long enough to hold objects of different sizes) to complex multi-fingered robot hands.

8.6.1.2 Vacuum gripper

In the experimental setup, the vacuum gripper uses a round vacuum cup as the gripping device. It can provide good handling if the objects are smooth, flat and clean. In addition, it has only one surface for gripping the objects. More importantly, it is not suitable for handling the objects with holes or uneven surface, such as the surface of a PCB.

In order to improve the performance, it is viable to apply gripping aid (such as a layer of Vaseline) on the surface for better contact. Furthermore, applying multiple suction cups in one tool to increase the contact surface or applying a heavy-duty ball joint type vacuum gripper to expand the contact angles and surface area are other potential solutions. Various size and configurations of the vacuum grippers have been illustrated in Figure 8.15.

8.6.1.3 Cutting tool

The circular saw blades used in this experiment were Erbauer Metal Cutting Discs, which are extra narrow for fast cutting. However, it can be challenging to cut through hard materials, such as metals, as the discs can bend whilst cutting. Additionally, the heat generated during the operation may make some material melt and become sticky on the edge of the blade, which may in turn impact the

Figure 8.14 Various gripper designs.

Figure 8.15 Vacuum gripper designs.

cutting performance. In order to improve the cutting efficiency, other types of cutting blade can be investigated, such as the blade with cutting grade carbide teeth and with anti-kickback toothed shoulder, or with a heat vent expansion slot design. Various cutting blades can be used in different cases (i.e. materials), as shown in Figure 8.16, but this may depend on the cost of the system, as well as the tool wear over time.

8.6.1.4 Multi-head tool design

One way to minimise the tool exchange time is to design a tool that can perform multiple functions in different directions. For example, a customised tool head designed with multiple end-effectors including gripping tools and a mill head is shown in Figure 8.17. In general, the operation of tool exchange is removing the original tool, returning it back to the tool stand, then picking up the suitable tool and moving back to the work area. However, with the application of multi-tool, the operation of tool exchange can be simplified with one operation of rotating the robot arm.

8.6.1.5 Fixturing

Regarding the fixturing, currently, the system consists of a gridded tabletop which is fixed on the bench and a set of accessories. However, problems were found: the target component can only be fixed on the surface of the table top which limits the approach to the bottom of the components, and the fixture accessories set also hinder the tool from approaching the component from particular directions.

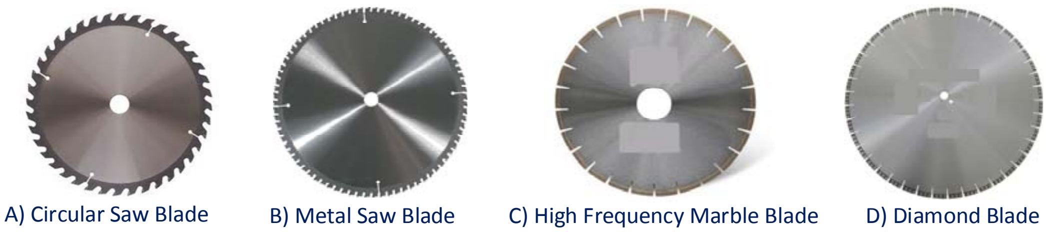


Figure 8.16 Cutting blade designs.

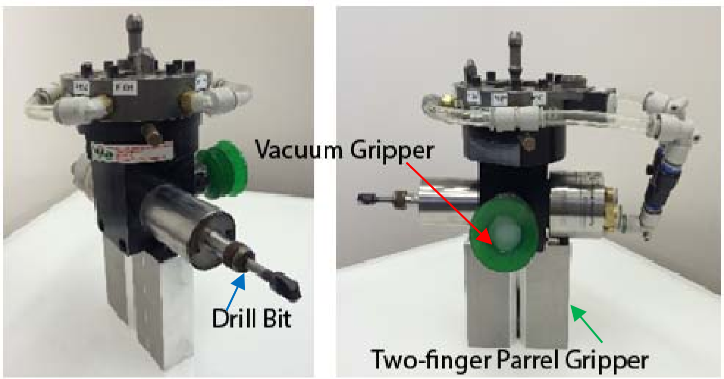


Figure 8.17 A Multi-head tool design.

Modern modular fixtures provide an alternative approach that is capable of holding a range of various part designs, but often require some manual intervention, in particular during the changeover of fixture set-up to accommodate new part designs with unusual shape. A number of key considerations during the fixture design for robotic disassembly application are the abilities to 1) minimise the need for re-orientation of workpiece through provision of sufficient access for robot arm during a single visit; 2) hold work piece without comprising the working envelope of robotic arm to avoid tool collision with fixture accessories; 3) be able to position the workpiece accurately and repeatedly; and 4) hold in place the workpiece firmly during disruptive and destructive disassembly procedures to minimise vibration and unintentional repositioning for subsequent processes.

In order to increase accessibility and fulfil specific requirements, the application of a turning or flip table would simplify the automatic robotic disassembly process as an alternative approach (see Figure 8.18). For instance, in terms of the power management ECU, after the milling operation on the lid, the lid and PCB can be separated when the fixture table is flipped over without a need for a tool exchange and gripping operations. However, this could also cause inaccuracies in separating the PCB, because other sub-assemblies of the component could also fall out at the same time as the lid end up in the wrong recycling stream.

Alternatively, the utilisation of another robot could provide additional flexibility to the existing disassembly system. The additional robot could be used to fixture the target components while the other carries out the disassembly processes. This would effectively provide the same benefits of both the modular fixturing table and the turning table; however, it would be mean having a larger initial investment cost.

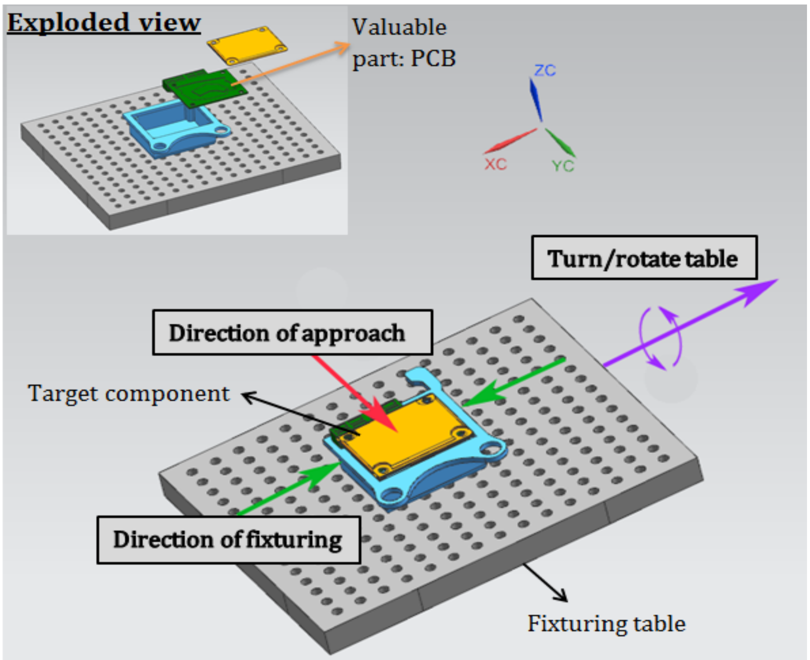


Figure 8.18 Fixture design for effective robotic disassembly.

8.6.2 Optimisation of robotic operations

The first objective focuses on the optimisation of the operation parameters, including the testing and validation of two major parameters: the overall **disassembly time** and the **reliability & repeatability** (success rate). Determining the best strategy to disassemble EV components needs the efforts from the economic and technological aspects. The evaluation method is developed to assess the economic cost and technological feasibility for various automated disassembly processes.

8.6.2.1 Operational parameters

During automatic operation, the set-up of variables is another critical issue. For example, the speed of the tool may influence time consumption and its performance of disassembly. In the case of the power management ECU, different operation speeds (ranging from 5.5% to 8%) were tested for an optimal speed during the screw milling process. If the speed was set too high, a large amount of heat was generated and caused sparks; while if the speed was set too low, the milling process took an unnecessarily long time and affected the overall milling quality.

8.6.2.2 Reliability and repeatability

The performance of this robotic system also includes the reliability and repeatability of the automated operations. Regarding the fixture mechanism, it is preferred that, despite the variation in the component construction (i.e. wires, brackets, etc.), the fixture mechanism can be applied as widely as possible for one type of component in a reliable and repeatable way. In addition, the automated operations should be feasible in a continuous manner and achieve a high success rate, i.e. >90%.

In the case of the power management ECU, the removal of the lid requires the removal of the screws on the lid. The application of inappropriate drill bits can result in disrupting the milling process and affecting the milling performance, perhaps causing problems for the following processes.

8.6.3 Optimisation of material recovery

The recovery of valuable materials makes, in general, good economic sense. However, it is noted that the recovery rate of the materials varies, depending on the technologies capability to recover the specific materials. It is identified that the economic value of the disassembly process is associated with a number of variables, such as the complexity of the component itself and the fixturing, the numbers of the setup changes and operations required, and the total time to complete disassembly per component. Once a suitable factor has been selected and determined, the indicator of material recovery rate can be quantified, as demonstrated in Equation 8.1 and Equation 8.2.

$$\sum Material\ Removal\ Rate\ \left(\frac{Kg}{sec}\right) = \frac{\sum Material\ (Kg)}{Time\ (Sec)} \quad \text{Equation 8.1}$$

$$\sum Value\ Removal\ Rate\ \left(\frac{£}{sec}\right) = \frac{\sum(Material\ (Kg) \times (Value\ \left(\frac{£}{Kg}\right))}{Time\ (Sec)} \quad \text{Equation 8.2}$$

Further consideration as to the feasibility of material recovery is that of achievable material yield rates. It is noted that the yield rate for specific materials depends on the availability of feasible recycling and recovery technologies, e.g. the recovery rate for metallic materials, such as steel and aluminium is higher than the recovery rate of plastic and composite materials.

8.6.4 An illustration of optimisation and validation of automated disassembly

For the third step in the automated approach, the power management ECU has been selected to demonstrate and exemplify the optimisation and validation of the automated disassembly approach. Based on the information gained from manual disassembly and initial automated disassembly (step 1 and step 2), various trials were undertaken as described below, with the experiment results summarised in Table 8.4.

- **Trial 1**: four angled brackets were utilised in the fixturing. A 6 mm diameter Tungsten Carbide drill bit was used to drill off the screws; while a standard two-finger parallel gripped was used to remove the PCB.
- **Trial 2**: besides the four angled brackets, a holding plate was utilised to fix the components to the modular table. The mill and gripping tools were replaced with an 8 mm diameter Carbide Spotting Drill Cutter and a vacuum gripper.
- **Trial 3**: same fixturing method and gripper tool were applied as in Trial 2. In addition, a slightly larger drill bit with 10 mm diameter was used to improve the milling performance.

According to the experimental results, there is strong evidence that the observed reduce in fixturing time after several trials is likely due to the familiarisation of the operator to the fixturing process. In addition, the set-up of the tools was investigated for improving the efficiency and performance of disassembly operations. For example, the utilisation of a slightly increased tool size (i.e. the diameter of the drilling cutter increased from 6 mm to 10 mm) significantly reduced the milling time. It was also identified that the improvement in selecting the most appropriate gripper in specific cases would increase the success rate. In Step 3, a number of operational parameters were validated and optimised to reduce the total disassembly time and improve the performance of these robotic disassembly operations. For example, the approaching angle and the feeding speed of the gripper were tested to improve the repeatability and reliability of the gripping operation.

Table 8.4 Automated disassembly datasheet for power management ECU.

Operations		Description	Time (seconds)				
			EoL-EV Framework				
			Step 2				Step 3
			Trial 1	*Trial 2*	*Trail 3*	*Trail 4*	*Trail 5*
1	Fixturing	Fix the component on the table	60	120	120	100	100
2	Robotic set up	Get the milling tool from the tool stand	15	15	15	15	15
3	Manual operation	Tear off the sticky tag	3	3	3	3	3
4	Milling process	Mill 6 screws on the lid	100	80	60	50	46
5	Tool exchange	Put the milling tool back and get the vacuum gripper	25	25	25	25	25
6	Lifting process	Lift off the lid and the PCB, put the PCB in a storage box	35	30	25	25	25
7	Tool return	Put the vacuum gripper back to the tool stand	10	10	10	10	10

It should be noted that the main different in overall disassembly time between manual and automated robotic disassembly operations is very likely due to the time spent on fixturing the component to the table. Nevertheless, it is expected that the total disassembly time would be significantly reduced based on a commercial set-up of this robotic disassembly cell with customised fixture and tools. Due to the economic constraints, these approaches were not applied in this research.

8.7 Chapter summary

This chapter has broken down the automated approach into three principal steps, namely non-destructive manual disassembly, semi-destructive automated disassembly and validation and optimisation processes. Design and material characteristics of EV components have been analysed, whose differences in design results in wide variations in overall material composition and construction. Based on the information gained from manual disassembly, the assessment of the environmental, economic and technological feasibility of both manual disassembly and automated disassembly processes have been determined, as well as the data helping with the generalised identification and classification of target EV components. Before the semi-automated disassembly process is applied to the EV components, the robotic work cell set-up has been demonstrated. Furthermore, automated robotic disassembly activities under different scenarios have been conducted for components, to understand the capability of the automated system and explore the technically feasible automated operations. Various experimental findings have been recorded, analysed and compared. The last step of the automated approach is to validate and optimise the automated approaches for EV components, considering the experiment set-up and the operational parameters. The consideration of the environmental, economic and technological feasibility for EV recycling will be focussed in Chapter 9, and the research will be tested using case studies in Chapter 10.

CHAPTER 9 ASSESSING ENVIRONMENTAL, TECHNOLOGICAL AND ECONOMIC FEASIBILITY FOR EV RECYCLING

9.1 Introduction

The EoL-EV framework described within the previous chapter highlighted the need to assess the environmental, technological and economic impacts of different EoL options for EV components. This chapter highlights the benefits of such assessments for effective decision making in the management of EoL EVs, and presents a methodology to quantify the environmental, technological and economic performance associated with EV recycling and recovery activities. The chapter begins by providing a rationale for applying a systematic assessment for EoL management of EV components. The Multi-criteria assessment methodology is then presented followed by a multi-criteria decision-making tool to support comparison of EoL solutions within the framework.

9.2 Environmental, technological and economic feasibility of robotic disassembly

The review of automobile evolution and existing vehicle recycling in Chapters 4 and 5 identified issues most relevant to the management of EoL EV components. Due to large volumes and various sizes of ELVs, current recycling technologies often rely on a sense of fragmentation techniques and processes. These existing technologies and processes were mainly used for recycling and recovering metallic materials (i.e. ferrous and non-ferrous) that account for majority of vehicle weights (EPSRC, 2014). However, other precious materials (i.e. SIMs and PMs), contained in electronic components in EVs were neglected. This research has explored the potential use of robots for pre-concentrating SIMs and PMs from EV components before they are processed through traditional automotive recycling and recovery routes, to enable greater recyclate quality and therefore increased recyclate value. To ensure that the proposed EoL recycling process is realistic in a business environment, it is necessary to assess the economic viability of implementing such automated robotic disassembly operations.

This research has developed and utilised an assessment tool which was inspired by the eco-compass technique (Steuer and Na, 2003). This has three dimensions to provide a comparative evaluation of the environmental, technological and economic impacts. These three dimensions are explained below:

i) ***Rate of material recovery****:* refers to the physical percentage of materials that can be recovered. It reflects the improvement in the rate of material recovery associated with the alternative recycling approaches;

ii) ***Total disassembly time***: overall disassembly time closely related to the economic sense, and the technological feasibilities of different recycling techniques and processes;

iii) ***Cost and Revenue***: focuses on the economic feasibility of recycling approaches and evaluates the trade-offs between the cost and benefits of applying different recycling scenarios.

In the environmental assessment, the best case scenario is that the ability to recycle 100% of materials, whereas, in the worst case scenario, none of the material can be recovered. For technological assessment, the ratio of time for manual disassembly and automated disassembly is evaluated, with the best case scenario defined where the automated disassembly time is less than half of the manual disassembly time, and worst case scenario is when the automated disassembly time is twice the value of manual disassembly time. This implies that a negative value for environmental and technological assessment results in dismissing the automated robotic disassembly, even if this results in a positive economic gain, as robotic disassembly is not solely proposed for economic benefits.

The scope of the multi-criteria assessment is illustrated in Figure 9.1, in which the environmental evaluation takes precedent over technological and economic assessments; and similarly environmental evaluation and technological evaluation take precedent over economic evaluation. In this assessment, the following assumptions are made in this research:

1) Only the rate of recovery of PMs and SIMs are considered due to data availability;
2) An average disassembly time is considered as these vary based on disassembly time (morning or afternoon shift) and numbers of repetition;
3) The revenue from recycling materials does not take into account the variability in actual cost of final refining. A fixed value of processing cost is used in this research.

It is noted that simultaneous evaluation of environmental impact, technical feasibility and economic benefit is complex, and there may interaction and conflict. For example, the environmental assessment is based on the disassembly results (i.e. disassembly steps, methods, times and materials analysis), which are also the fundamental inputs for the technological and economic assessment. Alternatively, if the robotic disassembly is not technologically feasible, (i.e. automated disassembly operations are not technically efficient than manual disassembly processes), this recycling process

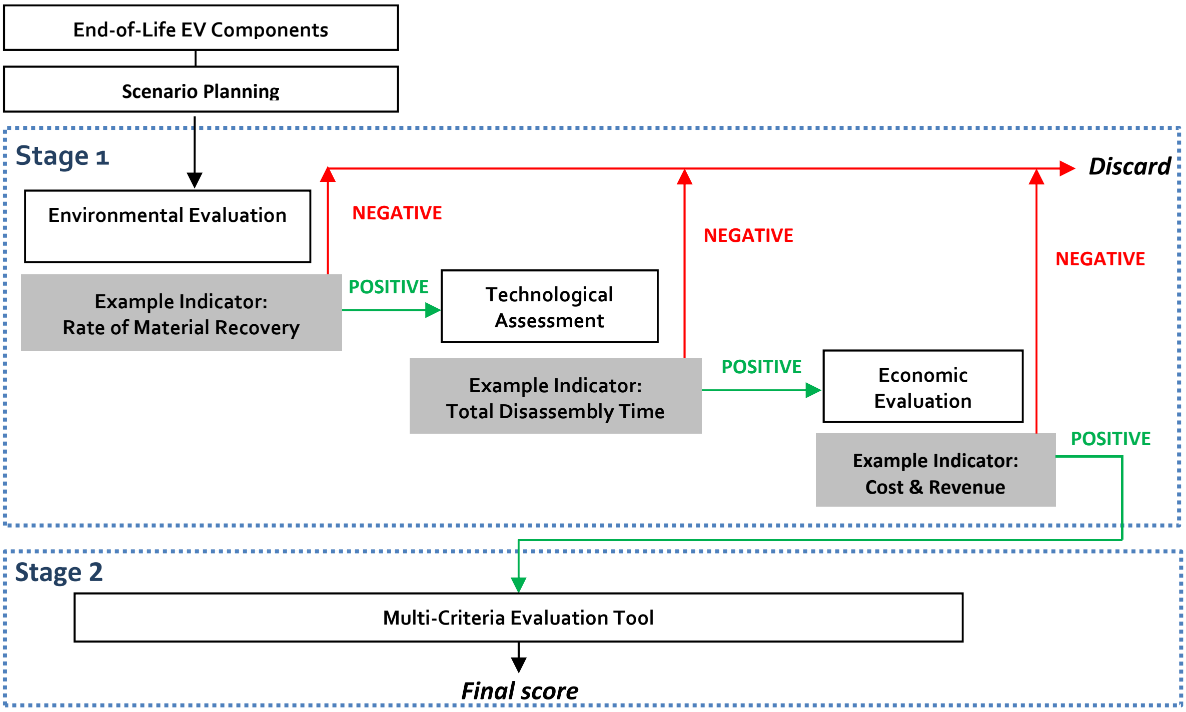


Figure 9.1 Overview of evaluation methodology for EoL management options.

would not be accepted as an EoL management scenario regardless of its economic performance. Therefore, these three criteria are not considered in parallel, and rather they are investigated in sequence, to ensure the efficiency of the multi-criteria assessment approach. In addition, a two-stage evaluation approach has been developed which assesses each criterion (environmental impact, cost and technology) individually, and then combines the individual outcomes to provide a single performance score. Two scenarios have been investigated for environmental assessment, namely scenario 1 (fragmentation and separation without dismantling & disassembly); scenario 2 (fragmentation and separation with manual dismantling & disassembly).

The individual outputs from each evaluation provide three performance measures for a robotic disassembly process. However, these performance measures may not readily identify a single preferred result (i.e. a particular scenario performs better in all three categories), and conflicts are likely to arise between the criteria. Therefore, a multi-criteria evaluation method is required to combine the individual scores into a representative assessment result. The application of the multi-criteria assessment tool is demonstrated through case studies in Chapter 10.

9.3 Environmental assessment of robotic disassembly

It is widely acknowledged that products can contribute to various environmental impacts ranging from detrimental impact on ecosystem and humans, and depletion of natural resources. It is also noted that the reuse, recycling and recovery can, therefore, lessen the negative consequences. As such, all stages of a product's life cycle should be considered to ensure that the environmental assessment gives the full picture of the environmental impacts that the product causes.

The method used to assess the environmental impacts of robotic disassembly is slightly adapted from the RRR approach. This approach is proposed by the European Commission Joint Research Centre and aligned to the International Electrotechnical Commission Report IEC/TR 62635 (Ardente and Mathieux, 2012). This environmental assessment method is structured as follows: i) Definition of the EoL scenarios for the considered EV components. Scenarios with and without dismantling & disassembly processes are analysed and compared. In particular, valuable sub-assemblies are extracted from dismantling and disassembly process; ii) Estimation of the recycling and recovery rate for different recycling solutions, and iii) Calculation of the environmental performance. Figure 9.2 provides the overview of the environmental assessment.

Recycling rates of various materials are estimated by performing the calculation by reference values adopted from the various publications in this assessment, namely Chancerel *et al.* (2009), Meskers and Hagelüken (2009) and IEC/TR 62635 (2012). For some critical raw materials (PMs and SIMs) the rations included in Table 9.1 indicates what percentage of the mass of target materials contained in the component is feasible to be extracted and recovered. It allows the measurement of what is the fraction of critical material that is potentially recyclable.

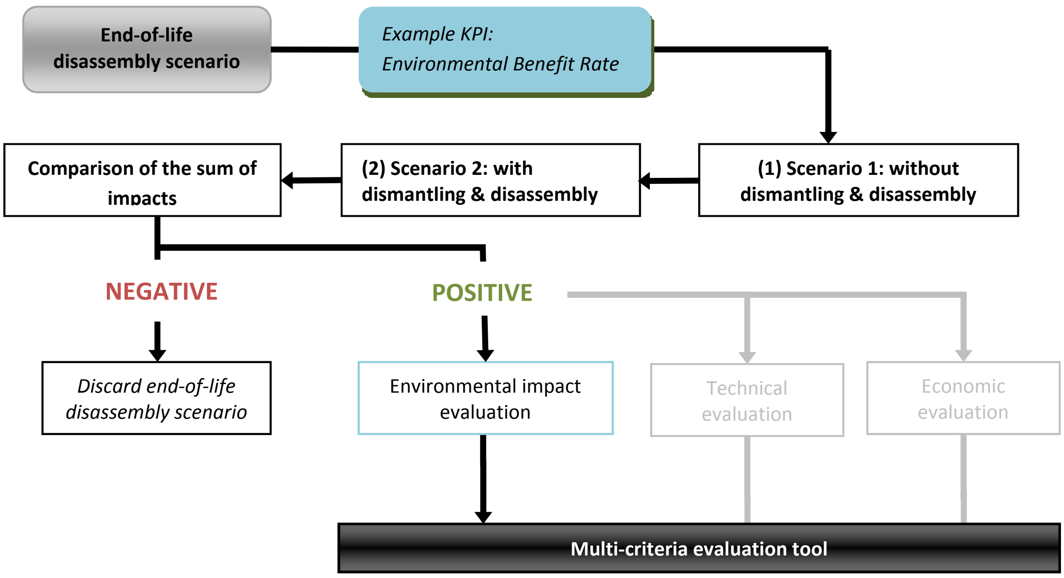


Figure 9.2 Detail of the evaluation method for environmental impact.

Table 9.1 Recovery of PMs by different recovery routes (adapted from Chancerel *et al.*, 2009; Meskers and Hagelüken, 2009).

	Recycling/recovery rate [%]			
Recycling routes	Cu	Ag	Au	Pd
Post-fragmentation separation	60%	11.50%	25.60%	25.60%
Pre-fragmentation disassembly	95%*	92%	97%	99%

Cu: Copper; Ag: silver; Au: gold; Pd: Palladium.
(*) IEC/TR 62635: recovery of copper from shredded parts

As discussed in Chapter 7 (see Figure 7.1), the first scenario is the traditional recycling chain; EV components go through de-pollution, fragmentation and material separation. The second scenario involves dismantling and disassembly of valuable or contaminating sub-assemblies for a separately processing procedure from the main vehicle core.

These dismantled and disassembled components or sub-assemblies may follow the same recycling chain (i.e. fragmentation and separation processes, but at a different time and possibly within different recycling facilities. In this way, cross-contamination during the fragmentation and separation processes can be avoided while increased quantity and improved quality of materials can be achieved. For example, the liberation of sub-assemblies (e.g. PCBs) improves the concentration of precious metals, e.g. Au, Ag, Pd, etc. within various waste streams.

PMs and SIMs, even if in small quantities, have an impact on resource depletion (as for example, the 'Abiotic Resource Depletion Potential – elements' (Van Oers *et al.*, 2002). Therefore, the selection of representative metrics plays a significant role in assessing the environmental impact for decision makers. In this context the, following are adopted in this assessment:

- Impacts due to virgin materials (V)
- Impacts due to the disposal of materials (D)
- Impacts due to recycling of materials (R)

The difference between the two scenarios represents the net benefit related to the application of disassembly process, estimated in terms of the additional mass of materials (PMs, copper) recycled per component. Table 9.2 has used the adapted RRR approach sourced from above mentioned publications (Ardente and Mathieux, 2012; Chancerel *et al.* 2009); Meskers and Hagelüken, 2009; IEC/TR 62635 2012). Based on ratios included in Table 9.1, and the weight of materials contained in the PCBs in the case study product (i.e. power management ECU), Table 9.3 summarises the expected value recovery from scenario 1 and 2. Following the prediction of materials recovered for each of the scenarios from ratios identified in previous publications, this research has defined the Environmental Benefit Rate (EBR) depicted in Equation 9.1 to compare the environmental benefit between scenario 1 and 2.

Table 9.2 Comparison between scenarios for a power management ECU.

PCBs - Power management ECU					
	Copper	*Silver*	*Gold*	*Palladium*	*Platinum*
Total mass (g/piece)	57.96842	0.31388	0.063031	0.002111	-
Recycling rates % (scenario 1)	60%	11.50%	25.60%	25.60%	25.60%
Recoverable materials in the scenario 1 (g)	34.78105	0.036096	0.016136	0.00054	-
Recycling rates % (scenario 2)	95%	92%	97%	99%	99%
Recoverable materials in the scenario 2 (g)	55.07	0.28877	0.06114	0.00209	-

Table 9.3 Calculation of the Recyclability benefit rate of a power management ECU.

Product Details						
Product Details	**Mass of the product**					
Power management ECU	729					
Recyable part	PCB					
Scenario 2_Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	5.7968E-02	95%	2.03E-03	1.14E-09	2.19E-04	9.97E-05
Gold	2.9770E-04	97%	5.82E+01	1.14E-09	2.22E-04	1.68E-02
Silver	6.6457E-05	92%	1.37E+00	1.14E-09	3.80E-06	8.38E-05
Palladium	2.1111E-06	99%	6.60E-01	1.14E-09	1.47E-03	1.38E-06
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	1.70E-02
Scenario 1_Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	5.7968E-02	60.0%	2.03E-03	1.14E-09	2.19E-04	6.30E-05
Gold	2.9770E-04	25.6%	5.82E+01	1.14E-09	2.22E-04	4.44E-03
Silver	6.6457E-05	11.5%	1.37E+00	1.14E-09	3.80E-06	1.05E-05
Palladium	2.1111E-06	25.6%	6.60E-01	1.14E-09	1.47E-03	3.56E-07
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	4.51E-03
		Recyclability Benefit Rate (%)	276.80%			

The EBR is therefore calculated using the following equation:

EBR (%) = $\frac{\mathrm{EB_{scenario\ 2}} - \mathrm{EB_{scenario\ 1}}}{\mathrm{EB_{scenario\ 1}}} * 100\%$ Equation 9.1

For example, for power management ECU using Equation 9.1, the EBR can be calculated as follows

In this case, EBR (%) = $\frac{1.70\mathrm{E}{-02} - 4.51\mathrm{E}{-03}}{4.51\mathrm{E}{-03}} * 100\%$ = 276.80%

9.4 Technological feasibility assessment of robotic disassembly

Unlike the vehicle de-pollution process that has a range of set procedures that can be carried out on all generic vehicle types, component removal and material recovery is very much a vehicle specific issue. The commonality between vehicles is that they all share the same standard functional assemblies. However, the material composition and design construction of the components are not as consistent, with specific components often requiring unique disassembly knowledge as to how best to remove the valuable sub-assemblies. Factors affecting component removal includes accessibility of sub-assemblies, joining methods, force and tools required. The diverse range of these factors highlights the need to use an analytical approach to assessing the technological feasibility of disassembly processes. A simplified technological feasibility assessment has been carried out in this research (see Figure 9.4). In particular, if the time and efforts to disassemble the components are too high, valuable sub-assemblies are not extracted; components are instead shredded together with other products. Data presented for time and cost associated with the disassembly could be utilised to assess different recycling scenarios within various target EV components. The outcome of this technological feasibility assessment is presented in a way that can be quantified with monetary-related terms (see Figure 9.3). Therefore, it is assumed that if the unit cost of automated robotic disassembly process for a component is less than the cost of manual disassembly, automated disassembly can be categorised as 'Technologically Feasible'. Other associated lead time of any production process, such as waiting time, setup time, process time, waiting time after process and transfer time have not been considered. The detailed time is illustrated in Table 9.4.

A simple cost model is proposed, based on experimental robot cell set-up cost (£50,000 for the purchase of robot, tools, fixtures and installation). A single worker is employed to work 8 hours a day, 250 days a year on the minimum wage of £15 per hour. This employee is responsible for several duties, including monitoring for faults and extracting components and sub-assemblies. The life of the robotic cell is estimated to be over 15 years based on the lifetime of the robot arm. The total costs associated with the disassembly arise from the setup cost (Sc) plus operating cost (O_C). In the case of

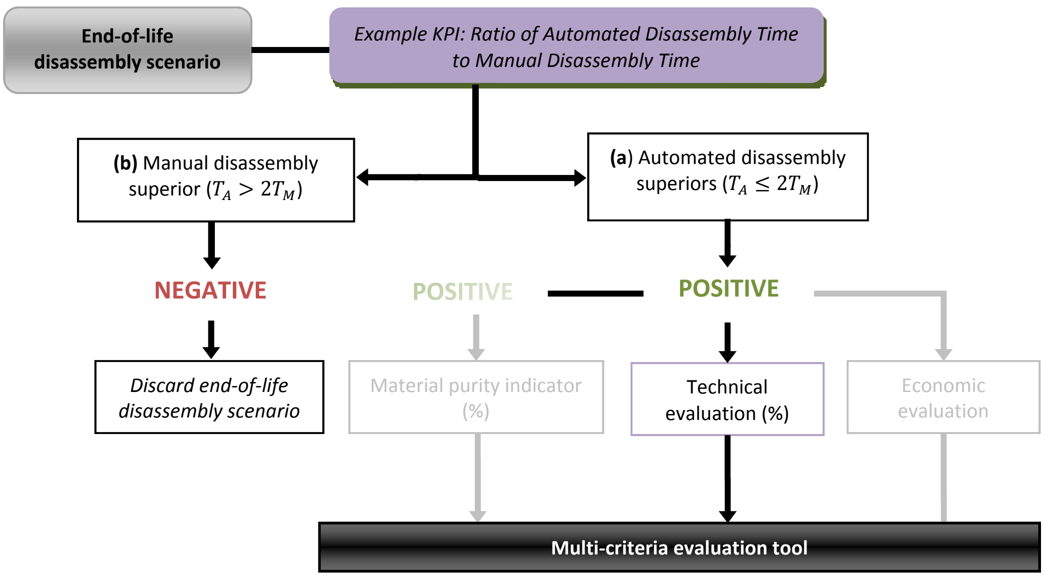


Figure 9.3 Detail of the evaluation method for technological impact.

Table 9.4 Fixturing time and tool exchange & handling time for manual and automated disassembly.

Manual Disassembly			**Automated Disassembly**		
Fixturing time (in seconds)		**in minutes**	**Fixturing time (in seconds)**		**in minutes**
Simple	10	0.17	Simple	60	1.00
Medium	20	0.33	Medium	80	1.33
Complex	30	0.50	Complex	100	1.67
Tool exchange and handling (in seconds)		**in minutes**	**Tool exchange and handling (in seconds)**		**in minutes**
Simple	10	0.17	Simple	50	0.83
Simple - Medium	25	0.42	Simple - Medium	80	1.33
Medium	40	0.67	Medium	110	1.83
Medium - Complex	60	1.00	Medium - Complex	110	1.83
Complex	80	1.33	Complex	170	2.83

manual disassembly, the total cost is only the operating cost, i.e. the labour cost (C_L). However, for automated disassembly, the setup cost for the robotic cell (Sc) needs to be taken into consideration. Thus, the associated costs include the labour cost, energy cost, setup cost and maintenance cost. It is assumed that the labour spends 1/5 of time on sorting robot issues and fixturing components. The detailed definition of parameters used in the technological assessment is illustrated in Table 9.5:

Tool Life (T_L) = 15 years= 2500 days = 30,000 hours

Total set-up cost = Cost {Robot, Tools, Cage, Fixturing} = £50, 000

Robot Life (T_L) = 15 years

Automated set-up cost (Sc) = £50,000/15 years = £1.67/hour

Operating cost (O_C) = Cost {Energy, Maintenance, 1/5Labour} = £1,000/year + £4000/ year + 1/5x £28,800/year = £33,800/year =£ 5.38 /hour

C_L = £15/hour

Therefore, assuming a labour cost for the disassembly process is £15/hour, and the unit cost for automated robotic disassembly is £7.17, therefore the extraction of PCBs is technologically feasible when the time of automated disassembly is equal or less than the twice of time of manual disassembly. If the automated robotic disassembly takes more than twice of the time of manual disassembly, it indicates that automation is not technologically feasible for the components.

Table 9.5 Definition of parameters used in technological feasibility assessment.

Costs	**Definition**
$D_{Cx} = DO_C + DS_C$	Total cost is the sum of setup cost and operating cost for the disassembly processes, in £
$DO_C = O_C \times D_T$	Operating costs for disassembly process, in £.
$DS_C = \frac{Sc}{T_L}$	Setup costs for the service life, in £ per 15 years.
O_C	Operating cost, in £ per hour.
Sc	Setup cost, including the initial investment for the disassembly cell, in £.
D_T	Disassembly time, in minutes.
C_L	Labour cost, in £ per hour.
Technological indicator	**Definition**
$T_x = \frac{DT_{A.D.}}{DT_{M.D.}}$	The key performance indicator (KPI) for technological feasibility assessment.

Therefore, assuming a labour cost for the disassembly process is £15/hour, and the unit cost for automated robotic disassembly is £7.17, therefore the extraction of PCBs is technologically feasible when the time of automated disassembly is equal or less than the twice of time of manual disassembly. If the automated robotic disassembly takes more than twice of the time of manual disassembly, it indicates that automation is not technologically feasible for the components.

For the power management ECU, the detailed calculation is illustrated in Table 9.6. The ratio is 1.138 which is less than 2, therefore, automated robotic disassembly is technologically feasible for the power management ECU.

9.5 Economic Assessment of robotic disassembly

The major economic driver behind these electrical and electronic components from EVs is the revenue from the recovery of PMs and SIMs. The economic assessment is based on the recovery yields, and on the average market value of recycled materials and disassembly times from both manual and automated disassembly. A Cost-Benefit Analysis (CBA) approach is adopted and developed in this economic assessment in order to provide an economic performance metric for EV components. This CBA is used to support decision-making among a variety of components with various material composition and design characteristics. From an economic impact perspective, financial estimations of the cost and benefits are developed to determine the economic viability.

CBA allows a relatively holistic approach to the evaluation of economic performance by extending economic analysis to include both direct and indirect benefits and costs (Doeleman, 1985), the economic assessment adopted in this research utilises a simplistic manner to quantify direct costs and revenues (see Figure 9.4). Results from the economic evaluation are presented to the decision makers, and the final economic performance score provides the inputs to the multi-criteria decision support tool.

In order to illustrate this approach, a summary of the parameters used in the development of this model is presented in Table 9.7, and outline below:

Table 9.6 Detail of the evaluation method for technological feasibility.

	Total Disassembly Time (minutes) Including Tooling & Fixturing Time		Fixturing time (minutes)		Tool exchange and handling time (minutes)		Disassembly Time (minutes)		Ratio of the manual disassembly time to automated disassembly times
	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	Ratio=Automated/Manual
Power management ECU	2.00	3.73	0.17	1.00	0.17	0.83	1.67	1.90	1.138

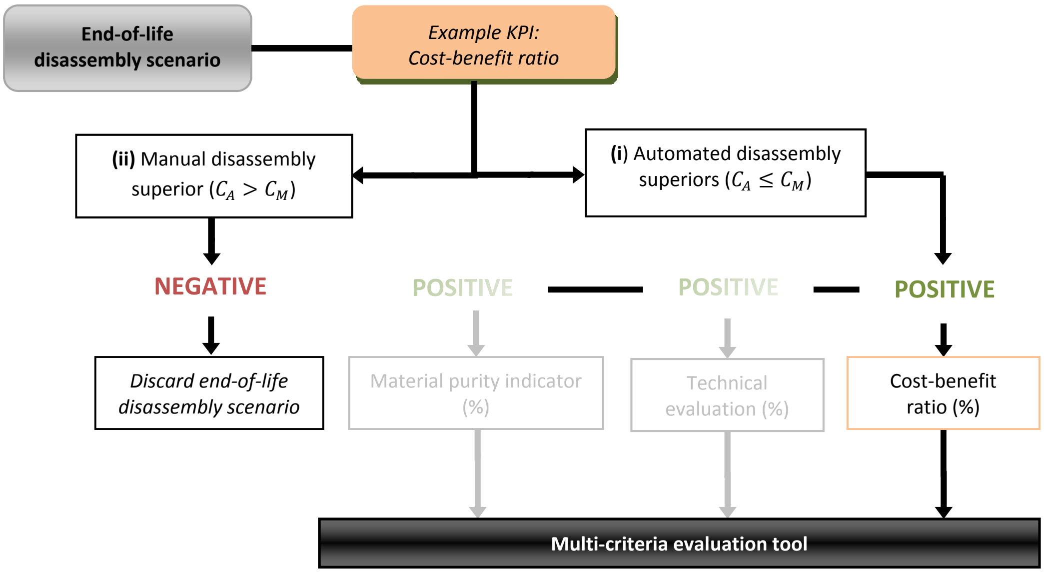


Figure 9.4 Detail of the evaluation method for economic assessment.

Table 9.7 Definition of parameters used in defining parametric cost-benefit models for disassembly methods.

Benefits	**Definition**
$MV_R = M_R \times M_V$	The revenue recovered from the recovery of valuable materials, in £. For any disassembly path one or more valuable materials may be extracted and recovered.
M_R	The weight of valuable material recovered, in Kg.
M_V	The market value of recovered material in £ per Kg.
Revenues	**Definition**
$\sum V_P = \sum MV_R - \sum D_C$	The profit recovered from the recovery of valuable materials, in £.
$\sum MV_R$	The material value of recovered materials, in £.
$\sum D_C$	The total disassembly cost, in £.

$$\sum MV_R = \sum(M_R \times M_V) \qquad \text{Equation 9.2}$$

$$\sum D_C = \sum((\frac{Sc}{T_L} + O_C) \times D_T) \qquad \text{Equation 9.3}$$

$$\sum V_R = \sum(M_R \times M_V) - \sum((\frac{Sc}{T_L} + O_C) \times D_T) \qquad \text{Equation 9.4}$$

$$\sum V_{P\_Manaul} = \sum(M_R \times M_V) - (C_L \times D_T) \qquad \text{Equation 9.5}$$

$$\sum V_{P\_Automated} = \sum(M_R \times M_V) - ((\frac{Sc}{T_L} + O_C) \times D_T) \qquad \text{Equation 9.6}$$

For instance, for the power management ECU, the value of recovered materials is £2.20 per unit (as shown in Table 9.8). The manual disassembly cost is £15/hour, and the set-up cost and operating cost in automated disassembly are £1.67 and £5.38, respectively. Furthermore, the total disassembly times including fixturing and tool exchange and handling for manual disassembly and automated disassembly are 2.0 minutes and 3.73 minutes, respectively.

Therefore, the revenues are

$$V_{R\_Manaul} = £2.20 - \frac{£15}{hour} * 2.0 minutes = £1.70$$

$$V_{R_{Automated}} = £2.20 - \left(\frac{£5.38}{hour} + \frac{£1.67}{hour}\right) * 3.73 minutes = £1.76$$

$$\frac{V_{R\_Manaul}}{\sum MV_R} = \frac{£1.70}{£2.20} = 0.77$$

$$\frac{V_{R\_Automated}}{\sum MV_R} = \frac{£1.76}{£2.20} = 0.80$$

It needs to be highlighted that throughout this section, values for each of the required parameters are developed from available data, originating from a variety of sources (experimental results and analysis).

Table 9.8 Material recovery values and disassembly times for power management ECU.

Component Name: Power management ECU			**Total Disassembly Time (Minutes)**	
Material(unit: g/gram)		Price (£/g)	Including Tooling & Fixturing	
Ag	0.289	0.37	Manual	Automated
Au	0.061	28.2	2	3.73
Pd	0.004	16.82	**Total Disassembly Cost (£/piece)**	
Cu	55.075	0.0041	Manual	Automated
Ni	0.801	The value of those materials is excluded in this cost model.	1.45	1.07
Pb	0.137		**Processing Cost (£/piece)**	
Sb	0.054		0.68	
Sn	4.358		**Recovery profit (£/piece)**	
Zn	5.146		Manual	Automated
MgO	0.508		-0.01	0.37
Al2O3	22.747		**Cost-benefit ratio**	
CaO	11.510		Manual	Automated
SiO2	37.442		-145	2.891891892
Fe	6.902			
Mn	0.146			
TiO2	0.745			
BaO	2.168			
Total £ per part $\sum MV_R$ = £ 2.12				

It is expected that the economic benefits of the automated disassembly would be greater if implemented in an industrial working environment as it is assumed more efficient tooling and fixtures would be used, and mass purchase of robots would lower the overall cost of purchase and installation. The challenges and limitations associated with data collection for the economic evaluation are illustrated and discussed through the case studies reported in Chapter 10.

9.6 A multi-criteria decision support tool

A multi-criteria evaluation tool has been developed to allow the output from the environmental performance, technological feasibility assessment and cost-benefit model to be considered together. This multi-criteria decision-making tool evaluates environmental benefits, technological feasibility and economic viability of each EoL scenario, and provides the most appropriate recycling approach. The Multi-criteria Matrix methodology is based upon classical techniques, referred to Eco-compass (Steuer and Na, 2003), which represents an important tool to produce a holistic description of various aspects to assist decision makers to address multiple criteria problems. Adapted from the Eco-compass approach, the multi-criteria decision-making tool has six poles or dimensions that are intended to encompass the proposed significant issues. In addition, assessment is more about valuing than about calculating. In the assessments, the question is not whether a proposed approach is acceptable, but whether it is the most suitable to serve the purposes and meeting the criteria.

The application of this multi-criteria decision support tool for EoL management of EV components is described in Section 9.6.1 – 9.6.4 below. The main limitation of this method is that the representation of the final assessment results requires all individual criteria to be expressed using the same format (units). This is not directly achievable using the previously discussed evaluation approaches in Section 9.3 - 9.5. In order to overcome this problem, a normalisation step is conducted on individual evaluation criteria, before the multi-criteria decision support tool is used. Since the multi-criteria assessment is a comparative tool, the results values can be normalised using a simple relative normalisation method.

9.6.1 Define evaluation criteria

An element of transparency is critical in supporting decision-making; therefore, the output from each assessment category is provided in two sub-categories. On the first level (E1, T1 and Eco 1), a set of parameters is presented as key performance indicators (KPIs) that have been detailed in Section 9.3, 9.4 and 9.5. The second set of parameters (E2, T2 and Eco 2) provides more illustrative evaluation results. These results are presented for a single comparison and represent the impact assessment results, prior to any normalisation. An overview of the assessment indicators and related formula are provided in Table 9.9.

Table 9.9 Definition of the assessment indicators.

Identifiers	Indicators	Formula	Normalisation Comments	Minimum	Maximum
E1	Environmental Benefit Rate	EBR (%) = $\frac{EBR_{robt-}EBR_{manu}}{EBR_{manu}}$	The minimum value has been set to 100% where recyclability benefit rate is 100% in the base case; and the maximum value is provided by the results from applied components.	100%	MAX
E2	Target Material Concentration	TMC (%) = $\frac{Mass_{target}}{Mass_{total}}$	The minimum value has been set to 0% when none of the targeted material is constituted in the component; and the maximum value has been set to 100% when targeted materials constitute 100% of the component.	0%	100%
T1	Total Disassembly Time	TDT (%) = $\frac{T_{manu}}{T_{robt}}$	The cost ratio of manual disassembly and automated disassembly is A which indicates that the threshold minimum value has been set to 1/A	1/A	MAX
T2	Robotic Disassembly Complexity	DC =$1/\sum_{1}^{3} M_i$	i refers to sub-categories, including total number of robotic operations, total number of required tool-change operations, and range and number of joining methods used in the target product. The minimum and maximum values are both provided from the assessment results from various components.	MIN	MAX
Eco1	Disassembly Cost/Revenue Ratio	$\mathrm{DCRR}\ (\%) = \frac{\frac{C_{manu}}{R_{manu}} - \frac{C_{robt}}{R_{robt}}}{\frac{C_{manu}}{R_{manu}}}$	The minimum and maximum value both depend on the assessment results from various components.	MIN	MAX
Eco2	Robotic Disassembly Profit	$P_j = R_j - C_j$	j refers to different components, and the minimum and maximum value both depend on the assessment results from various components.	MIN	MAX

The goal of the environmental assessment is to provide an evaluation of the environmental impacts of alternative EoL scenarios for the EV components (scenario 1, scenario 2). The first indicator, EBR presents the environmental performance of material production, recycling and disposal phases. Recovered and recycled materials are considered as avoided impacts, and the overall environmental impact is the sum of individual impact of each material. The concentration of the targeted materials is also selected as an indicator, to present the amount of scarce or depleting materials used in each component.

In the technological feasibility assessment, the first indicator is the total time ratio of manual disassembly (T_M) to automated disassembly (T_A) and the second indicator is the complexity of the automated disassembly process. Different factors have been considered to represent complexity in disassembly, including the total number of tool changes and operations, and the joining methods (see Table 9.10).

In the economic assessment, the first indicator indicates the difference between 'disassembly cost and revenue ratio' for manual and robotic disassembly divided by disassembly cost and revenue ratio' for manual disassembly. In order to have a straightforward understanding of the economic performance, the automated disassembly profit is selected as the second indicator.

9.6.2 Normalisation

The results for the three individual evaluation methods differ significantly and have no relationship to each other. This disparity is addressed in the subsequent normalisation step, which allows three performance metrics to be considered simultaneously in six poles or dimensions. The only similarity between the values for the individual criterion evaluation methods is that a high value represents a favourable outcome on scenario performance.

Table 9.10 Rules for assessing the automated disassembly complexity.

Score	**Number of tool change (M_1)**	**Number of operations (M_2)**	**Ease of breaking the joint method (M_3)**
0	N1>6	N2>10	Mixed materials, various joint methods
1	4<N1≤6	8<N1≤10	Mixed materials, bolted joint
2	N1=4	N2=8	Metallic materials, various joint methods
3	2<N1≤3	5<N1≤7	Metallic material; clip, snap-fit
4	1<N1≤2	3<N1≤5	Plastic materials; bolted joint or various joint methods
5	N1=1	N1≤3	Plastic materials; clip, snap fit
Overall Score (OS) = $\sum_1^3 M_i$			

9.6.2.1 Normalisation approach

Feature scaling, a simple normalisation approach, has been applied to standardise the independent variables to rescale the range of features to scale the range in [0, 1]. The general formula is given as

$$Env_{Ni} = \frac{Env_i - Env_{\min}}{Env_{\max} - Env_{\min}} \quad \text{Equation 9.7}$$

$$Tech_{Nj} = \frac{Tech_j - Tech_{\min}}{Tech_{\max} - Tech_{\min}} \quad \text{Equation 9.8}$$

$$Eco_{Nk} = \frac{Eco_k - Eco_{\min}}{Eco_{\max} - Eco_{\min}} \quad \text{Equation 9.9}$$

Where i, j and k represent the indicators, equal to 1 or 2; Env_i, $Tech_j$ and Eco_k are original values, Env_{Ni}, $Tech_{Nj}$ and Eco_{Nk} are the normalised values, and $Env_{\max/\min}$, $Tech_{\max/\min}$ and $Eco_{\max/\min}$ represents the maximum and minimum scores from different EV components for environmental, technological and economic impact, respectively. Normalised scores are expressed as a fraction of the difference score for each criterion. These scores are calculated automatically and are presented as numerical values which will be used for the comparison between different EV components across each of the three evaluation criteria and six indicators.

9.6.2.2 Determination of the value limits in the multi-criteria assessment

The maximum and minimum values for the normalisation approach are illustrated as shown in Table 9.9. For example, the minimum value for the environmental benefit rate is based on the assumption that in the worst case scenario, the pre-fragmentation concentration could perform 100% better than the post-fragmentation separation. Therefore, the rate would be 100%. The maximum value is the highest one among the assessment results as the best scenario. Additionally, the manual disassembly cost is as twice the cost of automated disassembly. In order to make the robotic disassembly approach economically viable, its time should be less than twice that of the manual disassembly time. Thus, 0.5 is set to be the minimum value (worst case).

9.6.3 Interpret results

Based on the single-figure impact scores from each assessment category, the eco-compass approach was adapted and utilised to present the impact assessment data. The normalised outputs are multiplied by five to scale range [0, 5]. The normalisation process regarding the environmental assessment is illustrated in Table 9.11.

Table 9.11 A normalised example in the environmental assessment.

Component	Original data	Normalised Score	
Power steering ECU	316.01%	4.914	Minimum score
Engine ECU	279.80%	4.090	
Driving support ECU	283.18%	4.167	100.00%
Power management ECU	276.80%	4.022	Maximum score
Airbag ECU	282.87%	4.160	
Combi-meter	319.79%	5.000	319.79%

In this section, the assessment results of the power management ECU are provided as an example. Figure 9.5 shows the compass plot of results for power management ECU. It is clear that relatively high scores of the environmental indicators, i.e. E1 and E2 indicate that the power management has great environmental performance. Even the automated disassembly took longer time than manual disassembly operations; it has great potential to improve the technological feasibility due to its relatively simple structure and joining method. Regarding the economic performance, compared to other EV components, the revenue-cost ratio is relatively low; but its disassembly profit has great potential among the targeted components based on current set-up of the robotic disassembly system.

9.7 Chapter summary

In this chapter, methods have been described for the evaluation of disassembly scenarios for EV components recycling based on three criteria. With regards to the evaluation of the environmental impact, a KPI - material recovery rate, has been used as one indicator to analyses the environmental performance of both manual disassembly and automated disassembly respectively. Technological feasibility has also been evaluated using total disassembly time and complexity. Economic impacts associated with automated disassembly are quantified using a simplified CBA method. These evaluation measures provide inputs to a multi-criteria assessment tool developed to support decision making during the design and

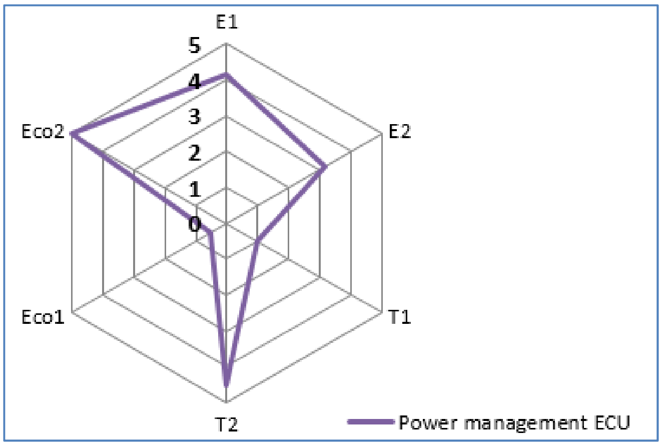


Figure 9.5 Multi-criteria assessment result for power management ECU.

development of automated robotic disassembly for EV components. This evaluation approach proposed to support decision making was refined using case study components and is further explored in following chapters to demonstrate the benefits and limitations of the assessment approach.

CHAPTER 10 AN AUTOMATED APPROACH FOR EV RECYCLING: CASE STUDIES

10.1 Introduction

The previous chapters have discussed the various stages in the EoL – EV framework. This chapter utilises three case study components that have been selected to demonstrate the application of the EoL-EV framework and its associated decision-making tool. The chapter begins by providing an overview of the case studies, followed by a systematic description of the application of the automated robotic approach and the multi-criteria assessment. The chapter concludes by analysing the results from all case studies, in order to reflect on the validity of the framework and assessment method in supporting the application of automated disassembly processes in EoL EV recycling.

10.2 Case study overview

The aim of the research reported in this thesis is to provide appropriate EoL management solutions for EVs through robotic disassembly processes. The foundation for this approach is the application of automation as a pre-concentration process of the vehicle recycling system. This automated robotic approach provides an opportunity for improvement in environmental, economic and technological performance.

Case study products need to be selected in order to demonstrate the application of the framework for EoL management of EVs as described in Chapter 7 of the thesis. The overall outcome of the screening of EV components is to identify suitable components to validate the environmental, technological and economic impacts of optimum recycling solutions.

10.2.1 Selection criteria for case-study products

The following paragraphs illustrate the criteria for the selection of the case study products. Criteria have been identified and can be grouped into three areas according to their subject:

A. Relevance of the case study products within the research scope

The selection of the case study products should focus on the EV components that may affect the current vehicle recycling and recovery system. Due to their sophisticated material composition and construction, a novel recycling approach is required to be developed for maximising the recovery value and minimise the environmental impacts.

B. Relevance of the case study products with potential requirements on materials

The scope of this criterion is to focus on the products that contain valuable and priority parts and materials that are relevant for their environmental impacts. The valuable materials include PMs (gold, silver, platinum), SIMs (palladium) and widely used basic materials (copper, steel, aluminium). It is noted that most of these materials are constituted in the PCBs and contained in the electrical and electronic components.

C. Relevance of the case study products for different scenarios

The scope of the case study is to test and validate the applicability of the automated robotic approach and multi-criteria assessment for different components embodied in EVs. The selected case study products should cover various cases in terms of the design construction and recovery value. Therefore, each EV component is categorised as one of defined groups based on permutation of its design (simple, medium and complex) and value (low, medium and high).

10.2.2 Overview of selected case study products

As discussed in the review of advancements in automotive technology in Chapter 3, electronic components in EVs have been steadily increasing to enable advanced safety features, improved energy efficiency and entertainment systems. Within this research, automotive parts that most suitable for disassembly are identified. Automotive electronic components can be reused or remanufactured for spare parts or recovered as materials for their intrinsic value (Optimat, 2013). For these parts that are more durable are more likely be directly reused or remanufactured, such as engines, transmissions, starters (Sawyer-Beaulieu et al., 2015) (that is beyond the scope of this research). Besides these options, some car parts would be more suitable for material recovery, such as electronic components, permanent magnets that contain a variety of PMs and REEs. Facing the challenges of high demand and export control, these materials are extracted and recovered from dismantling and disassembly operations (Saeki et al., 2014). The selection of target components involves the cooperation with an automotive manufacturer and precious metal recyclers. During the course of this research, the automotive manufacturer provided EV components, and the PMs recyclers were responsible for relevant chemical analysis and material recovery. The appropriate EV components have been selected (see Figure 10.1) based on the following criteria:

Identifier	Component
T01	Power steering ECU
T02	Engine ECU
T03	A/C unit and ECU
T04	Driving support ECU
T05	Power management ECU
T06	Airbag ECU
T07	Window regulator
T08	Radio/GPS
T09	Combi-meter

Figure 10.1 Potential case study components and their identifiers.

- Components are less durable and amendable for direct reuse or remanufacture, and contain valuable materials, i.e. PMs and REEs. Therefore, the majority of the components selected are ECUs and components contain PCBs.
- Components with various recovery values and design structure, such as components with high/low potential value, cased in plastics or metallic materials and with a regular or irregular shape.

In order to demonstrate the flexibility of applying the EoL-EV framework, selected components have been classified into categories based on their design construction and material recovery value. Components are analysed regarding their materials and construction as shown in Table 10.1. Furthermore, an economic evaluation was undertaken by the recyclers to assess the commercial viability of extracting valuable materials. Based on the percentage of the valuable materials (PMs and REEs) in the overall weight of a component, components are labelled as "high value (more than 70%), medium value (30% - 69%) and low value (less than 30%)". Regarding the design contracture, three categories are identified through the consideration of disassembly complexity, i.e. the number of parts, the sub-assemblies' geometric accessibility.

Nine potential components are assessed and classified in Figure 10.2 in which three components have been selected as case study products to reflect three different modes of application of the framework. They are also used to investigate the applicability of the automated robotic approach, which demonstrates compliance with improved environmental performance, technological feasibility and economic benefits. The first case study product demonstrates the application of automated approach in the component category of 'simple construction, low value'. The second and third case studies demonstrate the ability of the framework in supporting the automated approach in components with 'medium construction, high value' and 'complex construction, low value', respectively. The example component used in Chapter 8 and Chapter 9 represents the category of 'simple construction, high value'.

Table 10.1 List of potential case study components.

Component Identifier	Component Name	Description
T01	Power steering ECU	Plastic casings and PCBs
T02	Engine ECU	Plastic and metallic casings and PCB
T03	A/C unit and ECU	Very hard metallic casing and lid, specially designed safety screws, and a small piece of PCB
T04	Driving support ECU	Relatively easy to have access to the PCB, irregular construction make it difficult for fixturing and a small piece of PCB
T05	Power management ECU	Simple construction and consists of aluminium and steel casings and a large piece of PCB
T06	Airbag ECU	Simple construction and a relatively small piece of PCB
T07	Window regulator	Rare earth materials are contained in magnets, no PCB embodied in the component
T08	Radio/GPS	Large quantity of PCBs and very complex construction, difficult to access to the valuable parts/materials
T09	Combi-meter	Complex construction with plastic casings and a group of PCBs

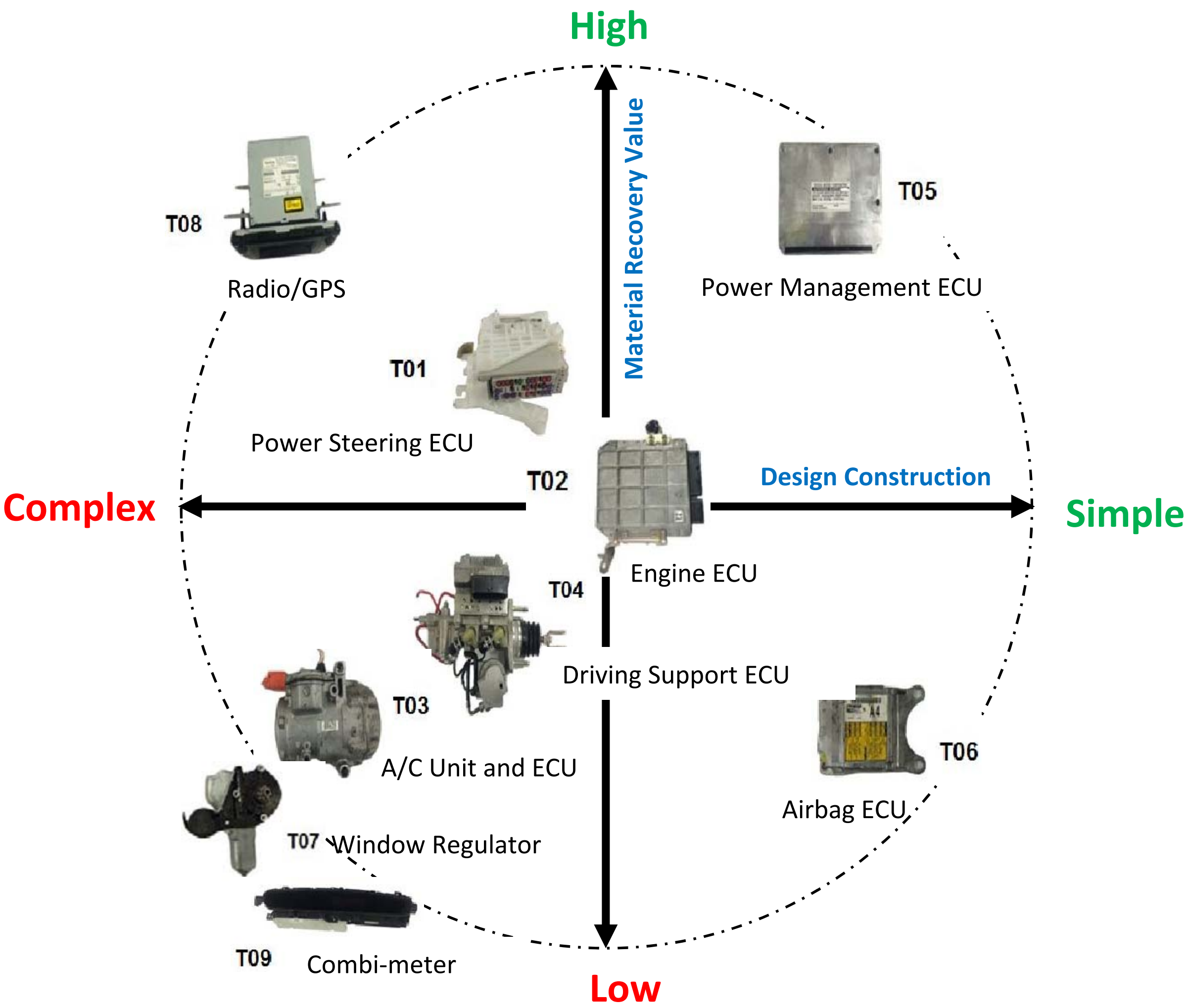


Figure 10.2 Classification of target components.

During the course of the research reported in this thesis, the automotive manufacturer was involved in a collaborative project with other material recyclers on a larger commercial scale to investigate alternative process routes for material recovery from EV components. The research reported in this thesis is based on small-scale laboratory experiments, in order to evaluate the suitability and feasibility of the automated robotic approach for future EV recycling; and to help inform their wider collaborative projects.

From the laboratory and industrial trials described above, different recycling routes have been identified as being feasible for the recycling and recovery of materials from EV components. In order to prioritise further development efforts concerned with the optimisation of the most suitable EoL recycling technologies and processes, it is necessary to evaluate the technical feasibility of the automated robotic approach and associated environmental and economic performance.

10.3 Case study 1: Airbag ECU

The electrical component under consideration in the first case study is an airbag ECU (see in Figure 10.3. An Airbag ECU is utilised to manage the deployment of a bag that fill with gas in the event of an accident. During the journey, the sensors and electronic system exchange real-time information and make record in the central monitoring system. Once a massive variation signal is detected by the sensors, this information is sent to and processed by the ECU. To deal with the collision, the air-bag will be deployed. This safety system significantly decreases injuries and fatalities during automotive accidents (Breakeryard, 2014). It has been selected because it mainly consists of metallic casings and a PCB, categorised as a simple construction and low value product. In keeping with the structure of the EoL-EV famework, as outlined in Chapter 7, the following phases are applied in all case studies: 1) an automated robotic approach, including three steps: manual disassembly, initial semi-automated disassembly and optimisation and validation of automated disassembly; and 2) application of multi-criteria decision-making assessment, including environmental performance assessment, technological feasibility assessment and economic viability assessment.

Figure 10.3 An airbag ECU.

Section 10.3.1, 10.3.2 and 10.3.3 below document the first three steps of the automated approach as applied to case study 1, including the description of a series of experiments and data collection. Section 10.3.4 describes the implementation of the case study and the application of the evaluation approach. Results from the multi-criteria evaluation method are analysed in section 10.3.5.

10.3.1 The first step: manual non-destructive disassembly

It is reported that disassembly has been considered as one of the critical elements in product recycling and recovery activities. The product configuration affects EoL management from the perspective of accessibility of valuable part and materials; and the complexity of the design construction. Therefore, as illustrated in Chapter 8, the first step of the automated robotic approach for EV recycling is complete, non-destructive manual disassembly. It is concerned with the definition and collection of relevant information and parameters which may constrain and dictate the nature of EoL options. This step aims to understand how components were constructed prior to developing a disassembly strategy. Through a complete, manual disassembly, the level of required disassembly and the potential recovery of (hidden) value can be identified by investigating the design construction and material composition of the targeted components.

The first step as per EoL EV recycling is the manual non-destructive disassembly, as shown in Figure 10.4. An airbag ECU consists of four parts, including an aluminium lid, a steel casing, a PCB and screws. It is identified that besides the metallic casings, the PCB is the valuable part that was aimed to be extracted through disassembly processes. This manual disassembly would provide knowledge regarding which sets of operations would be required to extract the targeted sub-assemblies from the component using the robot. An overview of the disassembly

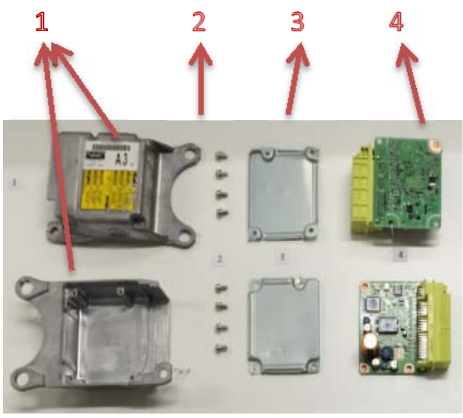


Figure 10.4 A breakdown of the airbag ECU.

Table 10.2 Disassembly datasheet for airbag ECU.

Name of the components		Airbag ECU	
Total weight (g)		267	
Total time (minutes)		1.4	
Weights for each parts (g)			
No.	Items	Weight (g)	Material
1	Rear casing	148	Steel
2	Screws and washers	7	Steel
3	Lid	32	Aluminium
4	Printed circuit board (PCB)	80	Multi- Material
Manual disassembly processes			
No.	Disassembly steps	Tools used	Time (seconds)
a	Fixturing	human force	10
b	Unscrews 4 screws on the lid	human force	54
c	Lift off the lid	screwdriver	5
d	Get the PCB out	human force	5
e	Tool exchange and handling	human force	10

result is illustrated in Table 10.2 including the total and individual disassembly times, and tools used during the disassembly. Therefore, based on the component construction and material composition, the airbag ECU is categorised as a ‘simple construction, low value’ component. The material composition analysis will be discussed in the economic feasibility assessment in the following assessment section.

It was identified that there were variations in design and EoL conditions. Ideally, the references used in fixturing need to be standardised for all designs without extra fixturing steps and accessories. Nevertheless, the various design features increase the complexity in fixturing and automated operations. In addition, it has been noticed that screws heads were in different conditions, i.e. complete, and partially ruined. For example, stripped cross-head screws require longer time and specific tools to remove it manually. However, in the case of automated disassembly, the stripped screws can be milled off directly rather than being unfastened.

10.3.2 The second step: initial semi-destructive automated disassembly

An automated semi-destructive disassembly process has been developed using a flexible robotic cell, as shown in Chapter 8. Based on this set-up, a number of various experiments were designed and undertaken to investigate the feasibility of robotic operations, the capability of the robotic tools and the suitability of the fixture platform. These experimental results will be used to support the validation and optimisation robotic disassembly processes in Section 10.3.3. In step 2, based on the information gained from manual disassembly, a specific set-up for fixturing and robotic operations required for disassembly of the airbag ECU were developed. The results from a series of disassembly trials in terms of different set-ups using various fixturing methods and tooling test are outlined below:

10.3.2.1 Fixturing mechanism

The disassembly plan aims to lift off the aluminium lid and extract the PCB inside. Therefore, the fixturing approach needs to avoid the fixturing accessories being used from the top of the components (i.e. clamp) to prevent the fixturing accessory getting in the way of the robotic tools in the operation.

As shown in Figure 10.5, in trial 1, five stops and bolts were used to fixture the airbag ECU on the table. However, it turned out this fixturing method lacked stability because the component did not have a regular shape and flat bottom. The Trial 2 has taken advantage of this particular characteristic of the component to improve the repeatability and reliability of the fixturing. The extended edge was fixed using a customised platform with a suitable height. Additionally, a clamp was utilised to fix the component from the top. Trials 3 provided a reliable fixturing

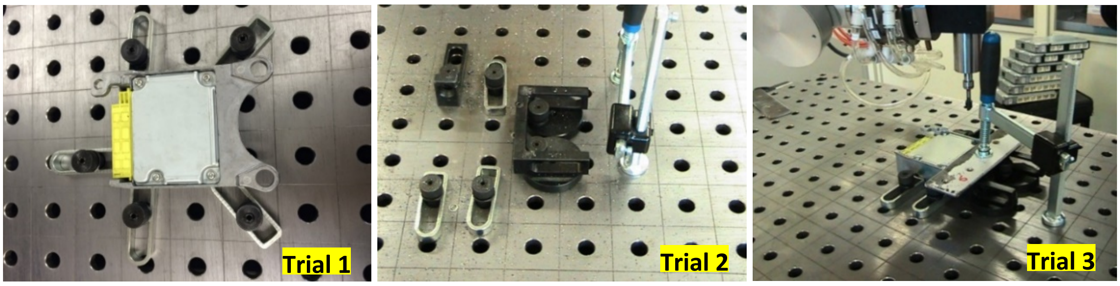


Figure 10.5 Fixturing methods.

mechanism, consisting of four stops, two angle brackets, six bolts, two eccentric pads, one piece of metal sheet and one clamp.

10.3.2.2 Tools test

A series of experiments have been implemented for exploring and investigating the capability of the tools. In this section, a particular emphasis has been given to identifying the most suitable tools to improve the disassembly efficiency and performance.

In the initial set of automated experiments, a comparative milling test has been completed. The test aims to investigate the feasibility and reliability of various types and sizes of the milling bit in the specific milling operation for airbag ECU (shown in Figure 10.6). The maximum shank capacity of the robotic milling tool is 6 mm, and the diameter of the screws of airbag ECU is 8 mm. Thus, the shank of the milling bits should be 6 mm to fit in the robotic tool. At this step, the diameters of 6 mm and 8 mm of the milling bits were tested. Additionally, it is noted that carbides are extremely hard and more brittle than steels; tungsten carbide milling bits are bonded together in a cobalt matrix and usually used for milling steels and cast irons, and AlTiN coated bits have a thin film coating that offers higher temperature resistance and slightly higher hardness than Titanium Nitride.

Overall it has been identified that the coated carbide milling bits provided a much smoother run than standard ones; the tungsten carbide milling bit has improved strength and hot hardness, and while larger mill bit head diameters (8 mm) and larger helix angles (120°) were

No.	Milling bits
1	6mm carbide 90° milling bit
2	6mm carbide 60° milling bit
3	6mm spiral-shape milling bit
4	6mm standard twisted milling bit
5	8mm point AlTiN coated carbide 60° milling bit
6	8mm Tungsten carbide 90° milling bit
7	8 mm Spot AlTiN coated carbide 120° milling bit

Figure 10.6 Various milling bits.

found to help reduce the milling time and mill failure. Additionally, coating the drill bit was able to mitigate the tool wear and extend tool life.

It was noted that the washers underneath the screws could interfere with the milling process. If the washer had not been removed in the milling operation, it could become attached to the screw and stop the screws being milled out, as shown in Figure 10.7. Therefore, bigger sizes of the milling bits have been investigated to resolve this problem. It turned out that increased helix angle and diameter of the milling bit helped expand the contact area so that the screws and washers can be removed easily.

In the gripping test, the standard two-finger parallel gripper failed to achieve a repeatable lifting process, due to the limitation in space around the lid and the PCB. However, the vacuum gripper in the trial experiments successfully removed the lid and PCB from the components. Ideally, the vacuum gripper is used on a smooth surface; therefore, different locations on the lid and PCB were tested to identify a repeatable lifting process. The aluminium lid was light and thin; therefore, a vacuum gripper was the suitable tool to lift it up. However, the surface of the airbag ECU lid was rough; various gripping locations on the PCB were investigated (see Figure 10.8). It is noted that soldering points on the back of the PCB caused the surface of the PCB also to be particularly rough, causing some problems for the vacuum gripper. Compared with these soldering point areas, relatively smoother areas were found on the PCBs that were easier to be attached and gripped. Therefore, five locations were fully evaluated. The furthest left one (shown in blue) had a longer distance to the centre of gravity that resulted in a relatively low success rate. Even though the surface condition of the furthest most right points (shown in pink and red) were superior to the other two, the positions centre of gravity was again not suitable, it still caused imbalance. Therefore, the location highlighted in yellow was selected to be the gripping point for the PCB in this instance.

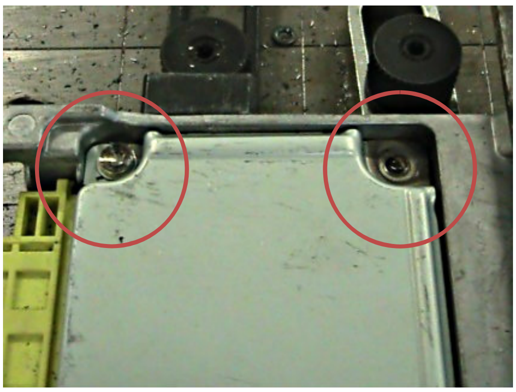


Figure 10.7 Washer issue.

Figure 10.8 Gripping test results for the lid.

10.3.2.3 Operating parameters test

In the evaluation of the milling operation, the length of the screw head is 3 mm, therefore, the primary milling depth was set to 4 mm. Based on the initial fixturing plan, the milling speed was set to 0.58% in manual mode. The first screw head was half milled off and the second screw head was burned and attached/melted to the washer. The second set of experiments aimed to increase both the milling depth and speed. The end success rate was 50% because the milling bit often missed the centre of the screw heads. After the enhancement of the fixturing reliability and refining of the screws position, the milling operation was divided into a two-step approach, associated with two milling depths, carried out one after the other. Between two attempts, the “wait end move” code was embedded into the program so that it ensured the individual milling process was completed, prior to the second starting, this left time to disseminate the heat from the milling drill bit.

10.3.3 The third step: optimisation and validation of automated disassembly

This step is concerned with improving the efficiency and repeatability of robotic disassembly processes to maximise the value recovery, including 1) identifying the most appropriate tool set-up and disassembly strategies for EV components; 2) developing the most efficient disassembly processes with minimised numbers of re-positioning, tool change and operations; and 3) assessing “trade-off” between disassembly level and recovery value to optimise the economic viability of disassembly operations. Thus, overall processing times of tool operations and tool changes can be reduced, within any extraneous movements thus removed or shortened.

Various factors are taken into consideration, including fixturing, operating parameters and tool exchange. The main difference in total operational time observed between manual and semi-automated approaches in these experiments is due to the fixturing time of the component.

Compared with the initial fixturing plan, more complex fixturing consists of increasing numbers of accessories use to secure the components, generally increasing the fixturing time. Besides the time consumption, the fixturing reliability and repeatability are also significant in the automated robotic disassembly processes. It is expected that in a commercial implementation of such a robotic disassembly cell, an especially designed fixture would be developed which would significantly reduce the total fixture time. Additionally, an increase in tools size and type helped reduce the milling operation time. It was identified that the 8mm-diameter spot AlTiN coated carbide 120° milling bit took the shortest time to mill off the screw heads. Without a cooling system, however, the heat generated from the milling operation may exacerbate the tool wear significantly. Therefore, it was found that after operation of 20 components, the milling bit would need to be re-sharpened in the workshop.

In the initial set of experiments, the operation speed is the maximum capacity in the manual mode. However, when the fixturing and automated operations have been finalised, the robot can be set to the automated mode which maximum speed is twice as fast as the ones in manual mode. However, due to safety considerations, the tool pick-up, exchange and put-back operations were not set with maximum speed, this was to avoid accidental damage to any of the tools and the robot, however in a commercialised operation a more controlled tool exchange would most likely be used allowing for the tool exchange programs to be put at the same speed as the other operations. The results from different experiments are illustrated in Table 10.3. In trial 1, five stops and bolts were used to fixture the airbag ECU to the table. The tool used to mill out the screw heads was the tungsten carbide drill with 6mm diameter head. A vacuum gripper is used to lift off the aluminium lid and extract the PCB from the casing.

Table 10.3 Automated robotic disassembly result of airbag ECU.

Operations		**Description**	**Time (seconds)**				
			Step 2				**Step 3**
			Trial 1	Trial 2	Trial 3	Trial 4	
1	Fixturing	Fix the component on the table	60	120	100	100	60
2	Robotic set up	Get the milling tool from the tool stand	10	10	10	10	10
3	Milling process	Mill 4 screws on the lid	95	80	85	65	45
4	Tool exchange	Put the milling tool back and get the vacuum gripper	15	15	15	15	15
5	Lifting process	Lift off the lid and the PCB, put the PCB in a storage box	30	20	15	15	15
6	Tool return	Put the vacuum gripper back to the tool stand	10	10	10	10	10

In trial 2, concerning the fixturing improvement, stops, bolts, a holding plate, a clamp, two eccentric pad and two angle brackets were utilised to improve the fixing of the component to the table. In trial 3, with regard to the operating parameters, the milling process was divided into two steps which increased the milling operation time slightly but significantly improved the reliability of the milling performance. Additionally, a slightly larger carbide spotting drill bit head with an 8 mm diameter was used.

In trial 3, regarding the operating parameters, the milling process was divided into two steps which increased the milling operation time slightly but significantly improved the reliability of the milling performance. In trial 4, similar fixturing method and gripper tool were used in trial 2, but a larger vacuum cup was used for the lifting process.

The last set of experiments aimed to validate the repeatability of the milling operation. It turned out that using the final fixturing method, a milling process with a depth of 4.5 mm had more than 50% success rate while with a depth of 4.7 mm it had more than 90% success rate. At the end of a series of milling tests, to ensure the reliability and efficiency, the milling parameters were set with two-step milling operation (3 mm, followed by 1.7 mm) at the speed of 0.63%.

It was observed that this fixturing time gradually decreased after several trails due to the familiarisation of the operator to the fixturing process (as shown in the datasheet in Appendix C). Additionally, the increase in tool size and type was required to reduce the milling time and lifting time. It was identified that the 8 mm-diameter milling bit took the shortest time to mill off the screws and that the larger vacuum cup had a better gripping performance, especially on the aluminium lid.

10.3.4 Multi-criteria assessment for case study 1

10.3.4.1 Definition of the EoL scenarios for case study

Based on the laboratory and industrial trials investigating alternative EoL recycling routes, three EoL scenarios have been identified as feasible solutions for EoL management of the EV components. These scenarios are defined in Chapter 9 of the thesis, namely:

i) Shredding and separation without dismantling and disassembly
ii) Shredding and separation with manual or automated dismantling and disassembly

In the first scenario, after the collection of EoL EV components, shredding and separation are conducted at the site. There is no mechanical dismantling and disassembly of EoL components. In the second, mechanical dismantling and disassembly of the EV component are carried out either in a manual way or automated way. No practical trials have been conducted to evaluate the feasibility of this method. However, it is noted and accepted that automation can be technologically feasible and economic viable in recycling practices.

10.3.4.2 Data for case study 1

Data defining each of the EoL scenarios evaluated in case study 1 are captured in the Table 10.4. This data is collected and collated from various sources and developed from real data and assumptions. In order to apply the evaluation to different scenarios, more detailed data is required regarding the environmental and economic attributes of the process described.

A. Data to support environmental performance assessment

The evaluation of environmental impact required the application of Life Cycle Assessment (LCA) methodology, as described in Chapter 9. Data to support and estimate the environmental impact and benefits is adapted from the research by European Commission Joint Research Centre (Ardente and Mathieux, 2012). The datasets summarised in Table 10.4 are identified as providing the closest representation of the processes utilised in the EoL scenarios, in the absence of specific data.

Table 10.4 Summary of data used to support evaluation of the environmental and economic impacts.

Data for environmental assessment	
Item	**Sources**
Ranking of materials according to their environmental impact (unit: per Kg of mass)	JRC technical report (Ardente and Mathieux, 2012)
Life cycle inventory data of materials	ELCD, 2010; PE, 2011
Normalisation factors for the environmental impact categories	PE, 2011
Content of Printed Circuit Boards (PCBs)	Material analysis provided by recyclers
Recovery of PMs by different recovery routes	Chancerel et al., 2009; Meskers and Hagelüken, 2009; IEC/TR 62635, 2012; UNEP, 2011
Data for technological feasibility assessment	
Element	**Sources**
Labour cost	GOV.UK
Set-up cost and operating cost	Estimated based on the lab-based automated disassembly cell
Disassembly operating time	Recorded from experiments
Data for economic assessment	
Element	**Sources**
Metal price	Metal Bulletin
Processing and refining charge per Kg material	Precious metal Recycler
Set-up cost and operating cost	Estimated based on the laboratory-based automated disassembly cell
Disassembly operating time	Record from the experiments

B. Data to support evaluation of technological feasibility

Data to support technological feasibility assessment is obtained from the experiment results based on the automated approach, and the detailed disassembly processes which are described in Chapter 8 of the thesis. The labour cost is based on the UK government minimum wage for work; the set-up cost and operating cost are estimated based on the lab set-up (a detailed calculation is illustrated in Chapter 9). Additionally, disassembly operating times are recorded from a series of manual and automated disassembly experiments.

C. Data to support evaluation of economic impact

As described in Chapter 9, the evaluation of economic impact using CBA requires quantifying all the costs and revenues arising during EoL management process. Cost data to support the case study is available from various sources. For each of the scenarios evaluated, the final step is for the recovery of PMs from the PCBs. Cost data was estimated based on the automated robotic cell that was set up on the lab scale. Recovered material values were obtained from PM recycling company, located in Europe, during the course of this research. The data used in the case study reflects an estimated cost profile for this process, based on experimental data and commercial data.

Case study 1 was implemented using the data and assumptions generated by the application of the framework and by the development of the automated approach using a three-step disassembly process which has been described earlier in Section 10.3.1 – 10.3.3 above. The following step of the framework was applied, which is the evaluation methodology developed in Chapter 9 of the thesis. Environmental impact was evaluated using the environmental benefit assessment method, technological feasibility was evaluated with the total disassembly time from various scenarios, and a revenue-cost spreadsheet was generated in order to support the economic assessment using the CBA model to generate a graphical representation of results. The numerical results from the individual evaluation methods were used as the input to the multi-criteria decision support tool.

10.3.4.3 Environmental impact assessment

The environmental performance of different EoL treatment options can be evaluated based on the impact generated during recycling and the avoided environmental impacts generated by preventing virgin material extraction, manufacture, recycling, recovery and disposal. These calculations can be used to prioritise the best-performing EoL treatments. The comparative analysis of the environmental performance is undertaken between automated disassembly and manual disassembly. The environmental impact is estimated by taking into account all PMs (Au, Ag. Pt and Cu) and basic metals, which will bring direct environmental burden. Table 10.5 demonstrates the material recovery difference between non-disassembly and with disassembly processes in the recycling system. The improved scenarios (with dismantling and disassembly) increases the material recycling rates and results in the growth of material yields. In addition, the basic calculation indicates that the sum of environmental impacts with dismantling and disassembly process is lower than the one without these processes; and the recyclability benefit rate is 283% (see Table 10.6). Therefore, this result indicates that an improved environmental performance can be achieved through minimising the amount of disposed of material waste to landfill, and by maximising the material recovery.

10.3.4.4 Technological feasibility assessment

Regarding the technological feasibility, total disassembly time is one of the indicators used to assess the viability of using robotics to undertake the disassembly processes. As discussed in Chapter 9, the operating cost of manual disassembly is twice the cost of automated disassembly. However, the last column in Table 10.7 states that the disassembly time ratio of automated disassembly to manual disassembly is 2.4 times larger, indicating that automated disassembly for airbag ECUs is not technologically feasible in terms of process time.

Table 10.5 Comparison between scenarios for case-study component – airbag ECU.

PCBs - Airbag ECU					
	Copper	*Silver*	*Gold*	*Palladium*	*Platinum*
Total mass (g/piece)	24.77895	0.109565	0.019546	0.000444	-
Recycling rates % (scenario 1)	60%	11.50%	25.60%	25.60%	25.60%
Recoverable materials in the scenario 1 (g)	14.86737	0.0126	0.005004	0.000114	-
Recycling rates % (scenario 2)	95%	92%	97%	99%	99%
Recoverable materials in the scenario 2 (g)	23.54	0.1008	0.01896	0.00044	-

Table 10.6 Calculation of the Recyclability benefit rate of case-study component – airbag ECU.

Product Details						
Product Details	**Mass of the product**					
Airbag ECU						
Recyable part	PCB					
Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	2.4779E+01	95%	2.03E-03	1.14E-09	2.19E-04	4.26E-02
Gold	1.9546E-02	97%	5.82E+01	1.14E-09	2.22E-04	1.10E+00
Silver	1.0957E-01	92%	1.37E+00	1.14E-09	3.80E-06	1.38E-01
Palladium	4.4444E-04	99%	6.60E-01	1.14E-09	1.47E-03	2.90E-04
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	1.28E+00
Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	2.4779E+01	60.0%	2.03E-03	1.14E-09	2.19E-04	2.69E-02
Gold	1.9546E-02	25.6%	5.82E+01	1.14E-09	2.22E-04	2.91E-01
Silver	1.0957E-01	11.5%	1.37E+00	1.14E-09	3.80E-06	1.73E-02
Palladium	4.4444E-04	25.6%	6.60E-01	1.14E-09	1.47E-03	7.49E-05
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	3.35E-01
		Recyclability Benefit Rate (%)	282.87%			

Table 10.7 Detail of the evaluation method for technological feasibility.

	Total Disassembly Time (minutes) Including Tooling & Fixturing Time		Fixturing time (minutes)		Tool exchange and handling time (minutes)		Disassembly Time (minutes)		Ratio of the automated disassembly time to manual disassembly times
Airbag ECU	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	Ratio=Automated/Manual
	1.4	3.4	0.17	1	0.17	0.83	1.07	1.57	2.429

It is clear that with regard to the disassembly time, manual disassembly spent significantly less time than compared to automated disassembly (i.e. fixturing time, tool exchange and handling time). Therefore, the increase in automated disassembly time outweighs the decrease in disassembly cost for the airbag ECU with simple construction and low value.

10.3.4.5 Economic feasibility assessment

The results of the economic impact evaluation are presented in Table 10.8, where the overall material recovery value is £0.68 and the cost for manual and automated disassembly are £0.35 and £0.41, respectively. It is clear from the result that the value of the targeted materials dominates the economic performance. In addition, the cost-benefit ratio provides a single figure result for the economic impact evaluation. According to the recovery profit, the manual disassembly has a better economic performance with a higher revenue-cost ratio.

Table 10.8 Material recovery values and disassembly times for airbag ECU.

<table>
<tr><th colspan="3">Component Name: Airbag ECU</th><th colspan="2">Total Disassembly Time (Minutes)</th></tr>
<tr><td colspan="2">Material(unit: g/gram)</td><td>Price (£/g)</td><td colspan="2">Including Tooling & Fixturing Time</td></tr>
<tr><td>Ag</td><td>0.1008</td><td>0.37</td><td>Manual</td><td>Automated</td></tr>
<tr><td>Au</td><td>0.01896</td><td>28.2</td><td>1.4</td><td>3.4</td></tr>
<tr><td>Pd</td><td>0.00044</td><td>16.82</td><td colspan="2">Total Disassembly Cost (£/piece)</td></tr>
<tr><td>Cu</td><td>23.544</td><td>0.0041</td><td>Manual</td><td>Automated</td></tr>
<tr><td>Ni</td><td>0.151</td><td rowspan="13">The value of those materials is excluded in this cost model.</td><td>0.35</td><td>0.41</td></tr>
<tr><td>Pb</td><td>0.151</td><td colspan="2">Processing Cost (£/piece)</td></tr>
<tr><td>Sb</td><td>0.024</td><td colspan="2">0.22</td></tr>
<tr><td>Sn</td><td>2.044</td><td colspan="2">Recovery profit (£/piece)</td></tr>
<tr><td>Zn</td><td>0.372</td><td>Manual</td><td>Automated</td></tr>
<tr><td>MgO</td><td>0.318</td><td>0.106</td><td>0.046</td></tr>
<tr><td>Al2O3</td><td>6.414</td><td colspan="2">Cost-benefit ratio</td></tr>
<tr><td>CaO</td><td>1.943</td><td>Manual</td><td>Automated</td></tr>
<tr><td>SiO2</td><td>12.104</td><td>3.302</td><td>8.913</td></tr>
<tr><td>Fe</td><td>1.764</td><td colspan="2" rowspan="5"></td></tr>
<tr><td>Mn</td><td>0.376</td></tr>
<tr><td>TiO2</td><td>0.203</td></tr>
<tr><td>BaO</td><td>0.778</td></tr>
<tr><td colspan="3">Total £ per part $\sum MV_R$ = £ 0.676</td></tr>
</table>

10.3.4.6 Multi-criteria assessment result

Individual results from the evaluation methods presented in the previous sections were imported into the ETE multi-criteria decision-making tool. By the application of normalisation process, the aggregated scores can be processed and used to present the performance of the automated approach in terms of the environmental, technological and economic impacts. As shown in Figure 10.9, automated disassembly is identified as being the preferred EoL option, based on the environmental performance (E1 and E2). With regards to the technological feasibility, the airbag ECU has a relatively simple construction which facilitates the automated disassembly with a relatively high score in T2. However, compared to the manual disassembly, automated disassembly spent more than twice the time that indicates that the automated disassembly is not technologically feasible for the airbag ECU. Concerning the economic impact the comparative cost/revenue ratio is relatively low (Eco1); while the automated disassembly is profitable (Eco2).

10.3.5 Analysis of results of case study 1

Case study 1 demonstrates the application of the framework for EoL management of EV components, as an example of the category with simple construction and low value. The results from the automated disassembly approach and the individual evaluation methods are summarised qualitatively. These results demonstrate that the application of non-destructive manual complete disassembly outline the breakdown of the sub-assemblies and detail the material composition. They also present the learning and continuous improvement processes for the automated disassembly and the result of the multi-criteria assessment, which provides a clear selection of a preferred EoL scenario from different alternative options. This study identified that for 'simple construction, low value' components automated disassembly results

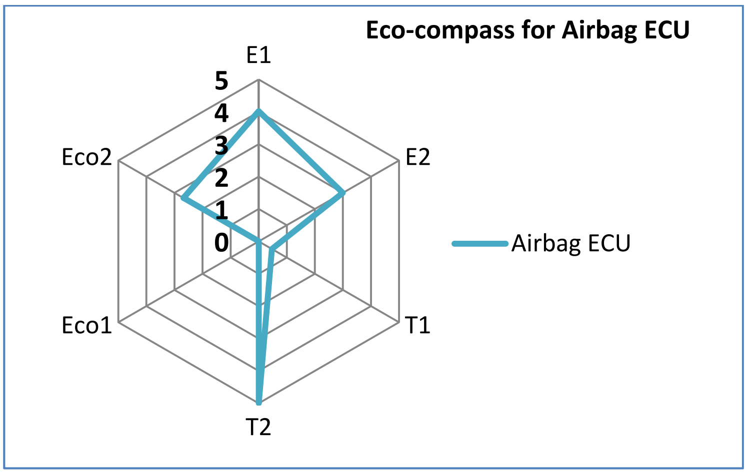


Figure 10.9 ETE multi-criteria assessment result of airbag ECU.

in improved environmental performance, but increases the economic cost, and so was not therefore technologically feasible. As such, this highlights the importance of the multi-criteria decision support tool that helps the development of a comprehensive understanding of EoL management from environmental, technological and economic aspects.

10.4 Case study 2: Power steering ECU

Case study 2 is the application of the framework for EoL management, focusing on the "medium construction and high value" EV components. A power steering ECU, selected for the demonstration (see Figure 10.10), receives torque sensor output and information to judge the vehicle conditions and determine the direction and force required to the power the vehicle.

10.4.1 The first step: manual non-destructive disassembly

A power steering ECU and its breakdown are presented in Figure 10.10 and Figure 10.11 respectively. Detail of the process and tools used are shown in Table 10.9, associated with the description in terms of the design and material characteristics. The findings can be summarised as follows: 1) it involves design variations, in terms of the wiring and the bracket; in addition, the shape of the component is not regular; 2) it consists of ten parts in which there are two

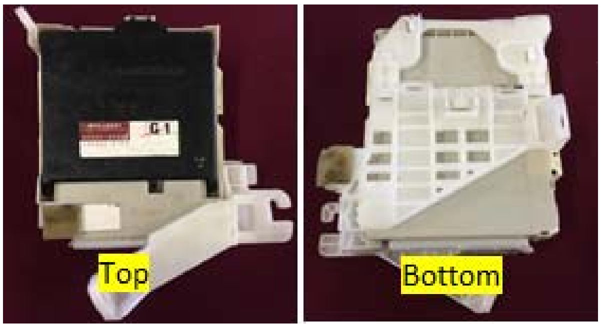


Figure 10.10 A power steering ECU.

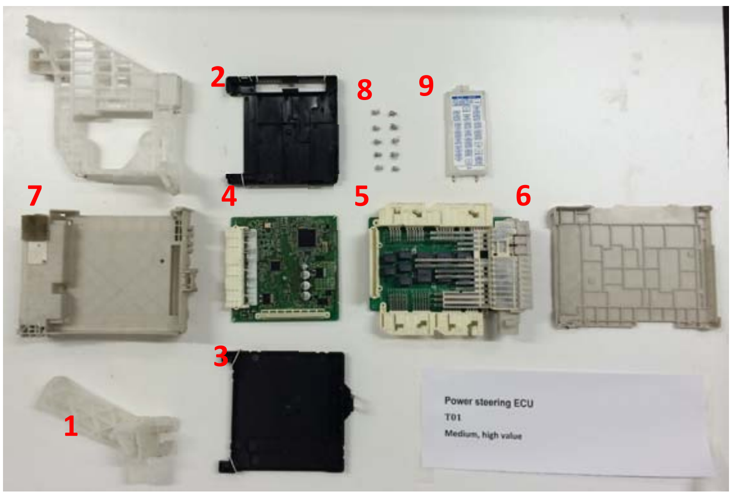


Figure 10.11 A breakdown of power steering ECU.

Table 10.9 Disassembly datasheet for the power steering ECU.

Name of the component		Power steering ECU	
Total weight (g)		759	
Total time (minutes)		8.4	
Weights for each parts (g)			
No.	Items	Weight (g)	Material
1	Wirings and bracket	Various	Multi-materials
2	Rear black casings	29	PP
3	Front black casings (front and back)	45	PP
4	Printed circuit board (PCB) $_1$	83	Multi-materials
5	PCB_2 with connectors	399	Multi-materials
6	Front cover of the bottom unit and clip	47	PP
7	Bottom casings	141	PP, nylon
8	Screws	9	Steel
9	Fuse box cover	6	PP
Manual disassembly processes			
No.	Disassembly steps	Time (second)	Tools used
1	Fixturing	20	Human force
2	Remove the fuse box cover	5	Screwdriver
3	Release the clips on sides to remove the black box	72	Pliers
4	Release the clips to get the front cover of the bottom unit	128	Pliers
5	Release the clips to open the black box	17	Pliers
6	Get PCB_1 out of the black box	30	Human force
7	Get PCB_2 out of the white bottom unit	93	Human force
8	Unscrew all screws on PCB_2	79	Screwdriver
9	Tool exchange and handling	60	Human force

pieces of PCB on both top and bottom sides. Therefore, the power steering ECU is categorised as a “medium complexity and high value” component; 3) valuable elements contained in the power steering ECU include the PCBs that contain PMs.

As shown in Figure 10.12, design variations of the power steering ECU include the location of the white brackets, the size of brackets and the presence of the wiring on the sides. Furthermore, the existence of the brackets and wirings make it difficult to develop a standardised fixturing method and automated disassembly operations.

10.4.2 The second step: initial semi-destructive automated disassembly

10.4.2.1 Fixturing mechanism

According to its construction, the uneven bottom surface requires the fixture accessories to keep the component stable. It is noted that there are variations in the construction of the power steering ECU, i.e. the brackets and the wires. Therefore, different fixturing methods have been developed, including the application of accessories such as straight edge stops, right angle bracket and ball lock bolts, as shown in Figure 10.13 A and B.

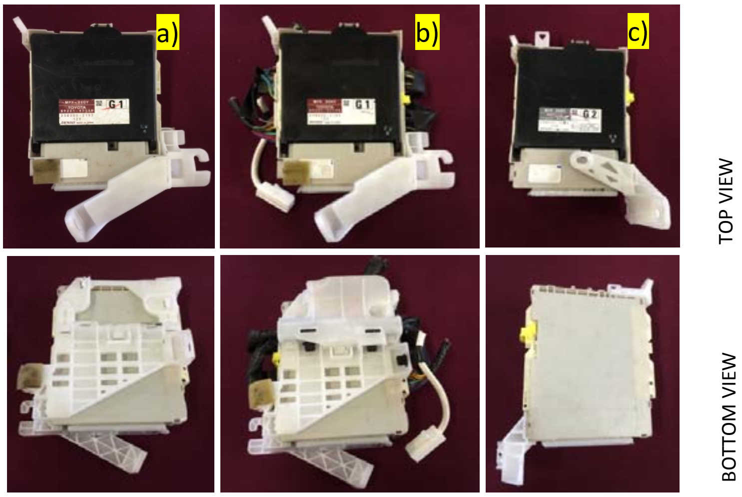


Figure 10.12 Variations in the design construction.

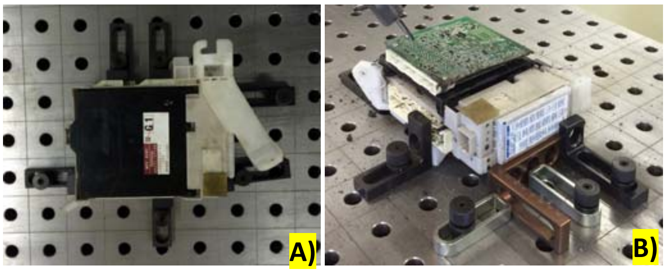


Figure 10.13 Fixture methods for majority of the power steering ECU.

10.4.2.2 Disassembly plans

In order to get access to the PCBs, the first approach method is to cut two sides of the black box (see Figure 10.14 a), which was sufficient to remove the black box from the white box. However, the black box was in a separate unit and the disassembly cannot go further, therefore, the PCBs remained inside the component. Another method is to cut the lid of the black box and lift off the lid (see Figure 10.14 b), which was easier to remove the lid and get access to the PCB_1. However, the PCB_1 was stuck in the whole unit and cannot be separated, therefore, the material stream was still highly mixed. An alternative way is to get the PCB_2 firstly from the bottom (see Figure 10.14 c). It turned out that the white lid can be cut and removed easily, but PCB_2 remained in the main unit and still cannot be easily lifted off. Based

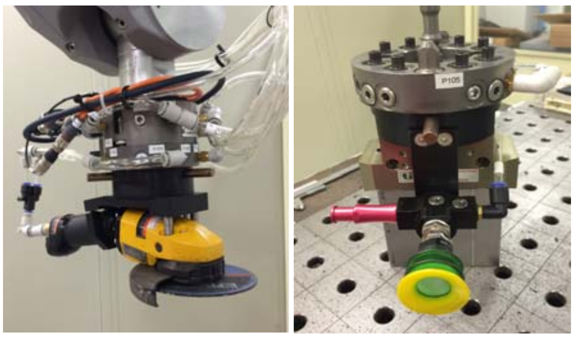
Figure 10.14 Approaches to get access to the PCBs.

on the findings, cuttings need to be replaced with more delicate operations on the joining locations (i.e. clips). As mentioned, there are two pieces of PCBs that are located in the top and bottom of the components. The one direction operation from the top provides access to one piece of the PCB but limits approaching to the other one. Complicated and extraneous movements are required to continue the one-direction operation. Therefore, in order to extract both the PCBs in an efficient way, the power steering ECU needs to be re-fixed on the table to put the unit upside down.

10.4.2.3 Tool test

A majority of the joining methods used in the power steering ECU are snap-fits which facilitate fast assembly but do not benefit the disassembly processes. Based on the disassembly plan, the capability of the cutting tool (angle grinder) and gripping tool (vacuum gripper) are tested as shown in Figure 10.15. In order to release the clips, besides cutting the entire edge of the black casing, delicate cutting on the clips spent less time and effort and had a higher reliability (see Figure 10.16 a and b. Additionally, various cutting angles were tested from 30° to 180°, see Figure 10.16 c, d and e. It turned out that the cutting tool was capable of completing the cutting operation under different circumstances. Furthermore, the vacuum gripper is capable of lifting off the lids and the PCBs.

A series of experiments have been carried out, and the findings from individual trials are summarised in Figure 10.16. It includes the identification of difficulties in disassembly and exploration of various operating parameters. Figure 10.17 (a) shows an example to test the cutting depth, and Figure 10.17 (b) indicates the importance of tool orientation. In Figure 10.17 (c), both the black lid and the PCB were successfully extracted whilst a little bit of PCB remained in the main component. In addition, during the trials, the white bracket could hinder the movement of the cutting blade as it was in the way of the cutting operations (see Figure 10.17 d). Therefore, the white bracket was removed at the beginning of the operations in the



(a) Angle grinder (b) Vacuum gripper

Figure 10.15 Tool used in automated disassembly for power steering ECU.

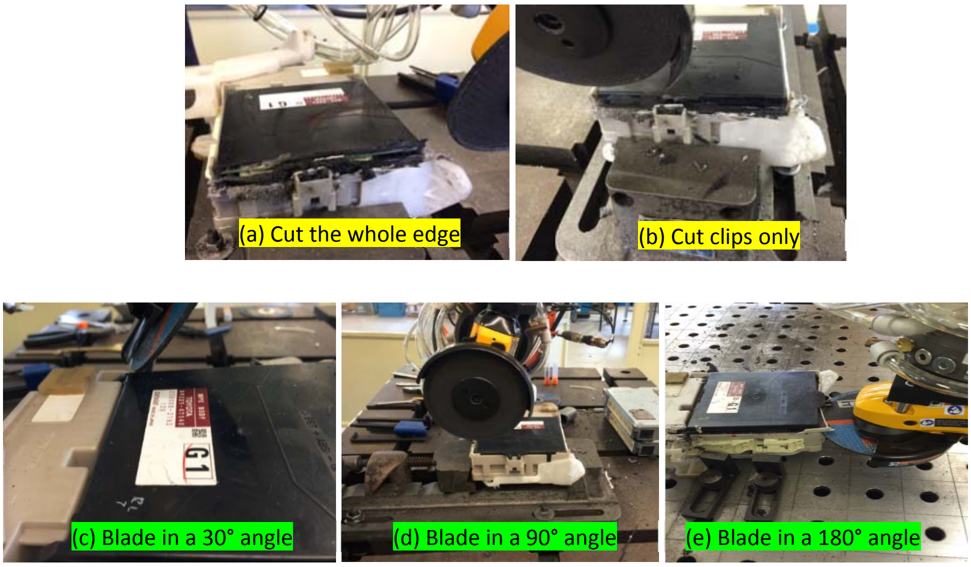


Figure 10.16 Cutting methods and orientation test.

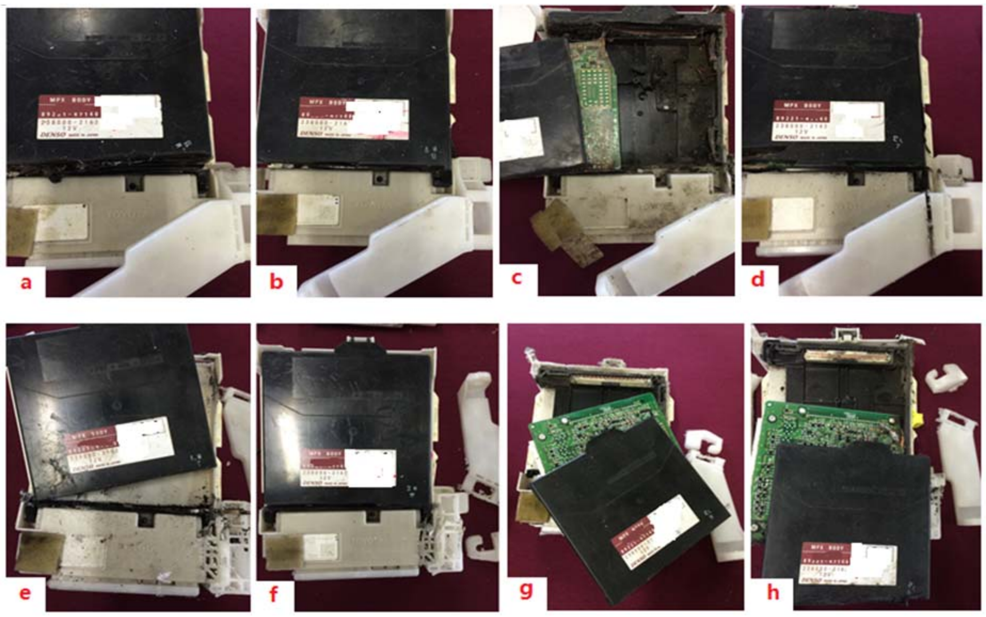


Figure 10.17 Various tests on power steering ECUs.

following experiments. It is identified that the black casings and PCB can be removed as a whole unit, however, the PCB inside was not able to be further extracted using the robotic operations (see Figure 10.17 e). Furthermore, Figure 10.17 (f) is an example of a failure trial that suffered from the variations in construction (i.e. height difference). Based on the findings from precedent, the PCB and black lid can be extracted with a success rate of 90% and the completeness of the PCB reached 95% (see Figure 10.17 g and Figure 10.17 h).

10.4.3 The third step: optimisation and validation of automated disassembly

A feasible automated disassembly processes for the power steering ECU has been developed, consisting of 1) cutting off the brackets and clips on the black casing; 2) lift off the black casing lid and PCB_1; 3) re-fix the component; 4) cutting off the brackets and clips on the white casing; and 5) lift off the white casing lid. In this way, the majority of the remaining sub-assembly is the PCB_2. Therefore, the targeted parts are extracted and the material stream is purified.

10.4.3.1 Fixturing mechanism

As mentioned beforehand, the design variation influences the fixture mechanism. Even in the same design construction, components have different heights. All these differences require the fixturing mechanism to be adjustable and reliable. Therefore, short right angle brackets were replaced by golden angle brackets that lift the whole component to a certain reference height (see Figure 10.18). Thus, this standardised fixturing method can be applied to various designs.

10.4.3.2 The operational parameters test

For the cutting operation, various orientations and different depths have been explored to identify the most appropriate method. It turned out that putting the cutting grinder parallel with the surface of the black lid helps the removal of PCB_1 and the lifting off of the black lid. In addition, it is noted that sometimes the blade guard pushed the white bracket towards the table and was running idle. This increases the disassembly time and jeopardised the efficiency, therefore, the removal of the white bracket is added to the disassembly process (see Figure 10.19). Additionally, it is identified that there was an electronic connector that connects PCB_1 and PCB_2. The extraction of the PCB_1 depends on the attachment of this electronic connector. In order to increase the success rate, the cutting grinder was positioned to be parallel with the black casing to cut through the electronic connector as shown in Figure 10.20 (a). Various cutting depths were tested to make sure the least time and effort were taken for breaking this connection. The cutting result is shown in Figure 10.20 (b) and (c).

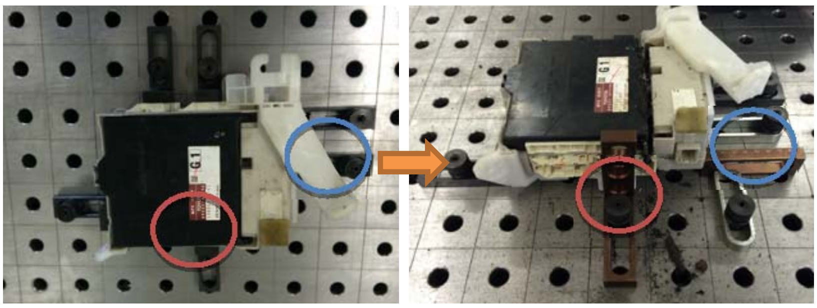


Figure 10.18 Fixture adjustment due to the height difference.

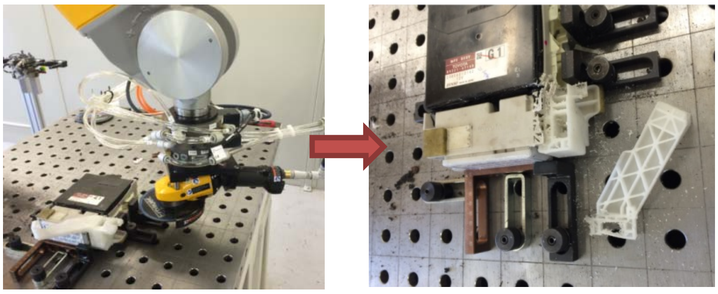
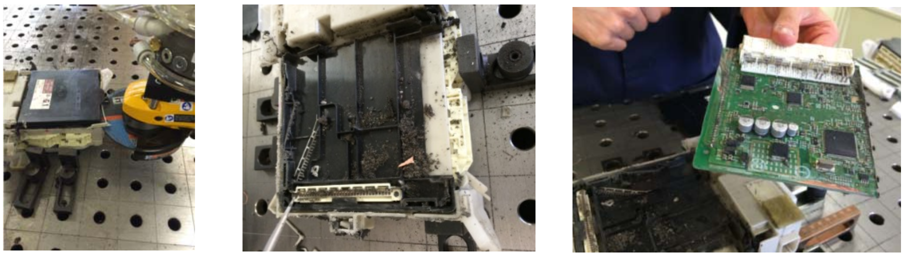


Figure 10.19 Bracket issue in automated disassembly.



(a) Cutting orientation (b) Electronic connector (c) Extraction of the PCB_1

Figure 10.20 Electronic connector issue in automated disassembly.

A series of experiments have been undertaken for the optimisation and validation process (see Table 10.10). In trial 1, five angle brackets and five bolts were used. The cutting blade was utilised to cut the clips and connectors, and the vacuum gripper was used to lift off the casing lid and the PCBs. The disassembly plan was to extract the PCB_1 from the black casing and then remove the white casing lid from the remaining sub-assembly (PCB_2).

Table 10.10 Optimisation and validation of the automated disassembly for power steering ECU.

Operations		Description	Time (seconds)			
			Step 2			Step 3
			Trial 1	Trial 2	Trial 3	
1	Fixturing	Fix the component on the table	110	110	150	80
2	Robotic set up	Get the cutting tool from the tool stand	10	10	10	10
3	Cutting process	Cut off the clips, connectors and the brackets on the white casing	300	250	220	166
4	Tool exchange	Put the cutting tool back and get the gripper	25	25	25	25
5	Lifting process	Lift off the lid and the PCB1, put the PCB1 in a storage box	60	50	50	37
6	Re-fixturing	Turn the component upside down and fix the component	100	0	0	0
7	Tool exchange	Put the gripping tool back and get the cutting tool	20	20	0	0
8	Cutting process	Cut off the clips, connectors and the brackets on the black casing	140	90	0	0
9	Tool exchange	Put the cutting tool back and get the gripper	20	20	0	0
10	Lifting process	Lift off the lid and the PCB2, put the PCB2 in a storage box	30	15	0	0
11	Tool return	Put the gripper back to the tool stand	10	10	10	10

In trial 2, the disassembly depth was analysed for maximising the return of the disassembly processes. As discussed in section 8.5.3, the indicator of material recovery rate indicates the optimum level of disassembly. The completed and partial disassembly times are 13.4 minutes and 5.3 minutes; while the weights of material removed are 759g and 435g, respectively. Based on Equation 8.1, the material removal rates for completed and partial disassembly are 0.942 and 1.368. Therefore, it is clear that for a certain level of disassembly, the majority of the sub-assemblies are extracted with recovery value. Continued disassembly however often just adds cost but with a very limited revenue increase. Thus, a partial automated disassembly was undertaken for the power steering ECU.

In trial 3, in order to develop a standardised fixturing method, golden angle brackets and two stops were utilised in addition to the right angle brackets and bolts, to improve the reliability of the fixturing. Bracket issues and electronic connector issues were also identified and solved.

In Step 3, developed standardised fixturing method was used; various operating parameters were optimised and validated. The overall automated disassembly time decreased and the repeatability has been validated (more than 95% success rate).

10.4.4 Multi-criteria assessment for case study 2

10.4.4.1 Environmental impact assessment

With regards to the environmental performance of various recycling scenarios, the material recovery difference is illustrated in Table 10.11 and is used in the further calculation of the environmental impact in Table 10.12. In terms of material composition, the power steering ECU contains large amounts of copper and silver. With the increase of the material recovery rate via dismantling and disassembly process, it is identified that the recycling benefit rate is 316.01%. This figure indicates the application of automated disassembly has greatly improved the environmental performance and minimised the environmental impacts from EoL material recycling and recovery process.

Table 10.11 Comparison between scenarios for case-study component – power steering ECU.

PCBs - Power steering ECU					
	Copper	*Silver*	*Gold*	*Palladium*	*Platinum*
Total mass (g/piece)	151.1474	0.780109	0.008804	0.001657	-
Recycling rates % (scenario 1)	60%	11.50%	25.60%	25.60%	25.60%
Recoverable materials in the scenario 1 (g)	90.68842	0.089713	0.002254	0.000424	-
Recycling rates % (scenario 2)	95%	92%	97%	99%	99%
Recoverable materials in the scenario 2 (g)	143.59	0.7177	0.00854	0.00164	-

Table 10.12 Calculation of the Recyclability benefit rate of case-study component – power steering ECU.

Product Details						
Product Details	**Mass of the product**					
Power steering ECU	759					
Recyable part	PCB					
Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	1.5115E+02	95%	2.03E-03	1.14E-09	2.19E-04	2.60E-01
Gold	8.8041E-03	97%	5.82E+01	1.14E-09	2.22E-04	4.97E-01
Silver	7.8011E-01	92%	1.37E+00	1.14E-09	3.80E-06	9.83E-01
Palladium	1.6566E-03	99%	6.60E-01	1.14E-09	1.47E-03	1.08E-03
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	1.74E+00
Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	1.5115E+02	60.0%	2.03E-03	1.14E-09	2.19E-04	1.64E-01
Gold	8.8041E-03	25.6%	5.82E+01	1.14E-09	2.22E-04	1.31E-01
Silver	7.8011E-01	11.5%	1.37E+00	1.14E-09	3.80E-06	1.23E-01
Palladium	1.6566E-03	25.6%	6.60E-01	1.14E-09	1.47E-03	2.79E-04
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	4.19E-01
		Recyclability Benefit Rate (%)	316.01%			

10.4.4.2 Technological feasibility assessment

In terms of the technological feasibility, disassembly times have been recorded as shown in Table 10.13. It should be noted that based on the analysis of the disassembly result, partial disassembly was undertaken rather than complete disassembly. This partial disassembly did not compromise much of the recovery value but significantly minimised the disassembly time. Considering the fixturing time, tool exchange, handling and operating, the total disassembly time ratio of manual to automated disassembly is 0.949 (less than 2) which indicates that the automated disassembly for the power steering ECU is technologically feasible.

10.4.4.3 Economic impact assessment

The results of the economic evaluation are presented in Table 10.14, with material recovery value, total disassembly time-related cost, processing cost and the disassembly profit. It is identified that the profits of both manual and automated disassembly are negative which indicates the disassembly process was not economically viable. However, the recovery efficiency in automated disassembly is higher than the manual disassembly, based on the disassembly profit obtained.

Table 10.13 Detail of the evaluation method for technological feasibility for power steering ECU.

	Total Disassembly Time (minutes) Including Tooling & Fixturing Time		Fixturing time (minutes)		Tool exchange and handling time (minutes)		Disassembly Time (minutes)		Ratio of the manual disassembly time to automated disassembly times
	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	Ratio=Automated/Manual
Power steering ECU	8.40	7.97	0.33	1.33	1.00	1.33	7.07	5.30	0.949

Table 10.14 Material recovery values and disassembly times for power steering ECU.

Component Name: power steering ECU			Total Disassembly Time (Minutes)	
Material (unit: g/gram)		Price (£/g)	Including Tooling & Fixturing	
Ag	0.717698	0.37	Manual	Automated
Au	0.008536	28.2	8.4	7.97
Pd	0.001645	16.82	**Total Disassembly Cost (£/piece)**	
Cu	143.588	0.0041	Manual	Automated
Ni	1.309	The value of those materials is excluded in this cost model.	2.1	0.95
Pb	0.083		**Processing Cost (£/piece)**	
Sb	0.000		0.73	
Sn	4.503		**Recovery profit (£/piece)**	
Zn	7.187		Manual	Automated
MgO	8.580		-1.7	-0.55
Al2O3	9.168		**Cost-benefit ratio**	
CaO	10.339		Manual	Automated
SiO2	42.291		-1.24	-1.73
Fe	23.657			
Mn	0.147			
TiO2	0.601			
BaO	1.175			
Total £ per part $\sum MV_R$ = £ 1.13				

10.4.4.4 Multi-criteria assessment result for power steering ECU

The results from the environmental, technological and economic evaluation are presented in Figure 10.21. Automated robotic disassembly significantly minimised the environmental impact (E1). Additionally, a large amount of valuable materials contained in the PCBs and were extracted, and this indicates that a significant improvement can be achieved in the dismantling and disassembly process (E2). The T1 related to the technical feasibility is a reasonable score. It indicates that the automated robotic disassembly brought the benefit of reducing the disassembly time and associated cost to a certain degree. Based on its snap-fit joining method and plastics casing construction, the score of T2 represents disassembly complexity of the power steering ECU is low and suitable for automated disassembly.

Economic benefit from material recovery is identified leading to a high score of economic assessment (Eco1). It is noted that the optimisation of the disassembly depth and validation of the processes contributed to the reduction of disassembly cost. While the material recovery efficiency has been considered within case study 2 to justify the 'trade-off' decision, added cost associated with further disassembly processes can be avoided. The score of Eco 2 indicates that the recovery profit per unit is relatively low.

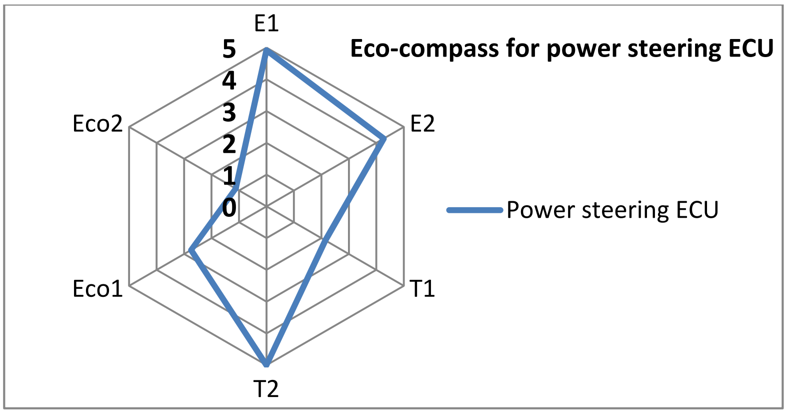


Figure 10.21 ETE multi-criteria assessment result of power steering ECU.

10.4.5 Analysis of results of case study 2

Case study 2 illustrates the application of EoL management framework into EV components with medium design complexity and high value. A number of conclusions can be made: first of all, it is noted that the design variations affect the fixturing methods and disassembly operations. The validation and optimisation processes helps identifying the 'hot-spots' for continuous improvement. Secondly, the 'trade-off' between the disassembly depth and the economic benefit are taken into consideration to make the automated robotic disassembly more cost-effective. Furthermore, economic benefit is dominated by the recovery of PMs becoming substantial when the PMs content increase.

10.5 Case study 3: Combi-meter

10.5.1 The first step: manual non-destructive disassembly

The combi-meter is a control panel that houses instrumentation and controls for vehicle operation. Items located in the combi-meter consist of a series of instruments i.e. gauges for speed, fuel and indicators such as warning lights for seat belt, parking-braking-engaging and engine malfunction. The combi-meter is not in a regular shape again, leading to difficulty in fixturing. In addition, the valuable parts contained in the combi-meter are the PCBs. Based on its design complexity and material composition, the combi-meter is categorised as "complex construction, low value" and selected as the third case study component (see Figure 10.22).

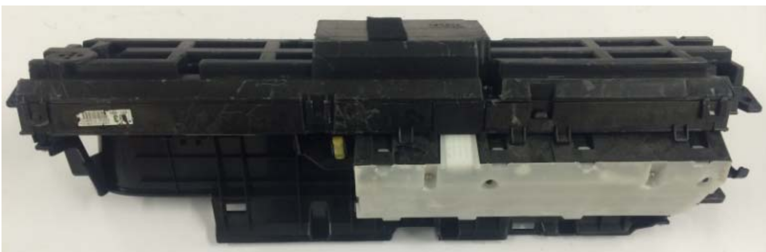


Figure 10.22 A combi-meter.

Manual, non-destructive complete disassembly was conducted (see Figure 10.23). Detailed process information, tools used, and description of the design and material characteristics is depicted in Table 10.15. The combi-meter consists of twelve sub-assemblies in which the majority of the part was made of various plastics. Besides the small amount of aluminium casings on the PCBs, PCBs are valuable parts that were targeted for extraction. It was identified that the parts of the combi-meter were joined from different sides and orientations. In addition, the majority of joining methods were traditional methods of fastening (screws) and snap-fit (cantilever snap joints).

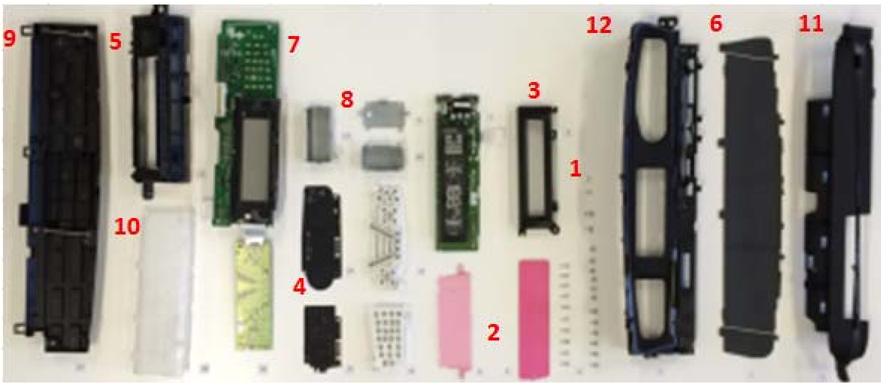


Figure 10.23 A breakdown of the combi-meter.

Table 10.15 Manual disassembly datasheet for combi-meter.

Name of the components			Combi-meter
Total weight (g)			1812
Total time (minutes)			5.79
Weights for each parts (g)			
No.	Items	Weight (g)	Material
1	Screws and washers	22	Steel
2	Pink protector	31	PP
3	PP mould frame	83	PP
4	Paper instrument	8	PP
5	Monitor casing	42	PP
6	Black protector	101	PMMA
7	PCB Groups	724	Multi-materials
8	Aluminium cover for capacitors	57	Aluminium
9	Black rear cover	154	PP-TD40
10	White cover	32	PP
11	Front frame	160	ABS
12	Middle frame	398	ABS-GF20
Manual disassembly processes			
No.	Disassembly steps	Time (second)	Tools used
1	Fixturing	30	Human force
2	Unscrew screws, release the clips and remove the front	54	Screwdriver
3	Unscrew screws, release the clips and remove the white	45	Screwdriver, pliers
4	Remove the PCBs from bother sides (connected by foil)	19	Human force
5	Remove the mould frame and paper instructions	22	Human force
6	Remove the pink plastics screen protector	10	Human force
7	Release the clips and get out of the middle frame	16	Pliers, screwdriver
8	Remove the covers from the middle frame and the black	13	Screwdriver
9	Release the clips and get out of the black protector	21	Pliers, human force
10	Remove the aluminium protection casing on the PCB	38	Screwdriver
11	Tool exchange and handling	80	Human force

10.5.2 The second step: initial semi-destructive automated disassembly

Based on the findings from manual disassembly, it has been identified that 1) the construction of the combi-meter was not regular, leading to a difficulty in fixturing; 2) targeted sub-assemblies (PCBs) were located inside the black and white lids on both sides; and 3) most of the casings were made of plastic, which can be easily cut through and removed.

In line with this, a semi-destructive automated disassembly process has been developed. The steps include: a) milling screws and pins on white cover and black covers; b) cut the top edge of the white cover, releasing all clips c) cut the bottom edge of the white cover, remove the white cover; d) cut the foil connector and remove the PCB_1; e) cut the top and bottom edges of the black cover, remove the black cover; and f) remove the PCB_2, as shown in Figure 10.24.

10.5.2.1 Fixturing mechanism

Various fixturing methods were developed in the initial series of experiments (see Figure 10.25). Fixturing Plan 1 caused the movement of the component in longitudinal direction. Plan 2 included two more golden angle brackets on the left side and a clamp on the right side to stop the component wobbling during the operations. However, various EoL component conditions affected the stability and reliability of the automated disassembly operations. In some cases, incomplete components, such as those with loose or missing parts, influence the set-up of the reference points for fixturing. Thus, all sample components were investigated in terms of the potential breakpoints and potential fixturing reference locations. Using the results of this investigation, the fixturing Plan 3 was developed, in which a platform raised the combi-meter to 3 cm above the table and the bottom while the component was kept parallel to the

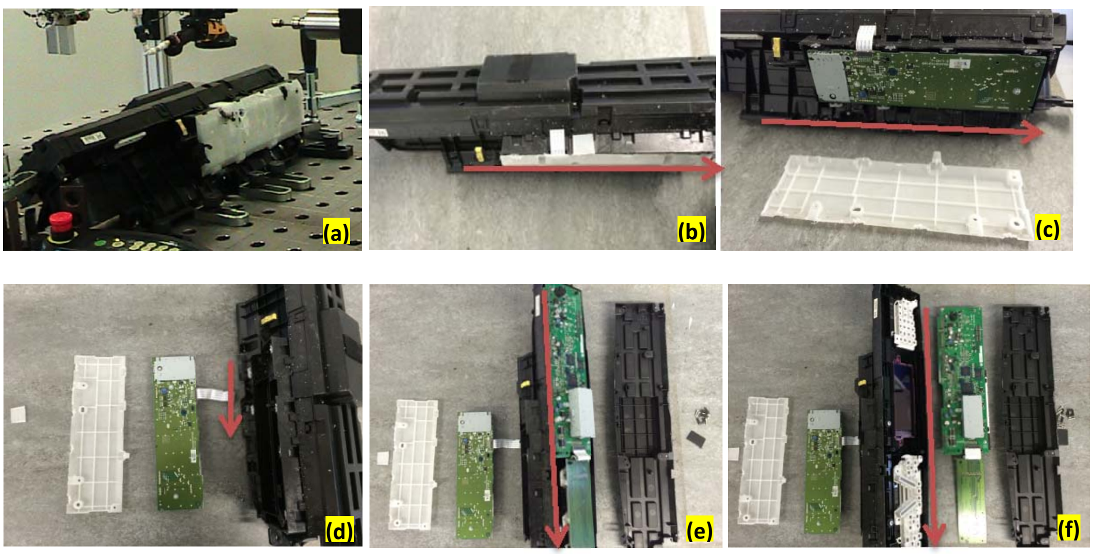


Figure 10.24 Automated disassembly processes for combi-meter.

Figure 10.25 Fixturing plans for combi-meter.

table. Additionally, fixturing reference points were replaced with new locations where the majority of the components would have the completed features. It is noted that the complexity of the fixturing leads to increasing numbers of the accessories used in the fixturing and associated increased fixturing time.

10.5.2.2 Tooling test

Based on the findings from manual disassembly, the most suitable method for approaching the PCBs was to remove the lids on both sides. A milling tool, cutting tool and gripping tool were utilised in the automated disassembly process to release the lids and extract the PCBs inside. Various milling bits with different sizes and shapes were tested for the removal of the screws. The cutting test includes evaluating the feasibility of the circular cutting blade for operations at specific cutting locations and performance on various materials. In addition, the gripping test is to assess the capability to remove the plastic casings and the PCBs that have different shapes and weights. The two-finger parallel gripper was not capable of gripping the raised frame due to the limitation of its construction and the space around the component. But the relatively smooth surface is suitable for the utilisation of the vacuum gripper.

10.5.2.3 Operating parameters test

It is noted that screws were located inside of the grooves as highlighted in yellow, magenta and green, and clips were marked in blue in Figure 10.26. Different approaching angles (from 0° to 45°) to the component, and different depths (from 3mm to 6mm) were tested in the initial set of experiments (see Figure 10.27). In the cutting process, a circular cutting blade was utilised for cutting the plastic clips on the components. Various cutting angles were utilised (see Figure 10.28), i.e. parallel or vertical to the fixture table. In the gripping test, the plastic lids can be removed by the vacuum gripper easily. The aluminium casing issue was addressed. On the black lid side, the aluminium casing on the PCB can be used as the gripping point for the removal of the PCB (see Figure 10.29 (A)). On the white lid side, the aluminium casing faced toward the inside and sometimes was distorted from the previous operations and attached to the remaining of the component (see Figure 10.29 (B)). This left-over aluminium

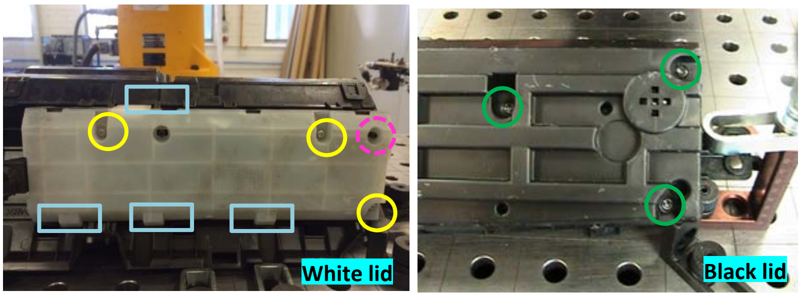


Figure 10.26 Screws and clips on the white lid.

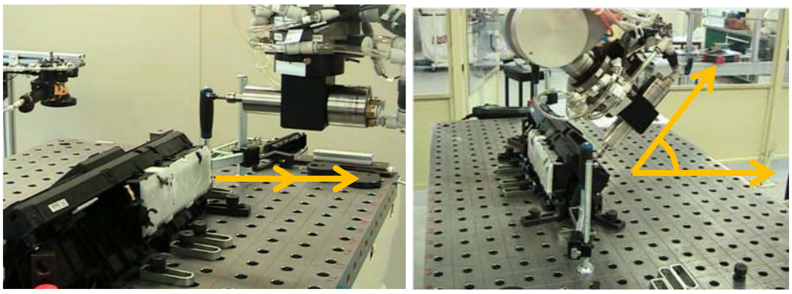


Figure 10.27 Test of milling angles for the combi-meter.

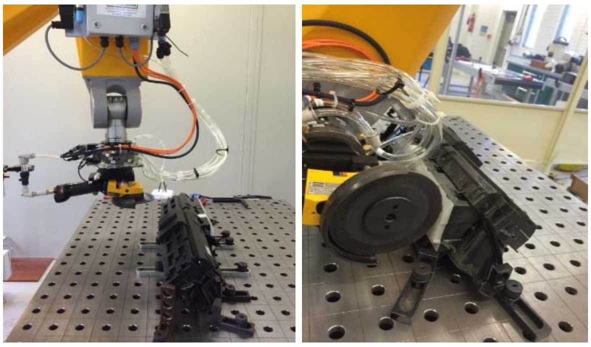


Figure 10.28 Test of cutting angles for the combi-meter.

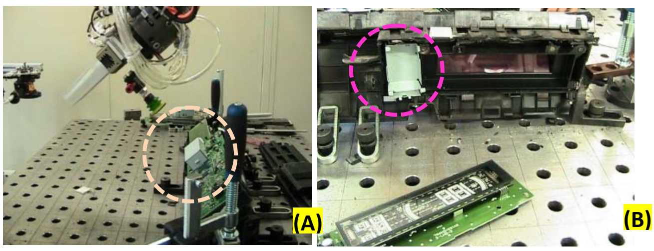


Figure 10.29 Gripping process for PCBs.

cover did not impact the removal of the PCB, but decreased the purity of the waste stream. Therefore, subsequent experiments were undertaken for adjusting the milling and cutting parameters.

10.5.3 The third step: optimisation and validation of automated disassembly

The final step of the validation and optimisation of the automated disassembly for the combi-meter will be discussed in the following section (see Table 10.16). In trial 1, five angle brackets,

Table 10.16 Automated robotic disassembly result of combi-meter.

Operations		Description	Time (seconds)				
			Phase 2				Phase 3
			Trial 1	Trial 2	Trial 3	Trial 4	
1	Fxituring	Fix the component on the table	75	120	200	160	100
2	Robotic set up	Get the milling tool from the tool stand	15	15	15	15	1510
3	Milling process	Mill 11 screws and 1 pin on both sides of the lids	510	400	330	300	274
4	Tool exchange	Put the milling tool back and get the sawing tool	25	25	25	25	25
5	Cutting process	Saw 7 plastics connecters	120	102	84	84	79
6	Tool exchange	Put the cutting tool back and get the gripper	25	25	25	25	25
7	Gripping process	Lift off the lids and PCBs from both sides	60	50	50	35	35
8	Tool return	Put the gripper back to the tool stand	10	10	10	10	10

four stops and nine bolts were used in fixturing. The tools utilised include Tungsten Carbide Drill Cutter (8 mm diameter), Erbauer Metal Cutting Blade (125 mm X 2.5 mm X 22.23 mm), and the vacuum gripper (6 mm diameter). It was identified that the re-adjustment of the component was required to be at a specific angle with the table to facilitate the adjustment of operating parameters, i.e. angle, depth.

In trial 2, additional steel angle brackets, stops and three bolts were used to facilitate the disassembly operations. Additionally, the original gripper cup (6 mm) was replaced with a larger size cup (10 mm diameter) that took less time and had a higher success rate. It was noted that the developed fixturing methods were applicable for the components in good EoL conditions but less reliable for the components whose parts were missing or broken.

Thus, in trial 3, a customised platform was designed and consisted of six stops, two metal sheets, two clamps and one steel angle bracket. This platform raised the component and used more reliable reference points for fixturing. In trial 4, based on the property and location of the screws and pins, a number of milling depths and speeds were assigned for them. Similar customisation was applied in the cutting process for different size of clips.

The last set of experiments was used for validating the repeatability of the automated disassembly operations and the overall success rate was found to be 95%. It turned out that using the fixturing method with the customised platform could be applied for the combi-meter in a variety of conditions. The aluminium cover issue was solved and the use of larger gripper cup reduced the total disassembly time.

10.5.4 Multi-criteria assessment for case study 3

10.5.4.1 Environmental impact assessment

Table 10.17 demonstrates the material recovery difference between different EoL scenarios in the recycling of combi-meter. The application of automated robotic disassembly increased the material recovery rates, associated with improved environmental performance in the further calculation (see Table 10.17). The majority of the casings were made of plastics and the PCBs contain PMs, especially the copper, silver and gold. It was calculated that for the combi-meter, the recyclability benefit rate is 319.79%, justifying the benefits from applying the robotic disassembly process as shown in Table 10.18.

10.5.4.2 Technological feasibility assessment

For the combi-meter, the total disassembly time ratio is 0.544 (less than 2), indicating that automated disassembly is technically feasible (see Table 10.19). It was identified that even though the combi-meter has a relatively complex construction, its plastic casings were suitable for the automated operations, i.e. cutting, gripping. The optimisation plays a significant role in minimising the numbers of disassembly operations and overall disassembly time.

Table 10.17 Comparison between scenarios for case-study component – combi-meter.

PCBs - Combimetre					
	Copper	*Silver*	*Gold*	*Palladium*	*Platinum*
Total mass (g/piece)	54.08421	0.476891	0.020464	0.002152	-
Recycling rates % (scenario 1)	60%	11.50%	25.60%	25.60%	25.60%
Recoverable materials in the scenario 1 (g)	32.45053	0.054843	0.005239	0.000551	-
Recycling rates % (scenario 2)	95%	92%	97%	99%	99%
Recoverable materials in the scenario 2 (g)	51.38	0.43874	0.01985	0.00213	-

Table 10.18 Calculation of the Recyclability benefit rate of case-study component – combi-meter.

Product Details						
Product Details	**Mass of the product**					
Combi-meter	1812					
Recyable part	PCB					
Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	5.4084E+01	95%	2.03E-03	1.14E-09	2.19E-04	9.30E-02
Gold	2.0464E-02	97%	5.82E+01	1.14E-09	2.22E-04	1.16E+00
Silver	4.7689E-01	92%	1.37E+00	1.14E-09	3.80E-06	6.01E-01
Palladium	2.1515E-03	99%	6.60E-01	1.14E-09	1.47E-03	1.40E-03
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	1.85E+00
Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	5.5674E+01	60.0%	2.03E-03	1.14E-09	2.19E-04	6.05E-02
Gold	2.0464E-02	25.6%	5.82E+01	1.14E-09	2.22E-04	3.05E-01
Silver	4.7689E-01	11.5%	1.37E+00	1.14E-09	3.80E-06	7.51E-02
Palladium	2.1515E-03	25.6%	6.60E-01	1.14E-09	1.47E-03	3.63E-04
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	4.41E-01
		Recyclability Benefit Rate (%)	319.79%			

Table 10.19 Detail of the evaluation method for technological feasibility for combi-meter

	Total Disassembly Time (minutes) Including Tooling & Fixturing Time		Fixturing time (minutes)		Tool exchange and handling time (minutes)		Disassembly Time (minutes)		Ratio of the manual disassembly time to automated disassembly times
	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	Ratio=Automated/Manual
Combi-meter	5.79	8.98	0.5	1.67	1.33	1.83	10.07	5.48	0.544

10.5.4.3 Economic impact assessment

The results of the economic evaluation are shown in Table 10.20. The material recovery value per component is £0.969; while the disassembly costs both manually and automatically exceed the recovery revenue. Besides, the processing cost of the materials makes the disassembly less economically viable.

10.5.5 Analysis of results of case study 3

Based on the results from environmental assessment (see Figure 10.30), the high score in E1 indicates that the recycling of the combi-meter benefits from dismantling and disassembly.

Table 10.20 Material recovery values and disassembly times for combi-meter

Component Name: Combi-meter			**Total Disassembly Time (Minutes)**	
Material(unit: g/gram)		Price (£/g)	Including Tooling & Fixturing Time	
Ag	0.438744	0.37	Manual	Automated
Au	0.019852	28.2	5.79	8.98
Pd	0.00213	16.82	**Total Disassembly Cost (£/piece)**	
Cu	51.382	0.0041	Manual	Automated
Ni	3.238	The value of those materials is excluded in this cost model.	1.45	1.07
Pb	10.418		**Processing Cost (£/piece)**	
Sb	0.193		0.9	
Sn	5.146		**Recovery profit (£/piece)**	
Zn	2.752		Manual	Automated
MgO	9.267		-1.381	-1.001
Al2O3	169.344		**Cost-benefit ratio**	
CaO	31.849		Manual	Automated
SiO2	221.327		-1.05	-1.07
Fe	84.346			
Mn	3.063			
TiO2	2.051			
BaO	8.645			
Total £ per part $\sum MV_R$ = £0.969				

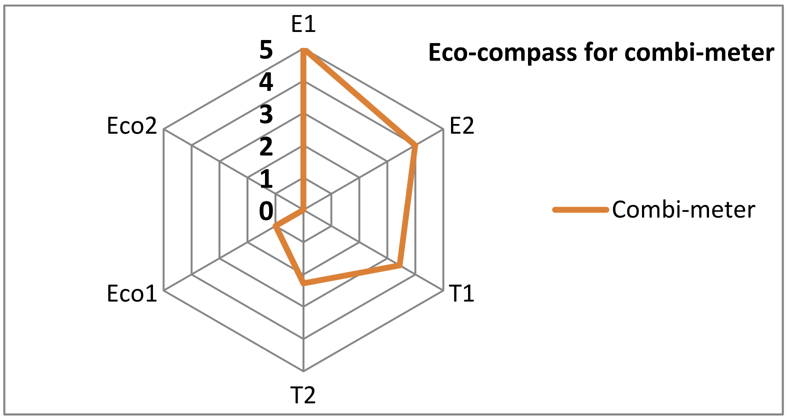


Figure 10.30 Multi-criteria assessment result for combi-meter.

The fact that targeted parts (PCBs) constitute a large amount of the components provides great potential for improving the ecological performance. Therefore, the score of E2 is relatively high. Regarding the technological evaluation, the complexity in construction design required various tools to be used in the automated robotic disassembly process. Thus, the disassembly complexity (T2) is at a medium level. However, a series of experiments for optimisation successfully minimised the disassembly time, making the automated robotic disassembly technologically feasible. Relatively low material recovery value cannot pay back the disassembly cost and further processing cost. Thus, the score of Eco1 is nearly the worst case. Nevertheless, the disassembly process had made economic benefit that is represented in the material recovery value (Eco 2).

It should be noted that case study 3 represents the application of the framework for EoL management for “complex construction, low value” components. Their complex design construction increases the disassembly complexity, while the relatively low recovery value adds to the burden of completing automated robotic disassembly in the recycling and recovery processes. In addition, if the current robotic disassembly cell is updated with more powerful and efficient tools, the disassembly time and cost could be further minimised.

10.6 Comparative analysis of the case studies products

To demonstrate the applicability of the developed Eol-EV framework and the feasibility of implementing it in a broad range of electronic components contained in the EVs, three case study components were assessed using the automated robotic approach and associated multi-criteria assessment. These results have demonstrated that automated disassembly enables high recovery rates for precious metals, as well as increased economic benefits compared to manual disassembly. However, small electronic products are nowadays commonly recycled in a size-reduction based treatment (shredding) or are directly treated in an integrated precious metal smelter-refinery. In this research, automated disassembly was investigated and applied to EV components. Results of the presented case studies demonstrate that automated robotic disassembly consistently brings about an improved environmental performance and economic revenue.

The case studies reported in this chapter apply the framework for EoL-EV management, introduced in Chapter 7 of this thesis, to the question of EoL management of EV components. Through Chapter 8 and Chapter 9, the power management ECU represents the component category of “simple construction, high value”. In the first case study, the framework is applied to a category of “simple construction, low value”. In the second and third case studies, the framework was then applied to a category of “medium construction, high value” and “complex construction, low value” respectively. Together, these four case study products demonstrate the flexibility of the framework with regard to the mode of application.

The product utilised in Chapter 8 and Chapter 9 identifies the automated disassembly approach as being the preferred EoL solution, based on the application of the multi-criteria assessment methodology within the research. The recycling and recovery of the valuable materials via disassembly enhanced the environmental benefits. From a technological point of view, its simple construction facilitates fixture and the automated disassembly operations, requiring small numbers of the tools and processes. From the economic point of view, besides the limited cost of the automated disassembly, its relatively high recovery value from the PMs justified economic viability.

The first case study in Chapter 10 had a similar structure as the previous component but much lower recovery value. The result from this case study indicated that although disassembly provides has improved overall environmental performance and been technologically feasible, based on the current set-up, automated disassembly is not commercially feasible for the components in this category. Nevertheless, it was identified that compared with automated disassembly, manual disassembly took less time and less cost for the value recovery.

The second case study identified the EoL solution for “medium construction, high value” components depends on the disassembly strategies. The results indicated that extraction of the valuable materials leads to the significant improvement on the environmental and economic aspects. However, more detailed examination of the results provides some more interesting insights. The increased complexity of the component construction brings about the challenges in disassembly strategies (i.e. sequence) that are related to the disassembly time, cost and value recovery. This result is specifically significant with regard to the economic ‘trade-off’ between disassembly lebel and value recovery for optimising the valuable material recovery rate. Case study 2, therefore, illustrates the important balance between the technological feasibility and economic viability for optimising the overall performance of the automated robotic disassembly processes for EV components.

The results from the third case study indicate that although automated disassembly did not provide the best economic performance, the technological feasibility of the automated disassembly system has been proven in dealing with various components with a variety of design constructions. It was indicated that limited benefit would be gained from the "complex construction, low value" category, as such components require comprehensive disassembly plans and need to follow a number of specific steps, increasing disassembly time and cost, while the material value recovered is relatively limited. Additionally, the results suggest that greater benefits could be achieved by application to the components with same complexity but higher recovery value.

The overview of the multi-criteria assessment results of targeted EV components is shown in Figure 10.31. This includes the assessment of the engine ECU and the Driving support ECU where the same procedure was followed during this research but is not repeated in this thesis. Each component has its strength and weakness in different categories, and the overall performance is the area outlined. This multi-criteria assessment is applicable for different purposes; therefore no weightings have been assigned to the indicators in this research. However, it is feasible to assign weightings in the assessment to meet specific requirements.

10.7 Summary of the findings from case studies

The results generated from the case studies illustrate the important link between product design and EoL management. It is clear that the application of an EoL management framework

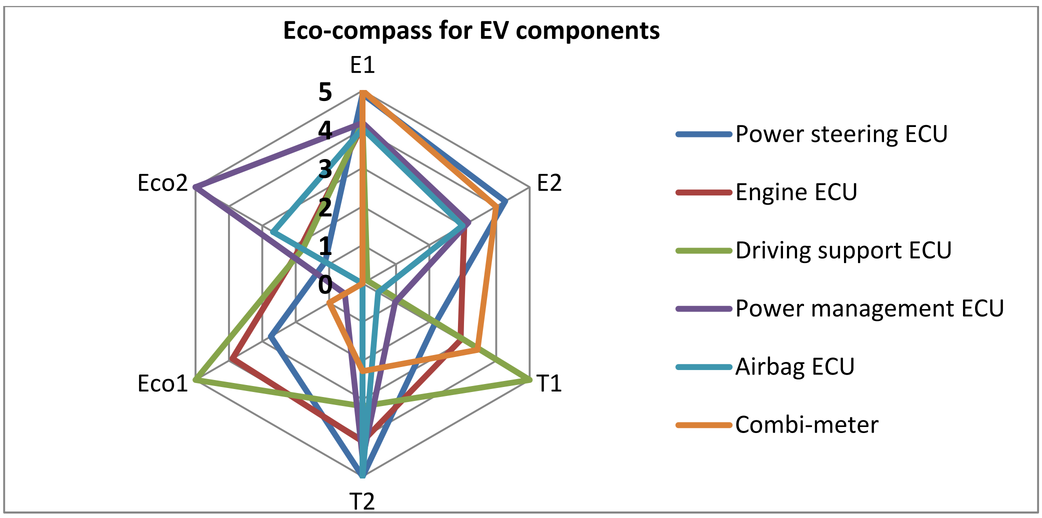


Figure 10.31 Multi-criteria assessment results for EV components.

such as that developed in this thesis, in a proactive manner, could support the direction of future vehicle recycling so as to maximise economic and environmental benefits in a technologically feasible way. Additionally, and perhaps of more value in the long term for future vehicle recycling, the case studies illustrate the application of a systematic approach to EoL management, which supported the development of a procedure that considers various performance criteria. As the industry moves toward large-scale commercialisation, the framework presented in this thesis and demonstrated through these case study components provides a useful tool to support the development of EoL management solutions which are environmentally beneficial, technologically feasible and economically viable.

When examining the results from different scenarios, it is noticeable that the environmental benefits arising from the pre-concentration process (dismantling and disassembly) outweigh the EoL recycling route without dismantling and disassembly. The benefits arise from the avoided impact assigned to the production of recycled precious metals, as well as recycling of material. This reflects the high environmental benefits associated with the production of virgin materials, considering the concentration of PMs presented in EV components. It should be noted that a complete LCA of the case study components would also take into account the detrimental environmental impacts of precious metal production in the manufacturing of the components life cycles. Nevertheless, the results from the case study indicate that these high impacts during virgin material extraction and manufacturing would be alleviated if efficient recovery of materials at EoL stage was achieved.

Besides the driver from environmental benefits, the technological feasibility also affects the EoL EV component recycling. As discussed in Chapter 9, automated robotic operations potentially provide a more economical solution, with more reproducible and predictable performance for recycling activities. It is noticeable that in the case of manual disassembly, costs are often based on direct labour charges, which in turn is proportional to operation times. Additionally, in the case of automated disassembly, costs consist of set-up cost and operating cost. Therefore, disassembly time is important in assessing the productivity and feasibility of disassembly operations. When used to evaluate the disassembly process, the economic aspect is instrumental in determining the disassembly feasibility. The results of the economic impact evaluation are presented with costs displayed as negative values, and recovery potentials displayed as positive values. It should be noted that the cost of implementing the automated robotic disassembly was estimated based on the laboratory set-up, using a single industrial robot, pneumatic tools and modular fixturing. By means of scaling-up the processing line, the increasing investment cost could be paid off by the growth of processing efficiency. The operation cost could also decrease because skilled workers would monitor several processing lines at the same time with the developed programme for the robots. Therefore, it is assumed that the material separation efficiencies of automated robotic disassembly are similar to those of a manual disassembly process; while automated disassembly is more cost-effective than manual disassembly in the long-term and for higher values.

Increasing resource scarcity and prices, as well as the enforcement of more stringent legislation for EoL management, have driven the development of innovative recycling processes for the recovery of among others, PMs and REEs. On the other hand, the automotive industry also strives to reduce material consumption and to lower the environmental load of their products for various reasons, such as direct economic benefits, legal obligation, social responsibility and financial incentives.

It has been noted that EoL treatments aim to liberate the different materials and allow subsequent material separation with the highest possible yield and purity. For this purpose, a shredder process is commonly adopted. After a shredder, the separation process can be either automated optical or a hand-pick operation. However, in this research, the automated robotic disassembly is investigated as an alternative economically preferable approach. Compared with the recycling route without pre-processing, the automated disassembly process increased the overall recycling efficiency for PMs and SIMs, with higher material purity and yields. The difference in value is because the higher mass that needs to be treated when the complete product is directly sent to a smelter-refinery, in which the same amount of material is recovered.

Therefore, a methodology is presented by which the environmental, technological and economic performance of alternative EoL treatment options are assessed to determine the feasibility for investing in automated robotic disassembly processes. Results of the presented case studies demonstrate that the preferred EoL treatment for an electronic component contained in EVs strongly depends on the recovery potential and technical complexity of the component itself.

It was recognised that the case studies would benefit from the availability of more specific data with regards to the alternative scenarios investigated. The scenarios explored represent conceptual processes, for which a level of feasibility has been demonstrated through the practical work described above. However, these processes have not been optimised for EoL management of EVs, nor have they been fully validated with ideal disassembly tools and systems. The case study, therefore, represents a first attempt at evaluating alternative EoL recycling options and paves the way for further, more rigorous investigation of EoL processes for EV recycling.

The selection of case study products helps not only demonstrate the application of the research concept developed within this thesis, but also provide feedback for automotive design stage. It is estimated that more than 80% of the benefit of applying disassembly was determined at the product design stage (Desai and Mital, 2003). Design for disassembly guidelines would assist the improvement of automotive design, facilitating the extraction and recovery of sub-assemblies and materials in an environmentally friendly and economically efficient manner (Go et al., 2012). In this regard, DFD guidelines can be used to reconsider the principal parameters in a way to improve the efficiency of disassembly and fulfil the EoL requirements (Saman and Blount, 2008; Afrinaldi et al., 2008).

A set of guidelines has been developed from previous studies (Moyer and Gupta, 1997; Scheuring et al., 1994). In a similar way, design plays a critical role in the effectiveness of applying automated robotic disassembly operations. To address this, based on the experimental findings from this research, the following suggestions are provided to improve the automated robotic disassembly processes through design amendment:

- Reduce the number of components and fasteners to simplify the automated disassembly processes and reduce time
- Minimise the use of different materials and use modular design to place the sub-assemblies in groups to mitigate material mix
- Promote the design for easy handling of the end-effectors and use of standardised tools to operate
- Provide access and visibility to enhance quick and easy automated robotic disassembly
- Use joining techniques and materials that are detachable and easy to destroy (e.g. plastic materials can be cut through easily, screws and snap-fits overweight glued or welded joints)

CHAPTER 11 CONCLUDING DISCUSSIONS

11.1 Introduction

This chapter brings together the main research issues highlighted within this thesis and discusses the conclusions that can be drawn from these issues. The first part of the chapter begins with a summary of the principal research contributions proposed in the thesis. The subsequent discussion follows the headings of the original research objectives and scope defined in Chapter 2, and aims to highlight the significant findings and knowledge gained from the research.

11.2 Research contributions

The research in this thesis has investigated EoL management of modern EVs. The major research contributions from the research can therefore be summarised as follows:

1) Identification of the need for novel recycling technologies for improving better material recycling and recovery, in order to ensure that environmental impact is minimised and economic viability is achieved.
2) Design and development of an automated robotic disassembly approach, to maximise the potential for value recovery from EV components, in particular the recovery of SIMs and PMs.
3) Defining a three-stage framework for EoL management of EVs, which is capable of generating design and material information and the knowledge required for defining and optimising robotic disassembly processes.
4) Establishment of the paramount importance of design improvement for facilitating the robotic disassembly operations and identification of appropriate guidelines for DfD for robotic disassembly.
5) Demonstration of a novel multi-criteria assessment methodology, which incorporates environmental, technological and economic criteria in order to aid the selection of the most appropriate EV components for the application of robotic disassembly.

11.3 Concluding discussion

The following sub-sections draw together and discuss the results of the main research activities outlined in Chapter 2 as part of the research scope.

11.3.1 A review of evolution of vehicle design

In order to establish the context for the research, it was necessary to carry out a literature review. Three specific areas of literature were identified as being of particular relevance to the research: the review of automotive technologies (especially of EVs) which is reported in Chapter 3 of the thesis, a review of automotive recycling technologies and processes which is reported in Chapter 4, and other relevant EoL management research is reported in Chapter 5.

Together, these review chapters identify that EVs have brought the promise of greener transportation. A substantial impetus for the technology lies in perceived environmental benefits resulting from high fuel efficiencies during the operation and usage of alternative fuels instead of fossil fuels. The ever increasing market growth of alternative fuel vehicles indicates that these vehicles are becoming the main types of future transportation. Additionally, all type of alternative fuel vehicle (electrical, hybrid electrical, fuel cell, etc.) tend to incorporate more electrical and electronic devices and involve increasing numbers of PMs and SIMs. Therefore, the introduction of these alternative fuel vehicles has brought new recycling challenges for future vehicles. Furthermore, the autonomous vehicle technology offers the possibility of fundamental changes in transportation. It would potentially increase the use of more electrical and electronic devices towards digital and electronics control of the vehicles. Another effect of this may be to increase the consumption of critical and precious materials in the long term.

With regard to the use phase, the length of the life cycle of the vehicles has become shorter and shorter, indicating that the overall numbers of the vehicles would increase, as well as the quantity of the ELV to be recycled and recovered.

The review has also identified that recent evolution in the design of electrical and electronic components has resulted in increasing efficiency and reliability. The requirement for improved environmental performance and growing sustainability implications have resulted in a change in the types and quantities of materials used in electrical and electronic components included in the EVs. Automotive electrical and electronic components involve a wide spectrum of materials, ranging from basic metals and various plastics types, to PMs and SIMs as well as harmful minor elements. It was clear that these new materials (such as gold, platinum, silver, palladium, etc.) must be distinguished from traditional materials such as wood, glass, rubber, plastics or basic metals; and recovered and recycled in a different manner. The critical materials and PMs and SIMs are normally rare, valuable, and are in a very limited supply. The

PMs and SIMs are commonly presented in the electrical and electronic components in minor quantities and are often combined with and linked to other materials.

It is also commonly reported that securing reliable access to such critical raw materials has become a great challenge for many resource-dependent industries including automotive manufacturers all over the world. This highlights a need to source such critical materials from virgin minerals as well as various EoL electrical and electronic components. Prudent consumption of materials and maintain the sustainable supply of these materials can be achieved through minimisation of waste generation during production, and by closing the loop in terms of their material recycling and recovery. Therefore, material recovery from ELV has been identified as one of the methods to improve resource efficiency and avoid resource depletion causing the PMs prices to rise.

Furthermore, the materials consumption is affected by the introduction of environmental legislative requirements in relevant sectors. The PCBs in electrical and electronic components may contain toxic materials such as lead, cadmium and beryllium. The shift to less hazardous materials often makes manufacturing more complex, or increases the demands for other materials (e.g. gold, silver, platinum) as substitutes. Furthermore, the potential material substitutes are more expensive than most of the hazardous materials. Another important observation from the initial research review was that despite the fact that we are facing scarcity challenge of PMs and REEs, associated recycling and recovery processes are not economically viable and appropriate technologies and facilities for recovering these materials are still lacking.

11.3.2 A review of EoL vehicle recycling and other relevant research

The freedom offered by transportation has made vehicles an indispensable part of life, and has resulted in significant growth of the number of vehicles on the road. The review presented in this thesis has highlighted an increasing interest and engagement by the research community, governments, and various stakeholders in automotive recovery and recycling. In addition, widespread use of EVs will begin to result in the eventual generation of an increasing volume of EoL EV components, which highlights the need for consideration of more effective EoL management options prior to greater market penetration of further EVs.

In traditional recycling practice, vehicles were individually treated through de-pollution, dismantling of valuable parts for resale, and recycling of a subset of materials. Due to the significant growth of EoL vehicles, the currently preferred EoL management option in the majority of cases is fragmentation and post-fragmentation material separation processes, which are driven by the economic viability.

Therefore the nature and dynamics of the ELV recycling have transformed from product recovery to material recycling. For example, a wing mirror from a traditional vehicle has a better value as a second-hand product rather than being recovered for its materials. However, there are an increasing amount of electrical and electronic parts that are embedded in the wing mirror in EVs and conventional vehicles (e.g. adjustment motors, heaters, cameras etc.) indicating that recovery of the hidden value (i.e. reclaiming the PMs) from the wing mirror of EVs may make more economic sense.

Consequently, recycling challenges have been identified related to increasing electrical and electronic components and associated PMs and SIMs in EVs as discussed in Section 3.5, Section 4.5 and Section 5.10. Because of the insufficiency of the fragmentation and separation, critical and precious materials that are represented in a small proportion in weight cannot be extracted and liberated effectively. The only feasible way to extract the materials is to increase the concentration by removing the components that contain these materials and processing them separately from the rest of the car. However, such dismantling and disassembly operations are expensive due to rapidly increasing labour cost in a majority of developed countries.

The literature survey in Chapter 5 has highlighted that although there has been academic research about robotic disassembly, it has been limited by a large number of factors. Firstly, robots are inflexible to carried out complex multiple tasks and disassembly operations. Furthermore, the robot requires specific tools and fixtures which have not been developed for disassembly. Finally, cost viability of applying the robot has not been assessed, resulting in the recycling industry not investing in such technologies and processes. Thus, this clearly highlighted the requirement to improve the automated robotic approach which has been the main focus of this research.

11.3.3 Development of an EoL - EV framework

In order to liberate the valuable materials from EVs, principally, there are two major challenges: the first is how to dismantle the parts from the vehicles; and the second one is having dismantled the parts from the vehicles, how to disassemble the part to access the materials. To accurately assess the viability of such dismantling and disassembly operations, a structured method must be followed. In order to ensure that this complex problem can be approached systematically, a simple three-stage framework was proposed. This framework provides a step-wise approach to assessing individual component regarding its environmental benefits, technological feasibility and economic viability for dismantling and disassembly.

One of the key challenges for this framework is how to identify a subset of the components from EVs that are suitable for dismantling and disassembly research. The rules that have been adopted in this research are clarified in Section 10.2.2.

In the absence of appropriate information and knowledge about EV components, there was a need within the research to investigate the design and material characteristics of such components prior to developing recycling strategies. However, there were common instances of incomplete and unavailable (confidential) data that significantly hindered the development of the automated robotic approach. Therefore, nine electrical and electronic components were selected from a commercially available EV as representatives for investigating their materials composition, component construction and the feasibility of applying the automated robotic approach.

Initial research identified that it was not appropriate to directly convert manual disassembly processes to robotic operations. For example, in order to have access to the PCB, manual disassembly operations will unscrew the screws and lift up the casing in a non-destructive manner. However, in automated disassembly, the robot can mill off the screw heads and grip the casing, in a semi-destructive way.

In addition, the framework considered the 'trade-off', regarding whether it was necessary to recover 100% of materials from the component. In some cases, the component structure was so complex that complete disassembly did not make economic sense, and only partial disassembly was required.

Additionally, in the wake of legislative pressure, it is identified that future recycling technologies need to not only improve the value recovery from EV components but also to achieve this with a reasonable and limited environmental impact. Thus, environmental and economic assessment formed one of the stages in the EoL – EV framework to justify the pre-concentration and liberation of precious materials using the automated robotic approach.

11.3.4 Development of an automated robotic set-up for EV components

The non-destructive manual disassembly experiments have identified the design and materials characteristics of the EV components. The learning from manual disassembly processes helped generate the initial set of robotic disassembly operations.

The standard modular fixtures used in this research are able to hold the piece firmly enough to prevent the part from moving or vibrating during the robotic disassembly operations. Furthermore, it is clear that the modularity of this fixturing system greatly increases the productivity and reliability that can be applied to a range of components with varied sizes and structures. For example, for some EV components with irregular shape, the corresponding fixturing mechanism can be developed by using a series of fixturing accessories on the grid table with reference locations.

The research findings also highlighted the need for improving the design of robotic tooling and fixtures. It was clear that if the tools and fixtures can be specially designed based on the flexibility and capability needed, the robotic disassembly performance can greatly benefit from such improvement. Additionally, in investigating the suitable fixture approaches, instead of using clamps to secure the component, angle brackets or stops can be utilised to achieve the same function but providing much larger operating spaces and greater flexibility.

Another consideration is about the specific robotic tools that are required in the disassembly operations. In investigating the capability of the robotic tools, a number of experiments were designed. It was identified that standard tools for robotic operations in manufacturing may not be the most suitable for disassembly operations. For example, in order to remove the screws joining the parts, various sizes of screwdrivers were replaced with a one size drill bit. Depending on the required application, various customised drill bits with different material composition (i.e. coating), drill point angle, and diameters were tested and validated in the robotic disassembly processes. In addition, the vacuum grippers have the capability to lift up parts that are made of various materials with two different sizes of vacuum cap, whereas the two-finger gripper could provide better reliability in the gripping process, especially in the case when the surface of components was not smooth and even. Based on the fixture and tooling considerations, the optimum strategies for robotic disassembly have been determined for minimising the operating times in an efficient manner.

11.3.5 Assessing environmental, technological and economic feasibilities

During the research, it became apparent that the sustainability of robotic disassembly had to be considered. Normally, three pillars of the sustainability have been considered: environmental, economic and social aspects. However, in this research, it was infeasible to assess the social impact of robotic disassembly, and hence the assessment included technological viability as one of the criteria.

As described in Chapter 9 the determination of the most appropriate EoL options to recycle EV components is a sophisticated process that involves the collection and analysis of available information and data related to a range of different EoL management scenarios. For example, the analysis of an EV component includes investigating its design and material composition.

In this research, disassembly processes as a pre-concentration approach are proposed to avoid the material contamination and maximise value from recovery of complex material streams that can be found within components of EVs.

In terms of the environmental assessment, materials contained in the EV components were identified to be associated with high environmental impacts in both production stage and EoL stage. The research therefore has adapted the European RRR approach to evaluate the environmental performance between EoL management options. While the author did not undertake a comprehensive LCA that consider all environmental impacts due to the limited time, however, it is noted that further exploration of other environmental impacts would be beneficial in the future.

One of the key considerations in the adoption of the robotic disassembly approach is the economic viability in comparison to manual disassembly. In this context, the CBA is proposed to be applied to the evaluation of EoL management options and has proved to be a useful tool for assessing economic viability. It is clear that value recovery is a key performance indicator; however, this is very much dependent on a number of other variables such as the complexity of part design, the range and amount of precious materials included in the component, and range of disassembly operations required to extract the valuable sub-assemblies. Given the novel area of the research, the technological assessment had to analyse the manual disassembly time versus the robotic disassembly, although this was influenced by the elementary approach to choosing robot, fixtures and tools in the research experimentations.

The individual evaluation of three performance parameters results in three diverse results that may conflict in their evaluation of different EoL options, leading to a number of challenges in decision making. The potential benefits of a methodology for amalgamating the three individual assessment results were identified. The evaluation methodology presented in Chapter 9 provides a flexible and customisable decision support tool, which provides clear and simple results with transparency. The application of a multi-criteria decision making tool was demonstrated in the case studies reported in Chapter 10, and provides a powerful approach for further development and optimisation of automated robotic approaches for EV components.

11.3.6 Demonstration of the framework through case studies

In order to validate the research concepts and refine the proposed framework, three case studies were carried out to demonstrate the automated robotic approach and the multi-criteria decision-making tool developed in this research. It is clear that these three case studies were conducted step by step based on different levels of complexity for the most eco-efficient, technologically feasible and cost-effective recycling option.

These three case studies have highlighted the influence of component design and material composition on the application of robotic disassembly. Three distinct case studies have been selected to represent various components groups that are classified based on the component structure and hidden recovery value, namely 'simple design, low value'; 'medium design, high value' and 'complex design, low value'. Through this research, it became apparent that in terms of material recovery, simple design and high value components unsurprisingly offer greatest potential for the robotic disassembly approach. The components that have complex structure and high value could also benefit from the robotic disassembly process. Additionally, it was clear that low value components were not suitable for this approach, considering the required efforts and limited economic benefit, regardless of the simplicity of the component design.

To investigate the feasibility of robotic disassembly, for each selected component, a series of experiments have been undertaken and repeated in a few different scenarios such as different fixturing methods, tools used, disassembly sequence and depth etc. It is clear that the disassembly results are influenced by multiple factors, including tools, fixtures, robot design, operating parameters (i.e. speed, angle, depth etc.), before achieving the optimal disassembly strategy to be used for the component.

Product design is of paramount significance to EV component recycling. As shown in Figure 10.2, in each of the component categories, a best option forward can be identified. It became clear that simple structure, high value components can benefit less from design improvement efforts. Similarly, low value components, either in the form of simple structure or complex structure, do not merit design improvement based on their limited hidden recovery value. The components that are most likely to benefit from design improvement are those with complex structure and high hidden value.

From the case study results based on the current set-up, the economic viability of the robotic disassembly has not been achieved for most of the components examined. However, it should be noted that his research aimed to answer the question that "Whether the robot can undertake disassembly processes for EV components". The case studies have demonstrated that robotic disassembly is both technologically feasible and environmentally viable. But this now leads to the next research question which is "How to make this robotic disassembly system more economically viable?" For example, lack of labelling of parts and materials can contribute to inefficient disassembly. However, future product labelling technologies such as RFID tags and other technologies such as wireless technology, have the potential to reduce the cost and time of robotic disassembly significantly.

11.3.7 Constraints and limitations of this research

While the previous discussion indicates that the research has been successful in addressing the original aims and objectives, several weaknesses are acknowledged.

The principal weakness in the research stems from the very nature of the components under consideration. The main challenge arises from the various characteristics of electrical and electronic components contained in the EVs. Without collaboration with a metal recycler, the lack of sufficient data about the components would significantly increase the complexity of multi-criteria assessment. In addition, due to the varying nature of each component, when applying the automated robotic approach to any new components, all three stages need to be undertaken.

Aside from limitation resulting from the components, it is acknowledged that the evaluation methodology, and in particular the CBA model, could be further developed to provide a more robust evaluation of economic impacts. The current robotic disassembly cell is a laboratory-based unit which potentially has the capability to achieve high economic revenue when used on an industrial scale. Increasing the numbers of robots could increase their collaborative work, allow them to be more efficient and with appropriate tools and fixturing systems be utilised very effectively for disassembly processes.

Based on this experience, the absence of literature specifically addressing the environmental impacts of EV components raises some questions. In the environmental assessment, some of the research data is based on assumptions and synthesised data. The lack of real data, with which to challenge and validate the theories presented in this thesis, is a weakness.

Also, while it has been attempted to develop an interface to facilitate the application of the evaluation methodology, it is acknowledged that the development of software lies outside the author's primary skill-set. As such, it is clear that a more sophisticated and automated tool can be developed, based on the principles outlined in the thesis.

CHAPTER 12 CONCLUSIONS AND FURTHER WORK

12.1 Introduction

This chapter draws together the principal conclusions of the research presented within this thesis, and proposes possible directions for further extension of the work.

12.2 Research conclusions

The main conclusions that can be formulated from this research are as follows:

i. The growing number of current and future alternative fuel vehicles, such as EVs, combined with increasing complexity in their design and material mix, clearly necessitates a distinctly different approach to vehicle recycling based on a number of pre-shredding dismantling and disassembly processes to retrieve the hidden value from sub-assemblies with PMs and SIMs.

ii. At present, manual dismantling and disassembly approaches are not economically viable in the majority of cases, and in some cases, there are health and safety concerns associated with these operations. This highlights the need for a more automated approach for liberating such materials. Existing automated approaches based on fragmentation and separation are not capable of extracting and recovering the valuable materials that are present in very small quantities in proportion to total vehicle weight. Hence, alternative automated processes are required to concentrate these materials prior to fragmentation and separation processes.

iii. The need to have access to SIMs and PMs has resulted in automotive manufacturers considering getting involved in recycling of the electrical and electronic components, to ensure the long-term availability and access to such materials. Consequently, for the first time design improvements to aid recycling to make both ecological and business sense to these manufacturers.

iv. The research has highlighted that the proposed robotic disassembly approach has the potential to significantly improve the concentration of PMs and SIMs. However, the technical limitation of the robotic system indicates that an automated approach to dismantling and disassembly will be significantly different to manual operations, thus requiring a distinctly different approach to planning for dismantling and disassembly of

EV components using robots. This should consider the 'trade-offs' between both the economic and environmental benefits.

v. The case studies have shown that the practical challenges regarding disassembly of EV components can in part be met by existing fixturing and tools, however, it has been noted that current fixturing and tools utilised in robotic manufacturing are not suitable for an efficient and economically viable EoL disassembly processes.

vi. Investment in the development of specially design fixtures and tools, tailored to the bespoke requirement of dismantling and disassembly, could significantly reduce the overall processing time and cost, thus making the proposed robotic disassembly approach economically feasible for a wider range of electrical and electronic components.

vii. Design improvement is of paramount importance in supporting future robotic disassembly, particularly in the case of high value products with high levels of complexity. Due to technical limitations within robotic disassembly, such components though they contain a significant amount of targeted materials, cannot at present be economically disassembled.

viii. The research has concluded that the ever-increasing productivity within the manufacturing sector due to improved automation necessitates a similarly effective and efficient use of automation in remanufacturing and recycling activities. In this context, the robotic disassembly proposed by this research has the potential to be re-adopted within the recovery of other electrical and electronic products where the concentration of materials prior to the shredding process is required. This can be both for valuable electrical and electronic products (i.e. iPhones, iPads) and less expensive fast consuming electrical and electronic products (i.e. electronic toys) where large volume processing could still be economically viable.

12.3 Further work

The author recognises the following as areas of further work which represents the most valuable extensions of this research:

12.3.1 Improvement on fixturing and tooling

The objective of this research has not been to develop an optimised fixture and tools for automated robotic disassembly of EV component, but rather to provide a framework by which an EoL solution could be realised in an automated robotic cell. The fixturing and tools used within this research were designed and developed for current small-scale laboratory experiments. The limitation of their capabilities highlighted the need for design improvements on fixturing and tools applied to automated disassembly processes. Hence, bespoke multi-head tool and robotic based fixtures have significant potential to be further explored to facilitate the flexibility and reconfigurability of the robotic disassembly operations, and to reduce the overall cost and time of processing. The proposed reconfigurable recycling system has been presented in a paper included in this thesis in Appendix D.

12.3.2 Optimisation of the planning process for robotic disassembly

It is envisaged that a vision system (i.e. cameras and sensors) associated with intelligent labelling (i.e. RFID tag) can be used to store and process relevant information of the products. The stored data is detected and processed by a RFID reader and then transferred to a robot. Therefore, customised disassembly plans and operations will be developed and carried out by the robot automatically in the future.

12.3.3 Cost model enhancement

The diverse range of costs and revenues within EoL vehicle recycling, combined with the range of operational and strategic decisions involved in maintaining profitability have highlighted the need for a more comprehensive cost modelling solution to consider the 'trade-offs' between the environmental benefits and economic viability. In addition, the current cost model is developed on the basis of the laboratory set-up which may be totally different to an actual industrial set-up. Therefore, further work is needed to properly assess the actual economic impact of different components on real life applications.

12.3.4 Development of the automated disassembly machine for high volume and low variety components

The research reported in this thesis has demonstrated the feasibility of an industrial robot to be used for automated robotic disassembly. However, it is acknowledged that improved performance can be achieved with more appropriate disassembly facilities. In particular, where there is a high value and low variety design (e.g. Flat TV and computer screens), a further research direction may be investigated to design and develop an automatic disassembly machine.

12.3.5 Application of the robotic disassembly approach in other industrial sectors

This research has proposed the robotic disassembly approach in support of EoL recycling and recovery activities within the automotive sector. It is believed that the framework for EoL management provides a systematic approach for exploring and evaluating these issues, and could be applied to other sectors. It is believed that this research can be further investigated and modified to be applied to other industrial sectors.

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APPENDIX A

AN AUTOMATED APPROACH FOR DISASSEMBL AND RECYCLING OF ELECTRIC VEHICLE COMPONENTS

This paper was presented at the 2014 IEEE International Electric Vehicle Conference (IEVC) in Florence, 17th – 19th December 2014.

An Automated Approach for Disassembly and Recycling of Electric Vehicle Components

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***Abstract*—Electric Vehicles (EVs) are now seen as one of future solutions for sustainable transportation, and therefore their market share is annually increasing. However, due to their more sophisticated technologies and complex material mixture, EVs cannot efficiently be recycled using existing automotive recycling facilities. This paper presents the challenges involved in recycling EVs, and describes a systematic framework for developing an automated approach for disassembly and recycling of EV components. The initial results from application of such automated approach to disassembly of EV have also been presented.**

***Keywords*—recycling of electric vehicles; electronic and electrical components disassembly; robotic disassembly**

I. INTRODUCTION

The convenience of personal transportation has become a fundamental requirement for human society. However, the increased use of vehicles with internal combustion engines has resulted in a rapid growth in demand for fossil fuel. It is estimated that 96% of the world`s transportation systems depend on petroleum-based fuels and associated products [1], with the global transportation sector accounting for about 40% of the world`s oil consumption [2]. It is estimated that the European vehicle production accounts for approximately 23% of annual global output [3], while around 9 million vehicles reach their End-of-Life (EoL) and need to be recycled in the EU [4]. Recent innovations in automated flexible production systems and shortened technology lifecycles are among the most important factors contributing to this rapid growth in vehicle production and disposal.

There are concerns associated with current methods of disposal of End-of-Life Vehicles (ELVs), not only due to potentially recyclable materials ending in landfills, but also because of the hazardous nature of some of ELV material contents. These concerns have been mostly addressed by the European ELV Directive (2000/53/EC); which aims to reduce the amount of hazardous waste, increase the re-use, recycling and recovery of materials from ELVs and to improve the environmental performance of operators involved in the production, maintenance and EoL treatment of vehicles [5].

In addition due to the rapid increase use of vehicles, the environmental impact associated with their fuels and their long term availability has become a great source of concern. Electric Vehicles have become very popular as a more sustainable mode of transport. However, the introduction of these new vehicle types necessitates novel approaches and processes for their recycling, as their material contents are radically different to traditional vehicles.

Electrically powered vehicles were first produced by several European and American companies in the 1890's. However, due to the limitations associated with mobile electrical storage (batteries) and the rapid developments of Internal Combustion Engine (ICE), large scale production of such vehicles became defunct. Nevertheless, compelled by the fuel crisis in the 1970s and 1980s, the interest in electrical vehicles has been renewed. In addition, the concept of Hybrid-Electric Vehicles (HEVs) was to bring the benefits of electrical vehicles into conventional ICE vehicles. In addition, the introduction of the electric motors and control strategies (e.g. regenerative braking), together with the improvement of battery technology have also significantly improved the HEVs` energy efficiency and environmental performance compared to traditional vehicles [6].

Over the last decade, the range and number of EVs and HEVs on the European road are gradually increasing. It is now estimated that on average these vehicles account for 1% of all new registration in the European countries, as illustrated in Fig. 1 [7, 8]. The research assertion made in this paper is that novel technologies and processes are required to ensure that EVs are efficiently recycled.

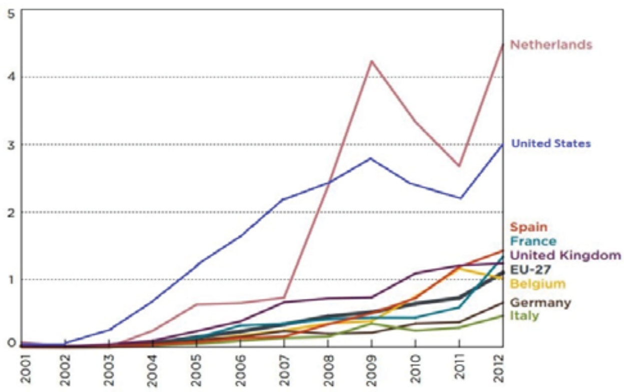

Fig. 1. Market share of HEVs (%).

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This paper describes the initial consideration on developing an automated approach for disassembly and recycling of components within EVs, in order to maximise the value recovery and minimise the environmental impacts. The initial part of the paper provides a brief review of relevant literature and an overview of current vehicle recycling and recovery practices. The later sections present a framework for assessing EoL requirements for EV components, and describe a semi-automated process based on robotic disassembly for recycling and recovery of precious material within such components.

II. An Overview of Relevant Research

Alternative power sourced vehicles are increasingly becoming important in modern society, as they are often associated with benefits of reducing dependence on fossil fuel; reducing pollution; improving energy efficiency and overall environmental performance [9]. Vehicles can be classified into a number of different categories, as illustrated in Fig. 2, based on their fuel source. Typically, EVs have a reduced weight compared to similar sized conventional ICE vehicles through a combination of material substitution and vehicle redesign, for example the replacement of heavy stamped iron and steel components with aluminium, high strength steel and polymer composites. However, compared to the conventional vehicles, EVs contain significantly large number of electronic equipment [10]. The majority of these electronics are used to improve the vehicle performance and control much of the electrical systems which deliver the environmental benefits expected from EVs.

Recycling is not only beneficial to the environment, but also enables automobile manufactures to replace raw ‘virgin’ material with cheaper recycled/recovered materials. An overview of current recycling/recovery routes for ELVs is illustrated in Fig. 3.

This consists of several stages including de-pollution, dismantling, shredding, post-shredder separation (e.g. pneumatic sorting, magnetic separation, eddy current separation, dense media separation etc.) and incineration [11].

Currently there are not any specific and effective methods of recycling EVs, however, a review of the literature has highlighted a number of research work specifically focused on recycling of various electrical and electronic components and their specific material contents, such as batteries; printed circuit boards (PCBs); rare earth elements (REE) and strategically important metals (SIM). In particular, the recycling of batteries [12, 13], and recovery of REE, SIM from PCBs and magnets has received significant attention [14-17].

III. Specific Challenges in EV Recycling

The review of current vehicle recycling activities and practices has highlighted a number of shortcomings for processing the EVs at the end of their lives, including:

A. Large Scale Fragmentation and Separation Processes Driven by Economic Factors

Traditional vehicle recycling methods typically target the recovery of metals, that constitute a substantial proportion of vehicle overall weight, as the primary source of valuable material from ELVs. However, the concentration of metal contained in modern vehicles, especially EVs, has significantly decreased due to the requirement for light weighting of components. Therefore, the hidden value within future ELVs is not within their metal contents but in their electrical and electronic components (in the form of precious materials such as SIM and REE) which make up only a fraction of the vehicles overall weight. This provides a greater challenge for separation and recovery of such materials.

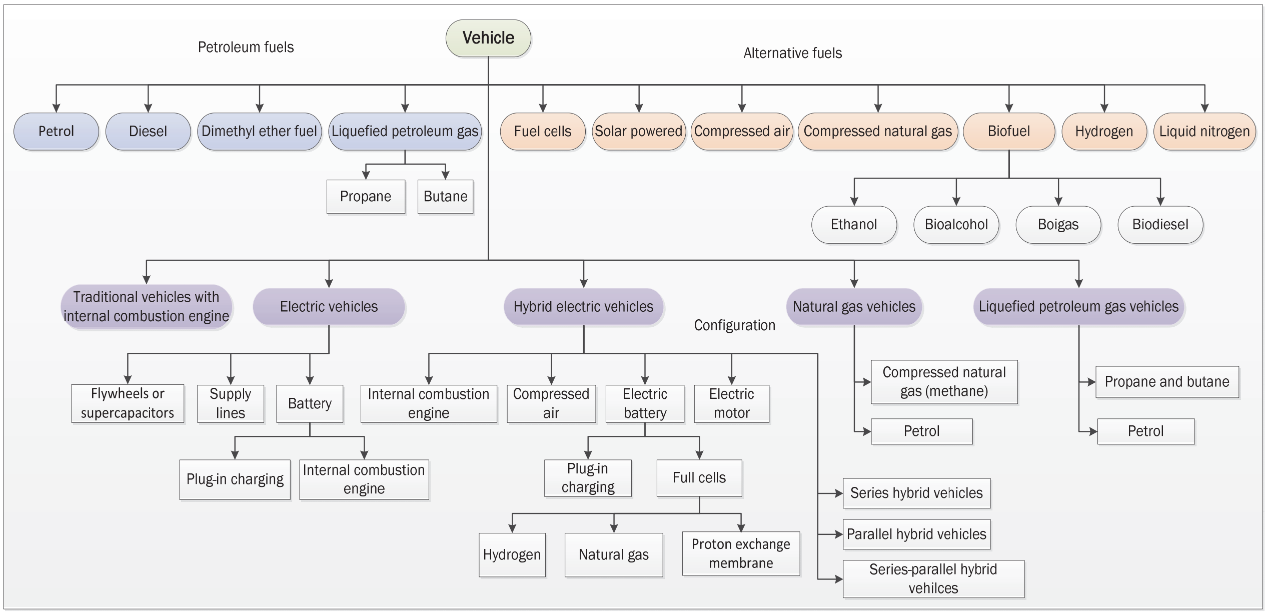

Fig. 2. Vehicle classifiaction.

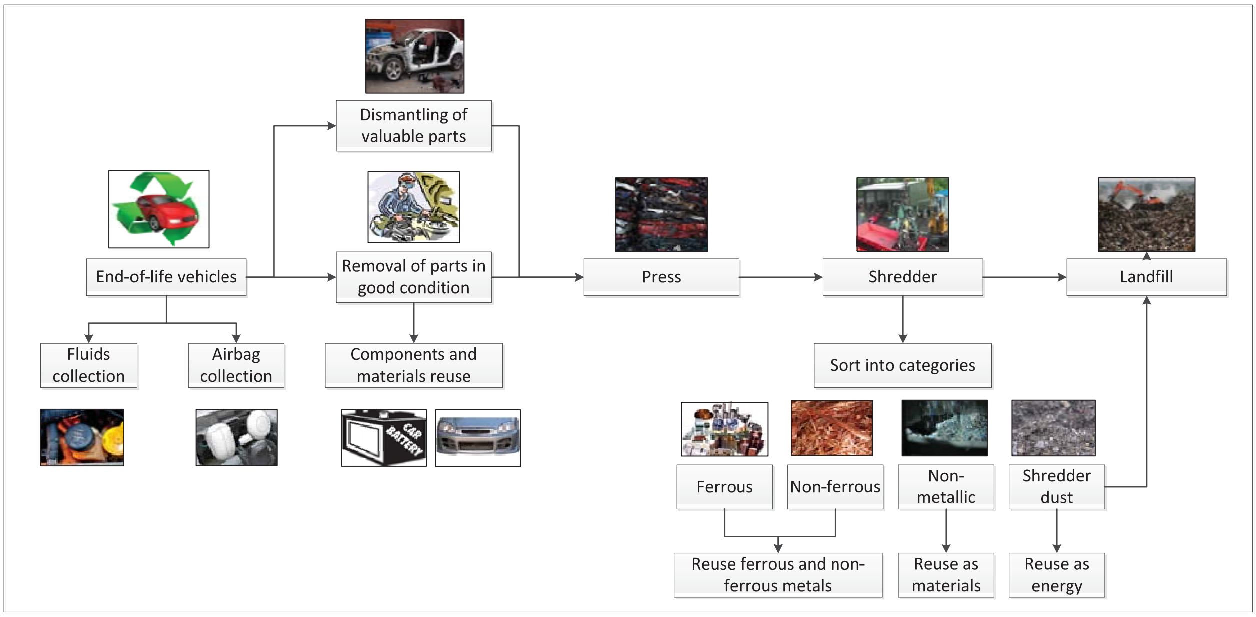

Fig. 3. Overview of of current recycling/recovery route for ELVs.

B. Lack of Automated Disassembly Processes to Support Remanufacturing and/or Pre-Concentration of Recyclable Materials

Manual disassembly of vehicle components often takes too long to be economically viable. The automated disassembly techniques have been applied in recycling of some electronic and electrical equipment, e.g. computer monitors, PCBs, etc. [18, 19], but not for the recycling of valuable parts and/or components of EVs. Disassembly of vehicle components is not only necessary for remanufacturing, but also could be used for pre-concentration of targeted parts/materials to maximise their potential value. The existing fragmentation techniques without such pre-concentration of valuable parts often result in poor liberation and separation of complex material mixtures, and in some case result in total loss of some valuable materials (such as SIM and REE) contained in EVs.

C. Lack of Component Information to Facilitate Recycling

Component structure and material composition information is a prerequisite for making an informed decision about selection of the most appropriate recycling strategy. The recent and rapid evolution of the automotive technologies has introduced a number of new components and/or complex materials within vehicles. However, currently the access to relevant information related to such components and materials is not readily available, resulting in inefficiencies and inconsistencies in treatment of EVs at the end of their lives.

IV. A Framework for EV Componenet Recycling

Two different approaches are proposed in order to decrease the material contamination and increase value recovery from complex materials included within EVs. The first one involves dismantling of valuable components/parts and processing these separately from the main vehicle core (e.g. chassis, seats, carpet, low value plastic components, etc.). These dismantled and sorted parts/components could follow the same recycling process chain (e.g. fragmentation and post-shredder separation process), however, improved material yield and quality will be achieved due to avoidance of cross-contamination of among various material types. The second approach extends this dismantling and separation processes, through further disassembly of parts/components and extraction of sub-assemblies (e.g. PCB and Magnets) to improve concentration of materials within various waste streams.

An overview of the framework developed to support the EoL management of EVs, referred to hereafter as the EoL-EV framework, is illustrated in Fig. 4. The EoL-EV framework consists of four stages, which are defined below.

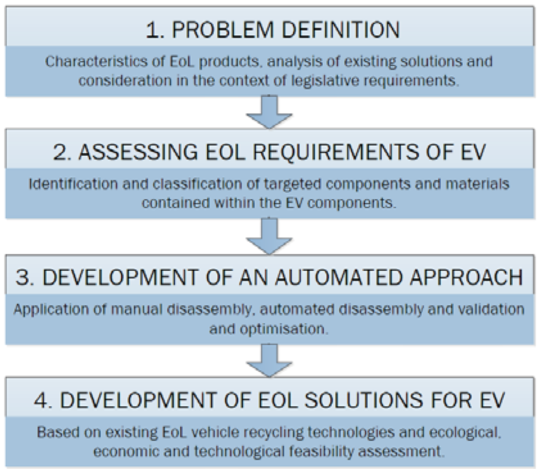

Fig. 4. The four stages in the EoL-EV framework.

A. Stage 1

The first stage of the EoL-EV framework is concerned with the definition and collation of all relevant information and parameters which may constrain or dictate the nature of possible EoL options. This include: i) the review of part/component design and material content; ii) the overview of the existing and appropriate recycling technologies and tools; and iii) the consideration of the challenges and constraints introduced by relevant legislation (e.g. European ELV Directive).

B. Stage 2

The second stage is based on assessing main requirements for EV recycling through addressing questions such as: a) what are new components contained in EV vehicles? b) is there any of these components that cannot be recycled using traditional methods? c) is the recycling of these components economically viable? The increased use of integrated electronics within EVs and their components makes the recycling more complicated. In addition, economic profitability and environmental performance of recycling practices need to be taken into account.

C. Stage 3

The third stage includes a novel approach for developing an automated disassembly process for EV components. It consists of three steps (see Fig. 5), namely; i) part design exploration through manual disassembly, ii) definition of automated Robotic Disassembly Process (RDP) and iii) validation and optimisation of RDP. These steps are further described in Section V of this paper.

D. Stage 4

In the final stage of the EoL-EV framework, the ecological, economic and technological feasibility and performance of various EoL management options are assessed. These three aspects are analysed individually before being considered together within a multi-criteria decision support model to select the most appropriate strategy for recycling of a particular EV vehicle component.

V. DEVELOPMENT OF THREE-STAGE AUTOMATED ROBOTIC DISASSEMBLY FOR EV COMPONENTS

A. Phase 1 Manual non-distructive Disassembly

Phase 1 aims at understanding how components were constructed prior to developing a disassembly strategy. This is achieved through conducting a complete, non-destructive manual disassembly to identify the level of required disassembly. The level of required disassembly is identified by investigating the construction and material composition of the targeted components, and their potentail recovery (hidden) value.

Each targeted component is then classified into one of six specific categories based on permutation of its construction (simple, medium and complex) and value (low and high).

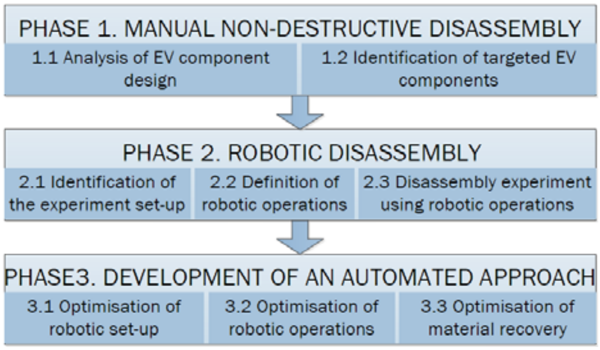

Fig. 5. A three-phase automated approach for EV recycling.

B. Phase 2 Robitic Disassembly

An automated semi-destructive disassembly process has been developed using a flexible robotic cell, as shown in Fig. 6. This robotic disassembly process is based on use of a standard six-axis industrial robot, a specially designed tool for robot arm, and a standard modular fixture. The specially designed tool is capable of a number of operations, including drilling, cutting, and griping using pneumatic power supply. Based on this set-up, a number of various experiments were designed and undertaken to investigate the feasibility of robotic operations, the capability of the robotic tools and the suitability of the fixture platform. These experimental results will be used to support the validation and optimisation robotic disassembly processes in phase 3.

The initial set of experiments aims to explore the feasibility of automated robotic disassembly process through testing the capability of the robot, especially designed tools and fixturing system by varying various operation parameters, such as speed, angle, length etc. The second set of experiments is then used for the generation of the optimised and validated automated robotic disassembly operations.

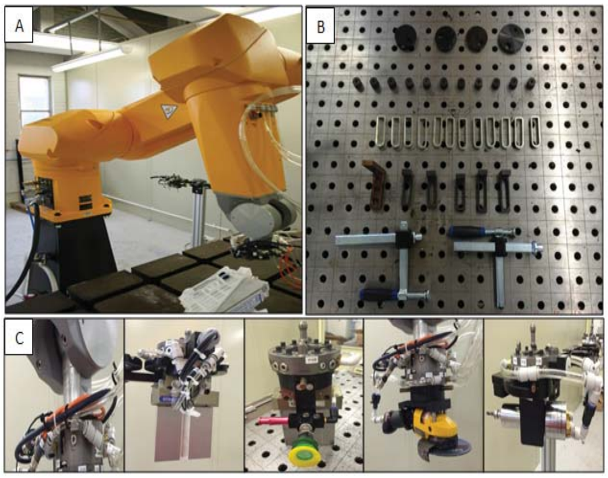

Fig. 6. Robotic disassembly cell containing A) the Staübli RX160 robot, B) the Divano 16 series fixturing platform with accessories and C) the customised pneumatic robotic tools including (from left to right) tool changer, 2-finger gripper, air-suction gripper, circular cutting saw and the drilling/milling tool.

C. *Phase 3 Validation and Optimisation of Robotic Operations*

This stage is concerned with improving the efficiency and repeatability of the robotic disassembly processes, which are defined and tested in phase 2, to maximise the value recovery. It consists of three tasks: 1) determining the optimum strategy to disassemble the EV components in an efficient manner using most appropriate tool set up; 2) developing a robotic setup that minimises the required number of component repositioning and time spent on re-fixturing the component; and 3) optimising the valuable material recovery rate through assessing economic ‘trade-off’ between level of disassembly and value recovery.

VI. Demonstration of Robotic Disassembly Using a Case Study Product

To illustrate the robotic disassembly process a simple Electronic Control Unit (ECU) for power management has been utilised. The first phase as per EoL-EV is the manual non-destructive disassembly ECU, as shown in Fig. 7. This would provide the set of operations required to disassemble the component using the robot, together with parts and subassemblies that should be targeted for disassembly. Table I provides an overview of the results of manual disassembly, including the total and individual disassembly times and tools used during the dismantling. Through this manual disassembly process, it was identified that the valuable parts within this ECU are the PCB and metallic casings. According to its construction and material composition, the power management ECU is categorised as a “simple construction, high value” component.

The PCB is located inside the casings (see Fig. 7), however, this board is hold in place using a sticky tag which provide a practical challenge for its removal using the robot gripping tool, as without manual removal of this sticky tag, PCB cannot be easily separated from the component. This can be addressed using a more sophisticated robotic gripping tool, but for the purpose of these experiments, this tag is removed manually.

TABLE I. Manual Disassembly Datasheet.

Name of the components		Power management ECU	
Total weight (g)		723	
Total time (minutes)		2.5	
Weights for each parts (g)			
No.	Items	Weight (g)	Material
1	Rear casing	292	Steel
2	Screws	9	Steel
3	Sticky tag	3	Polymer
4	Printed circuit board	229	Multi-Material
5	Lid	190	Aluminium
Manual disassembly processes			
No.	Disassembly steps	Tools used	Time (seconds)
a	Fixturing	human force	10
b	Tear off the sticky tag	human force	5
c	Unscrews 6 screws on the lid	screwdriver	84
d	Lift off the lid	human force	5
e	Get the PCB out	human force	3
f	Tool exchange and handling	human force	40

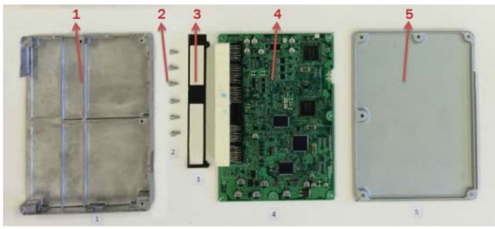

Fig. 7. A breakdown of power management ECU.

In phase 2, based on the information gained from manual disassembly, a specific set-up for fixturing and robotic operations required for disassembly of the ECU are developed. Table II summarises the results from three specific disassembly trials based on different set-ups using different milling tool bits, gripping tool and fixturing methods, as outlined below:

- **Trial 1**: four angle brackets are used to fix the component to the table. The tool used to mill out the screws is the Tungsten Carbide drill cutter with 6mm diameter. A standard gripper consisting of two retractable parallel figures is used to extract the PCB from the casing.
- **Trial 2**: in addition to four angle brackets, a holding plate is used to improve the fixing of the component to the table. Carbide spotting drill bit (8mm diameter) and a vacuum gripper are used.
- **Trial 3**: similar fixturing method and gripper tool used trial 2 are utilised, however, a slightly larger Carbide spotting drill bit with 10mm diameter is used.

TABLE II. Automated Disassembly Datasheet.

Operations		Description	Time (seconds)			
			Phase 2			Phase 3
			Trial 1	Trial 2	Trial 3	
1	Fixturing	Fix the component on the table	60	120	100	60
2	Robotic set up	Get the milling tool from the tool stand	10	10	10	10
3	Manual operation	Tear off the sticky tag	3	3	3	3
4	Milling process	Mill 6 screws on the lid	100	80	60	40
5	Tool exchange	Put the milling tool back and get the vacuum gripper	30	30	30	30
6	Lifting process	Lift off the lid and the PCB, put the PCB in a storage box	30	25	20	15
7	Tool return	Put the vacuum gripper back to the tool stand	10	10	10	10

It was however observed that this fixturing time would gradually decrease after several trails due to familiarisation of operator to the fixturing process. Additionally, increase in tools size and type was required to reduce the milling operation time. It was identified that the 10mm-diameter milling bit took shortest time to milling off the screws.

In addition, the standard U-shape gripper used in Trial 1 failed to achieve a repeatable lifting process, due to limitation in space around the PCB. However, the vacuum gripper in Trails 2 & 3 successfully removed the PCB from the casing. It should be noted that ideally the vacuum gripper is used for a smooth surface; therefore different locations on the PCB were tested to identify a repeatable lifting process. In Phase 3, various operational parameters (feed, speed and tool exchange) are investigated and optimised to significantly reduce total operation time, as shown in table 2 and Fig. 8.

The main difference in total operational time observed between manual and semi-automated approaches in these experiments is due to fixturing time of the component. It is expected that in a commercial implementation of such robotic disassembly cell, an especially designed fixture to be developed which would significantly reduce the total fixture time. In addition, the use of a more powerful tool head and a customised vacuum gripper could further reduce the overall robotic disassembly operational time.

VII. Conclusions

The rapidly growing market share of EVs and increased part complexity and material mixture included in such vehicles highlights a need to develop novel flexible recycling technologies and processes. The proposed systematic EoL-EV management framework enables the identification of the most valuable materials and recovery processes required to liberate these materials. This paper also presents a novel approach for EV recycling processes, based on semi-automated robotic disassembly. This major assertion made in this paper is the need for increased automation and flexibility in the future vehicle recycling processes. In this context, the robotic disassembly cell enables the valuable materials from EVs' components to be pre-concentrated and removed in order improve quality of recycled material, increase the economic potential and reduce the environmental impact associated both with producing virgin materials and with inappropriate disposal of such materials to landfill as shredder residue. Finally, due to flexibility offered through such robotic disassembly cell, this approach could be readopted for processing of other core products with e-waste.

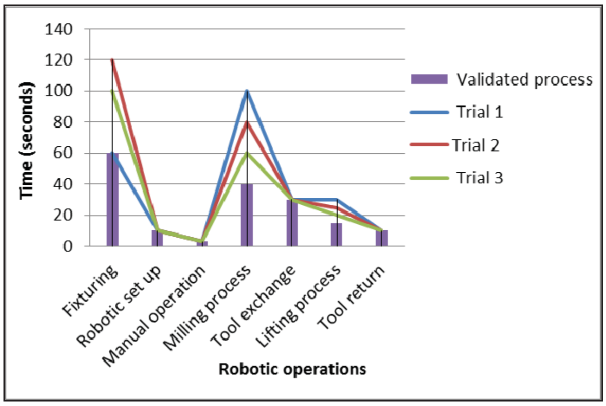

Fig. 8. Comparison between robotic disassembly options.

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APPENDIX B

DEMONSTRATION OF A COMPLETE SET OF PROCESSES IN THE AUTOMATED ROBOTIC DISASSEMBLY

This appendix illustrates a complete set of operations that are undertaken as part of the second and third stages of the EoL – EV framework, the completed set of robotic processes for power management ECU is included.

Introduction

To illustrate a complete set of operations that are undertaken as part of the second and third stages of the EoL-EV framework, the complete set of robotic processes for power management ECU is included in this appendix.

B1. Overview of application of the automated robotic disassembly approach

The flow chart in Figure B.1 was developed to demonstrate the processes that required in the application of automated robotic disassembly approach for power management ECU, namely: fixturing, milling processes, gripping process, and tool exchange and handling.

A series of experiments were undertaken to investigate various factors for continuous improvement (see Table B.1). For each factor, at least three trials were used to explore, optimise and validate the performance. Each experiment brought about new learning on tools and fixturing.

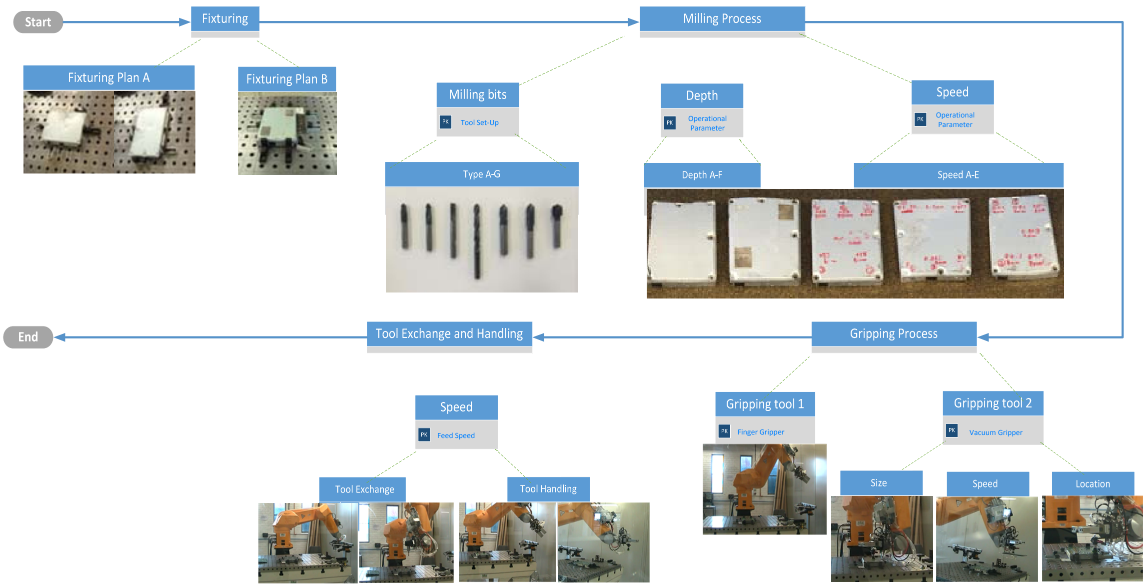


Figure B.1 An overview of the complete set of automated robotic disassembly processes for power management ECU.

Table B.1 Experiment plan.

Power management ECU					
Experiment No.	**Fixturing**	**Milling process**	**Gripping process**	**Tool handling and exchanges**	**Comments**
1					a) It is an continuous improvement process to explore various factors; b) In an iteration, each factor is tested at least three times.
2					
3					
4					
5					
6					
7					
8					

B2. Fixturing

The first aspect is the fixturing, with two different fixturing approaches being investigated. Based on the ECU design construction and proposed disassembly plan, simple fixturing accessories (i.e. angle brackets, stops and bolts) were utilised in the plan A; while various EoL conditions required the fixturing approach to be more standardised. Therefore, a more complicated, but generalised fixturing plan B was also design and developed.

As shown in Figure B.2, the component was fixed on the modular table with specific reference points to improve the reliability and repeatability of fixturing. Even increased number of the accessories was increased to fully fixture the component but the familiarisation of the fixturing operation resulted in reducing the time required to fixture over time. The Average operation time is provided in Table B.2.

B3. Milling process

In the milling test, the first step is to identify the most suitable drill bit for the milling process. As shown in Figure B.3 (a) and (b), the capability of the standard and spotting drill bits was

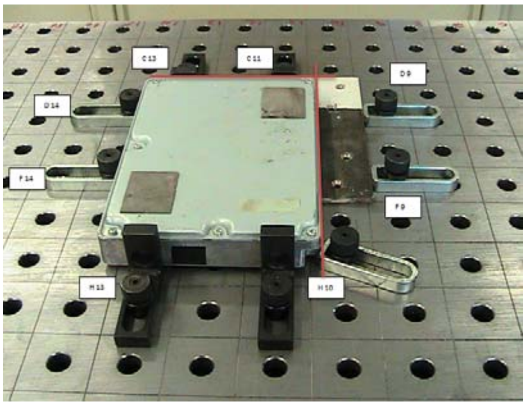


Figure B.2 Fixturing plan B for the power management ECU with reference points.

Table B.2 Operational time in the complete set of automated robotic disassembly for power management ECU.

Average operational Time (second)				
Experiment No.	Fixturing	Milling process	Gripping process	Tool handling and exchanges
1	60s	100s	50s	125s
2	120s	100s	50s	125s
3	100s	100s	50s	125s
4	100s	80s	30s	125s
5	100s	60s	25s	125s
6	100s	40s	20s	65s
7	100s	40s	15s	43s
8	100s	40s	15s	43s

tested on the sample. It turned out compared to standard drill bit, spotting drill bit was more effective. During the course of this step, tool wear problem were addressed, as shown in the Figure B.3 (c).

The following test aims to investigate the feasibility and reliability of various types and sized (shank circumference) of the milling bits, as shown in Figure B.4. It was identified that coated carbide milling bits provided smoother milling run; than standard ones; Tungsten carbide milling bits had improved strength and hardness, and larger mill diameter (8 mm) and helix angle (120°) reduced the time and failure rate. Additionally, the coating could mitigate the tool wear and extend tool life. Experimental results are shown in Figure B.5.

B4. Gripping process

For the gripping process, a parallel finger gripper and vacuum gripper was tested. For the removal of the aluminium lid, the smooth surface made it suitable for use of the vacuum gripper (see Figure B.6 (A). In addition, the application of the finger gripper required significantly more effort to grip the lid (i.e. feed angle) and had a lower success rate. Various gripping points on the PCB were selected to improve the reliability and repeatability of the gripping process (see Figure B.6 (B)).

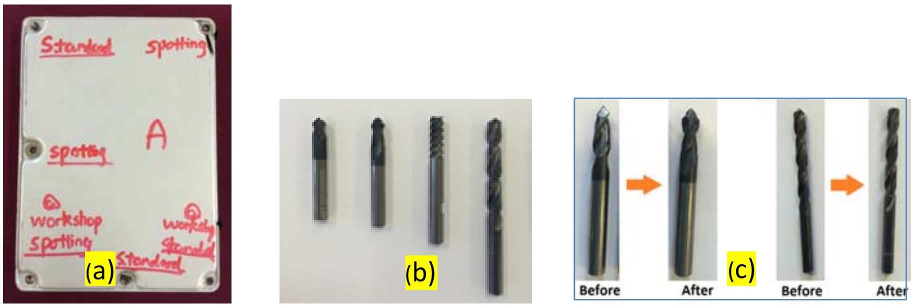


Figure B.3 Drill bit test, (a) the component test sample; (b) initial set of drill bits; and c) tool wear.

No.	Milling bits
1	6mm carbide 90° milling bit
2	6mm carbide 60° milling bit
3	6mm spiral-shape milling bit
4	6mm standard twisted milling bit
5	8mm point AlTiN coated carbide 60° milling bit
6	8mm Tungsten carbide 90° milling bit
7	8 mm Spot AlTiN coated carbide 120° milling bit

Figure B.4 Various milling bits.

Figure B.5 Experiment results**.**

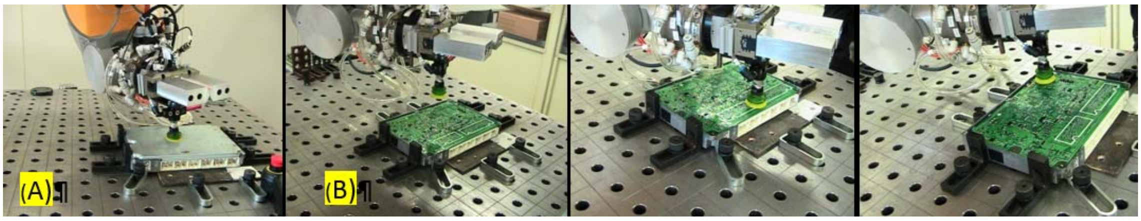


Figure B.6 Gripping tests: (A) Gripping the lid and (B) Gripping the PCB.

In order to increase the contact the vacuum gripper and the PCB, a specially designed cover was used, as shown in Figure B.7. It overcame the difficulty of attachment and significantly increased the success rate and reduced the operational time.

B5. Tool exchange and handling

In the initial set of experiments, the operation speed is the maximum capacity in the manual mode. However, when the fixturing method and automated operations have been finalised, the robot can be set to an automated mode which maximum speed is 100% faster than the ones in manual mode. However, due to the safety consideration, the tool pick-up, exchange and put-back operations were not set with maximum speed. The route and the number of the movements were optimised which improved the operational effectiveness. The cell highlighted with colour indicates where the continuous improvement from one factor to another factor occurred. It should be noted that the each experiment was undertaken at least three times for the average value. The aim of this automated robotic disassembly is to achieve the success rate of ≥ 90% and the application of this approach on the power management ECU has a 95% success rate (see Table B.3).

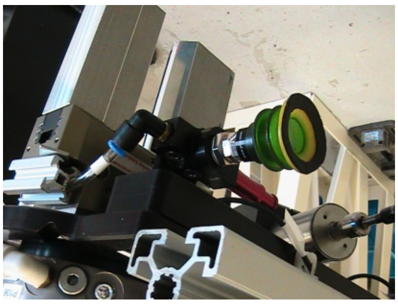


Figure B.7 A specially designed cover for the vacuum gripper.

Table B.3 Success rate in the complete set of automated robotic disassembly for power management ECU.

Average Success Rate (percentage)				
Experiment No.	**Fixturing**	**Milling process**	**Gripping process**	**Tool handling and exchanges**
1	50%	80%	30%	100%
2	80%	80%	30%	100%
3	95%	80%	30%	100%
4	95%	70%	60%	100%
5	95%	75%	60%	100%
6	95%	95%	90%	100%
7	95%	95%	100%	100%
8	95%	95%	100%	100%

APPENDIX C

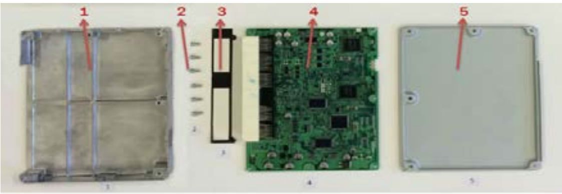
DEMONSTRATION OF THE DATASHEETS OF CASE STUDIES PRODUCTS

This appendix illustrates complete datasheets as a result of the application of EoL – EV framework in four EV components demonstrated in the thesis.

C1 Power Management ECU

EoL-EV Framework Datasheet: Power Management ECU

Overview of the part



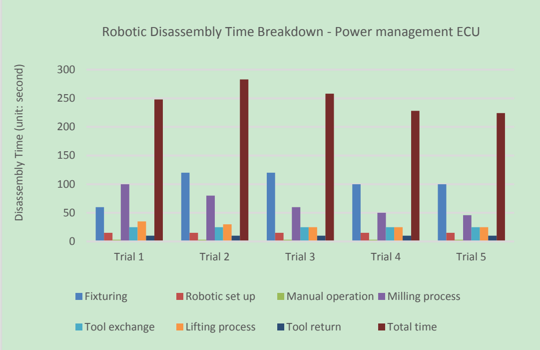
Fixturing Plans

Experimental Results

Manual Disassembly Datasheet ECU

Name of the components		Power management ECU	
Total weight (g)		723	
Total time (minutes)		2	
Weights for each parts (g)			
No.	Items	Weight (g)	Material
1	Rear casing	292	Steel
2	Screws	9	Steel
3	Sticky tag	3	Polymer
4	PCB	229	Multi- Material
5	Lid	190	Aluminium
Manual disassembly processes			
No.	Disassembly steps	Time (second)	Tools used
1	Fixturing	10	Human force
2	Tear off the sticky tag	5	Human force
3	Unscrews 6 screws on the lid	57	Screwdriver
4	Lift off the lid	5	Human force
5	Get the PCB out	3	Human force
6	Tool exchange and handling	40	Human force

Robotic Disassembly Experimental Results



EoL Scenarios and Environmental Assessment Result

Product Details						
Product Details	Mass of the product					
Power management ECU	729					
Recyable part	PCB					
Materials	Mass (Mrecyc_i) (g)	Recycling rate (RCi) (%)	Impact for the production of virgin materials (Vi)	Impacts for the disposal (Di)	Impact due to the recycling (Ri)	Mrecyc_i * Rci* (Vi-Di-Ri)
Copper	5.7968E-02	95%	2.03E-03	1.14E-09	2.19E-04	9.97E-05
Gold	2.9770E-04	97%	5.82E+01	1.14E-09	2.22E-04	1.68E-02
Silver	6.6457E-05	92%	1.37E+00	1.14E-09	3.80E-06	8.38E-05
Palladium	2.1111E-06	99%	6.60E-01	1.14E-09	1.47E-03	1.38E-06
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	1.70E-02
Materials	Mass (Mrecyc_i) (g)	Recycling rate (RCi) (%)	Impact for the production of virgin materials (Vi)	Impacts for the disposal (Di)	Impact due to the recycling (Ri)	Mrecyc_i * Rci* (Vi-Di-Ri)
Copper	5.7968E-02	60.0%	2.03E-03	1.14E-09	2.19E-04	6.30E-05
Gold	2.9770E-04	25.6%	5.82E+01	1.14E-09	2.22E-04	4.44E-03
Silver	6.6457E-05	11.5%	1.37E+00	1.14E-09	3.80E-06	1.05E-05
Palladium	2.1111E-06	25.6%	6.60E-01	1.14E-09	1.47E-03	3.56E-07
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	4.51E-03
		Recyclability Benefit Rate (%)	276.80%			

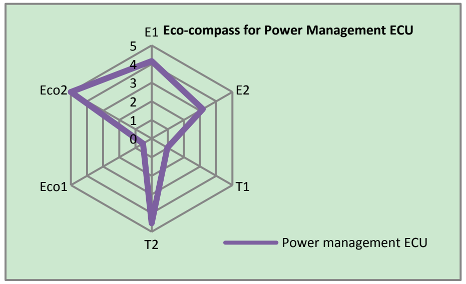
Material composition and Economic Assessment Result

Component Name: Power management ECU			Total Disassembly Time (Minutes)	
Material(unit: g/gram)		Price (£/g)	Including Tooling & Fixturing	
Ag	0.289	0.37	Manual	Automated
Au	0.061	28.2	2	3.73
Pd	0.004	16.82	Total Disassembly Cost (£/piece)	
Cu	55.075	0.0041	Manual	Automated
Ni	0.801	The value of those materials is excluded in this cost model.	1.45	1.07
Pb	0.137		Processing Cost (£/piece)	
Sb	0.054		0.68	
Sn	4.358		Recovery profit (£/piece)	
Zn	5.146		Manual	Automated
MgO	0.508		-0.01	0.37
Al2O3	22.747		Cost-benefit ratio	
CaO	11.510		Manual	Automated
SiO2	37.442		-145	2.891891892
Fe	6.902			
Mn	0.146			
TiO2	0.745			
BaO	2.168			
Total £ per part = £2.120				

Disassembly Times and Technological Assessment Result

	Total Disassembly Time (minutes) Including Tooling & Fixturing Time		Fixturing time (minutes)		Tool exchange and handling time (minutes)		Disassembly Time (minutes)		Ratio of the automated disassembly time to manual disassembly times
Power management ECU	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	Ratio=Automated/Manual
	2.00	3.73	0.17	1.00	0.17	0.83	1.67	1.90	1.138

Multi-Criteria Assessment Result

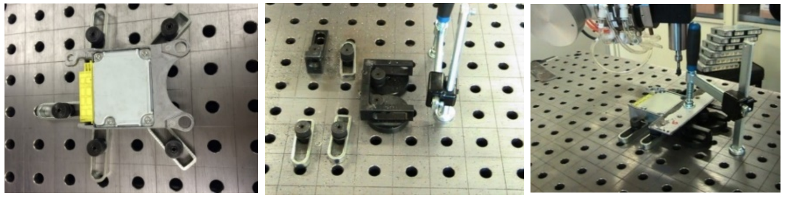


C2 Airbag ECU

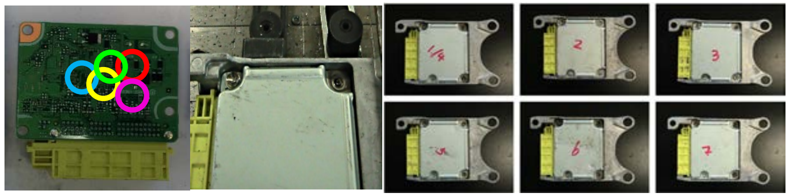
EoL-EV Framework Datasheet: Airbag ECU

Overview of the part

Fixturing Plans



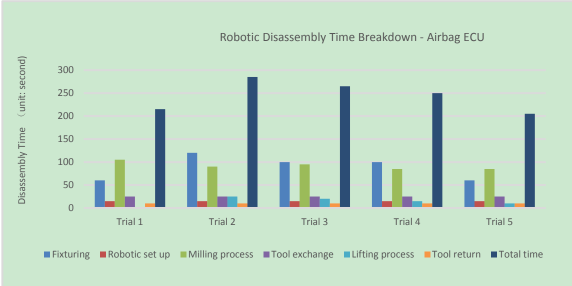
Experimental Results



Manual Disassembly Datasheet ECU

Name of the components		Airbag ECU	
Total weight (g)		267	
Total time (minutes)		1.4	
Weights for each parts (g)			
No.	Items	Weight (g)	Material
1	Rear casing	148	Steel
2	Screws and washers	7	Steel
3	Lid	32	Aluminium
4	PCB	80	Multi-material
Manual disassembly processes			
No.	Disassembly steps	Time (second)	Tools used
1	Fixturing	10	Human force
2	Unscrews 4 screws on the lid	54	Human force
3	Lift off the lid	5	Screwdriver
4	Get the PCB out	5	Human force
5	Tool exchange and handling	10	Human force

Robotic Disassembly Experimental Results



EoL Scenarios and Environmental Assessment Result

Product Details		
Product Details	**Mass of the product**	
Airbag ECU	287	
Recyable part	PCB	

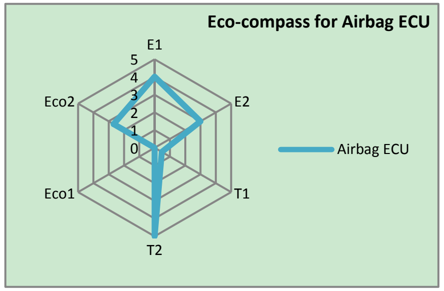
Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	2.4779E+01	95%	2.03E-03	1.14E-09	2.19E-04	4.26E-02
Gold	1.9546E-02	97%	5.82E+01	1.14E-09	2.22E-04	1.10E+00
Silver	1.0957E-01	92%	1.37E+00	1.14E-09	3.80E-06	1.38E-01
Palladium	4.4444E-04	99%	6.60E-01	1.14E-09	1.47E-03	2.90E-04
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	1.28E+00
Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	2.4779E+01	60.0%	2.03E-03	1.14E-09	2.19E-04	2.69E-02
Gold	1.9546E-02	25.6%	5.82E+01	1.14E-09	2.22E-04	2.91E-01
Silver	1.0957E-01	11.5%	1.37E+00	1.14E-09	3.80E-06	1.73E-02
Palladium	4.4444E-04	25.6%	6.60E-01	1.14E-09	1.47E-03	7.49E-05
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	3.35E-01
		Recyclability Benefit Rate (%)	282.87%			

Material composition and Economic Assessment Result

Component Name: Airbag ECU		
Material(unit: g/gram)		Price (£/g)
Ag	0.1008	0.37
Au	0.01896	28.2
Pd	0.00044	16.82
Cu	23.544	0.0041
Ni	0.151	The value of those materials is excluded in this cost model.
Pb	0.151	
Sb	0.024	
Sn	2.044	
Zn	0.372	
MgO	0.318	
Al2O3	6.414	
CaO	1.943	
SiO2	12.104	
Fe	1.764	
Mn	0.376	
TiO2	0.203	
BaO	0.778	
Total £ per part = £0.676		

Total Disassembly Time (Minutes)	
Including Tooling & Fixturing Time	
Manual	Automated
1.4	3.4
Total Disassembly Cost (£/piece)	
Manual	Automated
0.35	0.41
Processing Cost (£/piece)	
0.22	
Recovery profit (£/piece)	
Manual	Automated
0.106	0.046
Cost-benefit ratio	
Manual	Automated
3.302	8.913

Multi-Criteria Assessment Result



Disassembly Times and Technological Assessment Result

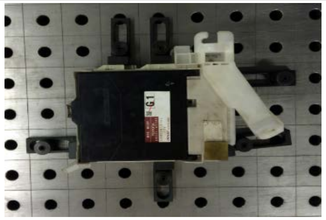
	Total Disassembly Time (minutes) Including Tooling & Fixturing Time		Fixturing time (minutes)		Tool exchange and handling time (minutes)		Disassembly Time (minutes)		Ratio of the automated disassembly time to manual disassembly times
Airbag ECU	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	Ratio=Automated/Manual
	1.4	3.4	0.17	1	0.17	0.83	1.07	1.57	2.429

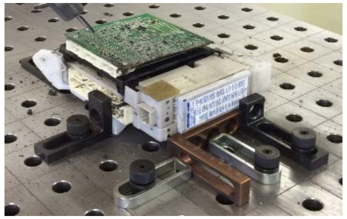
C3 Power Steering ECU

EoL-EV Framework Datasheet: Power Steering ECU

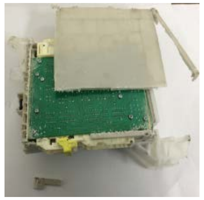
Overview of the part

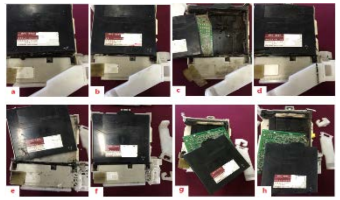
Fixturing Plans





Experimental Results





Manual Disassembly Datasheet ECU

Name of the component		Power steering ECU	
Total weight (g)		759	
Total time (minutes)		8.4	
Weights for each parts (g)			
No.	Items	Weight (g)	Material
1	Wirings and bracket	Various	Multi-materials
2	Rear black casings	29	PP
3	Front black casings (front and back)	45	PP
4	Printed circuit board (PCB) $_1$	83	Multi-materials
5	PCB$_2$ with connectors	399	Multi-materials
6	Front cover of the bottom unit and clip	47	PP
7	Bottom casings	141	PP, nylon
8	Screws	9	Steel
9	Fuse box cover	6	PP
Manual disassembly processes			
No.	Disassembly steps	Time (second)	Tools used
1	Fixturing	20	Human force
2	Remove the fuse box cover	5	Screwdriver
3	Release the clips on sides to remove the black box	72	Pliers
4	Release the clips to get the front cover of the bottom unit	128	Pliers
5	Release the clips to open the black box	17	Pliers
6	Get PCB$_1$ out of the black box	30	Human force
7	Get PCB$_2$ out of the white bottom unit	93	Human force
8	Unscrew all screws on PCB$_2$	79	Screwdriver
9	Tool exchange and handling	60	Human force

Material composition and Economic Assessment Result

Component Name: power steering ECU		
Material (unit: g/gram)		Price (£/g)
Ag	0.717698	0.37
Au	0.008536	28.2
Pd	0.001645	16.82
Cu	143.588	0.0041
Ni	1.309	The value of those materials is excluded in this cost model.
Pb	0.083	
Sb	0.000	
Sn	4.503	
Zn	7.187	
MgO	8.580	
Al2O3	9.168	
CaO	10.339	
SiO2	42.291	
Fe	23.657	
Mn	0.147	
TiO2	0.601	
BaO	1.175	
Total £ per part = £1.13		

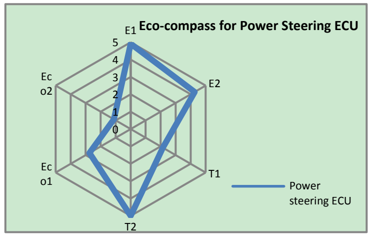
Total Disassembly Time (Minutes)	
Including Tooling & Fixturing	
Manual	Automated
8.4	7.97
Total Disassembly Cost (£/piece)	
Manual	Automated
2.1	0.95
Processing Cost (£/piece)	
0.73	
Recovery profit (£/piece)	
Manual	Automated
-1.7	-0.55
Cost-benefit ratio	
Manual	Automated
-1.24	-1.73

EoL Scenarios and Environmental Assessment Result

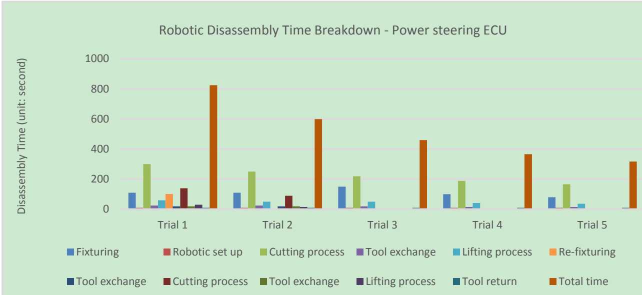
Product Details	
Product Details	**Mass of the product**
Power steering ECU	759
Recyable part	PCB

Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	1.5115E+02	95%	2.03E-03	1.14E-09	2.19E-04	2.60E-01
Gold	8.8041E-03	97%	5.82E+01	1.14E-09	2.22E-04	4.97E-01
Silver	7.8011E-01	92%	1.37E+00	1.14E-09	3.80E-06	9.83E-01
Palladium	1.6566E-03	99%	6.60E-01	1.14E-09	1.47E-03	1.08E-03
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	1.74E+00
Materials	**Mass (Mrecyc_i) (g)**	**Recycling rate (RCi) (%)**	**Impact for the production of virgin materials (Vi)**	**Impacts for the disposal (Di)**	**Impact due to the recycling (Ri)**	**Mrecyc_i * Rci* (Vi-Di-Ri)**
Copper	1.5115E+02	60.0%	2.03E-03	1.14E-09	2.19E-04	1.64E-01
Gold	8.8041E-03	25.6%	5.82E+01	1.14E-09	2.22E-04	1.31E-01
Silver	7.8011E-01	11.5%	1.37E+00	1.14E-09	3.80E-06	1.23E-01
Palladium	1.6566E-03	25.6%	6.60E-01	1.14E-09	1.47E-03	2.79E-04
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	4.19E-01
		Recyclability Benefit Rate (%)	316.01%			

Multi-Criteria Assessment Result



Robotic Disassembly Experimental Results



Disassembly Times and Technological Assessment Result

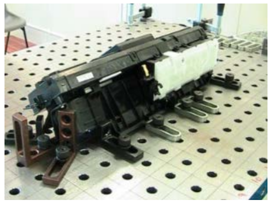
	Total Disassembly Time (minutes) Including Tooling & Fixturing Time		Fixturing time (minutes)		Tool exchange and handling time (minutes)		Disassembly Time (minutes)		Ratio of the automated disassembly time to manual disassembly times
Power Steering ECU	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	Ratio=Automated/Manual
	8.40	7.97	0.33	1.33	1.00	1.33	7.07	5.30	0.949

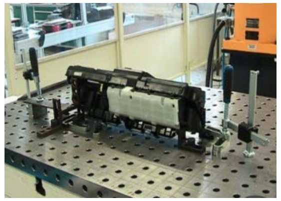
C4 Combi-meter

EoL-EV Framework Datasheet: Combi-meter

Overview of the part

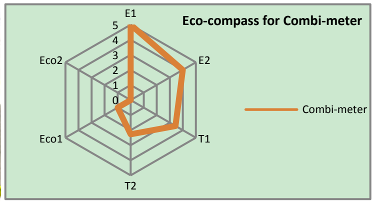
Fixturing Plans





Experimental

Multi-Criteria Assessment Result



Manual Disassembly Datasheet ECU

Name of the components		Combi-meter	
Total weight (g)		1812	
Total time (minutes)		5.79	
Weights for each parts (g)			
No.	Items	Weight (g)	Material
1	Screws and washers	22	Steel
2	Pink protector	31	PP
3	PP mould frame	83	PP
4	Paper instrument	8	PP
5	Monitor casing	42	PP
6	Black protector	101	PMMA
7	PCB Groups	724	Multi-materials
8	Aluminium cover for capacitors	57	Aluminium
9	Black rear cover	154	PP-TD40
10	White cover	32	PP
11	Front frame	160	ABS
12	Middle frame	398	ABS-GF20
Manual disassembly processes			
No.	Disassembly steps	Time (second)	Tools used
1	Fixturing	30	Human force
2	Unscrew screws, release the clips and remove the front black cover	54	Screwdriver
3	Unscrew screws, release the clips and remove the white cover	45	Screwdriver, pliers
4	Remove the PCBs from bother sides (connected by foil)	19	Human force
5	Remove the mould frame and paper instructions	22	Human force
6	Remove the pink plastics screen protector	10	Human force
7	Release the clips and get out of the middle frame	16	Pliers, screwdriver
8	Remove the covers from the middle frame and the black rear cover	13	Screwdriver
9	Release the clips and get out of the black protector	21	Pliers, human force
10	Remove the aluminium protection casing on the PCB	38	Screwdriver
11	Tool exchange and handling	80	Human force

Material composition and Economic Assessment Result

Component Name: Combi-meter		
Material(unit: g/gram)		Price (£/g)
Ag	0.438744	0.37
Au	0.019852	28.2
Pd	0.00213	16.82
Cu	51.382	0.0041
Ni	3.238	The value of those materials is excluded in this cost model.
Pb	10.418	
Sb	0.193	
Sn	5.146	
Zn	2.752	
MgO	9.267	
Al2O3	169.344	
CaO	31.849	
SiO2	221.327	
Fe	84.346	
Mn	3.063	
TiO2	2.051	
BaO	8.645	
Total £ per part = £0.969		

Total Disassembly Time (Minutes)	
Including Tooling & Fixturing	
Manual	Automated
5.79	8.98
Total Disassembly Cost (£/piece)	
Manual	Automated
1.45	1.07
Processing Cost (£/piece)	
0.9	
Recovery profit (£/piece)	
Manual	Automated
-1.381	-1.001
Cost-benefit ratio	
Manual	Automated
-1.05	-1.07

EoL Scenarios and Environmental Assessment Result

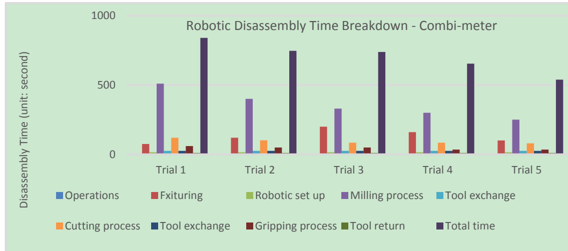
Product Details	
Product Details	Mass of the product
Combi-meter	1812
Recyable part	PCB

Materials	Mass (Mrecyc_i) (g)	Recycling rate (RCi) (%)	Impact for the production of virgin materials (Vi)	Impacts for the disposal (Di)	Impact due to the recycling (Ri)	Mrecyc_i * Rci* (Vi-Di-Ri)
Copper	5.4084E+01	95%	2.03E-03	1.14E-09	2.19E-04	9.30E-02
Gold	2.0464E-02	97%	5.82E+01	1.14E-09	2.22E-04	1.16E+00
Silver	4.7689E-01	92%	1.37E+00	1.14E-09	3.80E-06	6.01E-01
Palladium	2.1515E-03	99%	6.60E-01	1.14E-09	1.47E-03	1.40E-03
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	1.85E+00
Materials	Mass (Mrecyc_i) (g)	Recycling rate (RCi) (%)	Impact for the production of virgin materials (Vi)	Impacts for the disposal (Di)	Impact due to the recycling (Ri)	Mrecyc_i * Rci* (Vi-Di-Ri)
Copper	5.5674E+01	60.0%	2.03E-03	1.14E-09	2.19E-04	6.05E-02
Gold	2.0464E-02	25.6%	5.82E+01	1.14E-09	2.22E-04	3.05E-01
Silver	4.7689E-01	11.5%	1.37E+00	1.14E-09	3.80E-06	7.51E-02
Palladium	2.1515E-03	25.6%	6.60E-01	1.14E-09	1.47E-03	3.63E-04
Platinum	-					-
		Sum of the impact	6.02E+01	4.56E-09	1.91E-03	4.41E-01
		Recyclability Benefit Rate (%)	319.79%			

Disassembly Times and Technological Assessment Result

	Total Disassembly Time (minutes) Including Tooling & Fixturing Time		Fixturing time (minutes)		Tool exchange and handling time (minutes)		Disassembly Time (minutes)		Ratio of the automated disassembly time to manual disassembly times
Combi-meter	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	M.D.	A.D.	Ratio=Automated/Manual
	5.79	8.98	0.5	1.67	1.33	1.83	10.07	5.48	0.544

Robotic Disassembly Experimental Results



APPENDIX D

UTILISATION OF RECONFIGURABLE RECYCLING SYSTEMS FOR IMPROVED VALUE RECOVERY FROM E - WASTE

This paper was presented at the 22th CIRP conference on Life Cycle Engineering in Sydney, 7^{th} – 9^{th} April 2015.

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The 22nd CIRP conference on Life Cycle Engineering

Utilisation of reconfigurable recycling systems for improved material recovery from e-waste

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Abstract

The key features of reconfigurable manufacturing systems, including modularity, scalability and customisability, have provided production flexibility to enable manufacturers to deal with increasing demands for product variability and emerging smart materials. This increased complexity in design and material mix has also highlighted a need for more flexible and advanced technologies for recycling modern products at the end of their life. This paper examines the adoption of key features in reconfigurable systems to increase flexibility and automation in recycling activities. The application of such a ***'Reconfigurable Recycling System' (RRS)*** has been illustrated using a specially designed robotic cell which disassembles and concentrates strategically important materials from components of electrical cars.

Peer-review under responsibility of the scientific committee of The 22nd CIRP conference on Life Cycle Engineering

Keywords: Reconfigurable Recycling; sustainability; e-waste

1. Introduction

Manufacturing has traditionally been understood as the process by which raw materials are transformed linearly into value-added products for consumers. The future of the manufacturing industry however, looks very different; it will require manufacturing firms to be highly agile enterprises, capable of exploiting rapid market changes by increasing flexibility in their physical infrastructures and production processes [1].

A number of challenges driving these future changes within the manufacturing industry include:

- Increase in the demand for product variability [2-3].
- Increase in complexity of the material mix within products e.g. increased use of rare earth elements (REE) (as shown in Fig. 1) [4-5].
- Increase in complexity in the design and construction of products (Fig. 2) [6-8].

These challenges are already driving an increase in manufacturing responsiveness which has led to a shift away from traditional, high-volume, dedicated, inflexible production lines which are unable to respond quickly to product or material requirements, towards manufacturing systems that have flexibility and adaptability built-in from the outset [9]. These systems enable manufacturers to capitalise on the opportunities within dynamic markets where product variance and volume are rapidly changing. This shift away

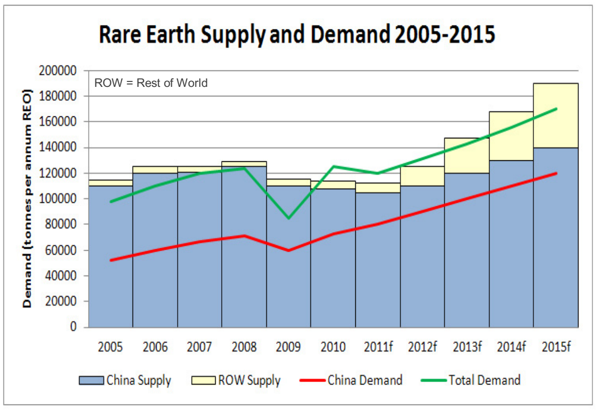

Fig 1. Predicted increase in demand of REE from 2005 up to 2015 [10].

from dedicated lines has not been echoed by the recycling industry, especially within the recycling and material recovery systems that deal with end-of-life (EoL) of electrical and electronic products; this has created a substantial gap between the volume of products that are manufactured globally and the volume of high-quality material recovered from e-waste recycling. The introduction of flexible and adaptable systems into the recycling industry could potentially enhance material recovery from EoL products enabling the material to be used again in high-quality, high-value applications, promoting a circular use of resources without a need to down-cycle [8].

Peer-review under responsibility of the scientific committee of The 22nd CIRP conference on Life Cycle Engineering
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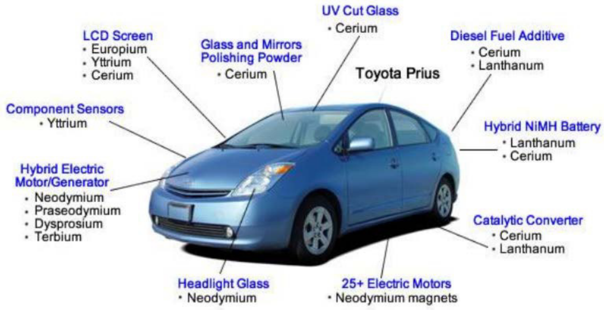

Fig 2. Increase in design and material complexity of certain modern vehicles [11].

This paper explores the adoption of the principles of reconfigurable manufacturing within recycling systems to increase the level of flexibility and adaptability. A review of the latest literature on the recycling of e-waste is performed along with an investigation into the key drivers behind a shift towards flexible recycling systems. Examination of the key characteristics and benefits of reconfigurable manufacturing systems are then explored so that an understanding can be gained of how they can be applied within recycling systems. The final section of this paper presents a flexible robotic disassembly cell and explores how this fits into a new paradigm based on 'reconfigurable recycling systems' (RRS).

2. Evolution of e-waste recycling system

The electrical and electronic equipment (EEE) industry has become one of the fastest growing manufacturing sectors. Due to the growing demand for technological innovation and shortened technology lifecycles, increasing amounts of waste from electrical and electronic equipment (WEEE) has become one of the fastest growing waste streams. It is estimated that up to 50 million tons of EEE is reaching EoL worldwide every year and needs to be recycled [12-13].

This has resulted in the introduction of the European Directive 2002/96/EC on WEEE and the restriction of the use of certain hazardous substances in EEE (RoHS). These directives are aimed at increasing the recycling of EEE products by enforcing manufactures to manage these products at EoL and decreasing the use of hazardous materials contained in the EEE. This is especially true for the printed circuit boards (PCBs) found in many EEE products. PCBs are integral parts in majority of the electronic equipment, are where the valuable materials are often found, yet only contribute approximately 3% of the total WEEE by weight [14]. Historically the construction of PCBs in EEE products has changed over time, from single-sided or double-sided boards to multi-layered types, which has resulted in increasing complexity and material mix. In addition, the electric connection technology has improved from older "through hole technology" to newer "surface mount technology" (see Fig. 3). With integration technology, a microchip can perform similar functions to a PCB except it contains many more circuits in a small chip. These changes in design and material mixes have caused EEE/PCB waste to attract a lot of attention due to the diversity of existing materials present. For example, toxic substances contained in PCBs can cause enormous damage to the environment and precious materials provide potential economic benefits from recovery processes. Therefore, besides development of environmentally responsible EoL management for EEE/PCBs, economic recovery of precious materials is also a matter of significant interest. In this context, a number of studies have focused on the recycling of EEE and the recovery of their specific material contents, such as batteries, magnets, precious materials and REE [15-16]. Furthermore other research has also been carried out to explore the use of automated systems to extract, recognise and sort parts and components from PCBs, but these experiments have seemingly only been applied to the disassembly of PCBs and not whole EEE components e.g. vehicle EEE components.

This area of research is particularly important within the automotive industry where alternative power sourced vehicles (i.e. electric vehicles (EVs)) have become increasingly important as a potential sustainable mode of transport. EVs are typically associated with benefits of reducing environmental impacts and improving energy efficiency, but also contain large amounts of electronic equipment, which is embedded in the EVs to improve the vehicle performance and control the electrical systems. However, modern automotive recycling and recovery processes have yet to utilise any specific or effective approaches to deal with the increasing amount of electronic equipment found in these or other modern vehicles. In this paper, an automated robotic disassembly cell has been utilised to explore how it can be used to allow flexibility in vehicle recycling, with further details presented in the case study section.

2.1 Specific challenges in e-waste recycling

The review of current e-waste recycling activities and practices has highlighted a number of shortcomings for processing the EEE when it reaches EoL, including:

1) Due to the exponential demand for electronic equipment with a short life time in which only a small percentage are re-used, significant amounts of low value electronic scrap tends to be landfilled or melted without material recovery. Traditional e-waste recycling methods target the recovery of solder, copper and bromine while more modern methods involve the recovery of precious metals which are often in relatively low concentration, meaning an energy-intensive chemical and thermal recovery operation is required.

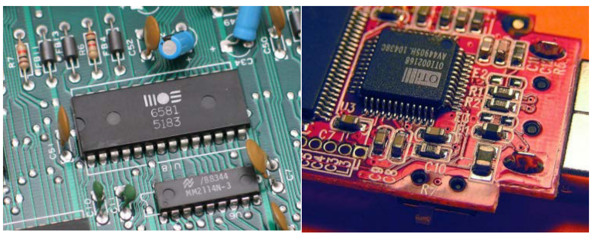

Fig 3. Electric connection technologies (from left to right): through hole technology and surface mount technology.

2) It is necessary to disassemble and sort various families of WEEE products, which contain valuable materials e.g. high value PCBs, with similar properties and process them in large volumes, in order to achieve economic viability. With manual disassembly of EEE products often taking too long to be economically viable, researchers have applied automated disassembly techniques to develop semi-automated disassembly cells for extracting 'reusable' components from PCBs [17-18]. However due to the short lifespan of EEE, there is limited opportunities in reuse of components such as PCBs. Therefore other more economically viable approaches should be investigated.

3) Each EEE component has a unique function and must be designed to perform that function with their specific physical, mechanical, electrical and thermal properties. The identification of component structure and material composition helps to make a suitable decision about selection of the most appropriate recycling strategy. The recent and rapid evolution of EEE technologies has introduced new manufacturing technologies, materials and constructions in EEE components. However, currently the access to relevant information related to such materials is not readily available, resulting in inefficiencies and inconsistencies in treatment of WEEE.

An overview of current recycling/recovery routes for PCBs is illustrated in Fig. 4. This consists of several stages including pre-treatment, separation and concentration and mechanical and/or/chemical refining. Currently PCB recycling systems are designed for specific material recovery processes which makes it difficult to integrate new recycling or recovery processes into the existing system. This highlights a need for a more flexible approach in e-waste processing using RRS.

The challenges that are faced when recycling e-waste are also indicative of the challenges facing the wider recycling industry as a whole and therefore there is a general need for mass transformation in the recycling industry to become more adaptable to future market demands. A major driver behind the need for transformation is the improvement in recycled material quality. Currently, most recycled materials recovered from EoL products are at a lower quality than virgin materials and hence cannot be re-used in place of virgin materials; these are typically down-cycled into lower quality applications. This represents a 'delayed time to landfill' approach rather than a true 'circular use of resources', as eventually during 3rd or 4th product lifecycles due to poor quality of material content, it will have to be sent to landfill. To help achieve a truly circular use of materials, the quality of the recycled material needs to be equal to or better than the virgin materials.

Another key driver behind the recycling system shift is the need to increase localisation of recycling and decrease transport miles of recovered materials. Economic considerations are also a key factor in transforming recycling systems. Large, fixed recycling facilities are capital- intensive to setup and require economy of scale with large volumes of EoL products to claw back investment over time. As EEE become more varied and geographically wider spread, this impedes the possibility of recovering large volume of similar products for processing. Introduction of flexible reconfigurable recycling facilities on a local level makes it economically more viable to recycle high variety of EoL products with in small batch sizes.

3. Reconfigurable Recycling Systems

Reconfigurablility is proposed as a mechanism through which the challenges of future recycling systems can be addressed. RRS are defined as systems with the built-in ability to rearrange or modify their recycling processes to adapt to the specific characteristics of a waste stream. This section explores the adoption of the characteristics defined by Koren

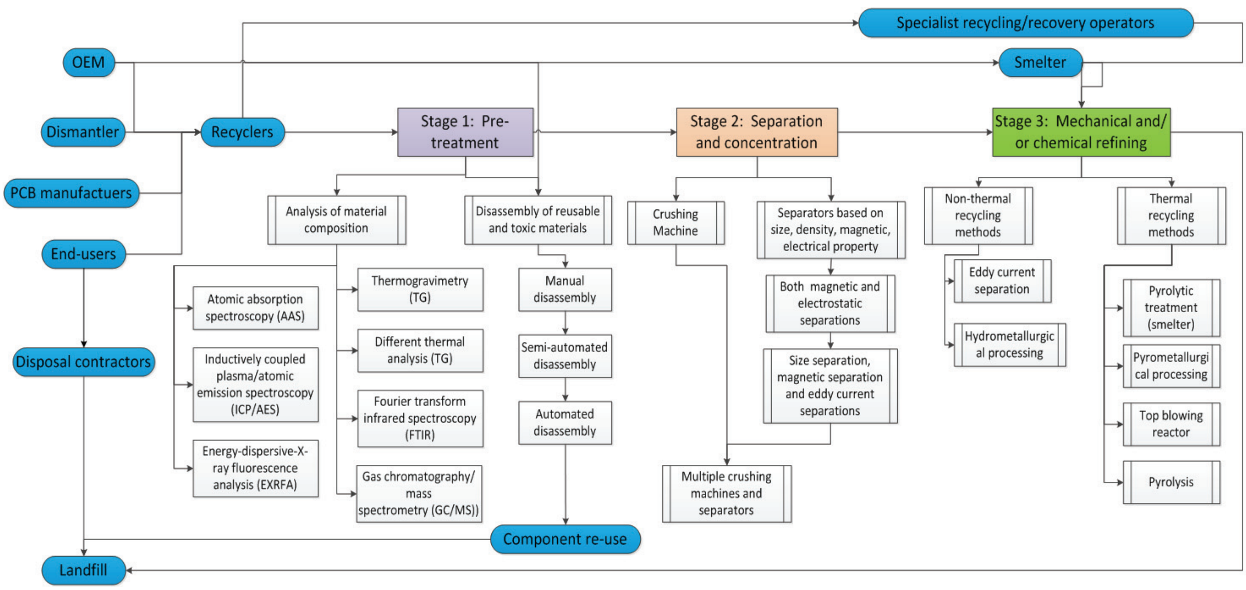

Fig. 4. Printed circuit board recycling technologies and processes [17-19].

et al., [9] and Rosio [20] for reconfigurable manufacturing systems and illustrates their requirement and application in. recycling systems to achieve the required future flexibility, as illustrated in Fig. 5, and described below.

3.1 Mobility in RRS

Mobility is the ability of a system to be tailored to meet the specific requirements of a waste stream. This ability would be greatly beneficial in applications where large batches of various families of products have to be processed over a period of time e.g. recycling of high value e-waste streams containing precious metal and REE.

3.2 Convertibility in RRS

Convertibility is an attribute of a system which allows for the transformation of its configuration on different levels to meet changing requirements after its original setup and installation. Within recycling systems, convertibility can allow a system to be adapted and upgraded quickly e.g. convertibility of a television recycling line to accommodate the shift from flat screen televisions to curved televisions.

3.3 Modularity in RRS

Modularity is the characteristic of a system that is designed to consist of a number of autonomous units that are linked together to form a processing line. This allows removal, replacing and reordering of the recycling processes to suit requirements, e.g. removal and/or reordering of air-based separation processes based on material density and particle sizes. This would reduce unnecessary processing and could increase the quality of the recovered materials.

3.4 Diagnosability in RRS

Diagnosability within systems allows the system to automatically detect the state of the system at any time and feedback this information. This would enable RRS to check the quality of the recovered materials in the processing line, adjust system parameters and hence provide consistent quality materials from waste streams e.g. monitoring granulated plastic size and or colour within a plastics recycling line to maintain size conformity and colour purity.

3.5 Scalability in RRS

Scalability is the attribute which allows systems to deal with variation in processing volume; this includes capacity expansion and reduction. Often in traditional terms, scalability is thought of as the ability to handle increasing volumes, but as product variety increases and batch size decreases, the ability to recycle ever smaller batch sizes of different waste streams becomes more important e.g. recycling of a large variety of footwear products in small volumes within a single shoe recycling line.

3.6 Integrability in RRS:

Integrability is the ability for modules within a system to be combined by mechanical control and informational interfaces rapidly and accurately. RRS being modular in nature would require a high level of integrability; otherwise the process of changing the system becomes difficult, e.g. transportation of waste between different recycling processes using modular conveyer systems.

3.7 Automatability in RRS

Automatability is the capability of a system to alter and upgrade the level of automation to suit requirements e.g. for fluctuating volume requirements. This becomes important in RRS when considering the increasing level of technology and therefore complexity changes in new products e.g. transforming a low volume, semi-automatic disassembly station into a high volume, robotic disassembly station.

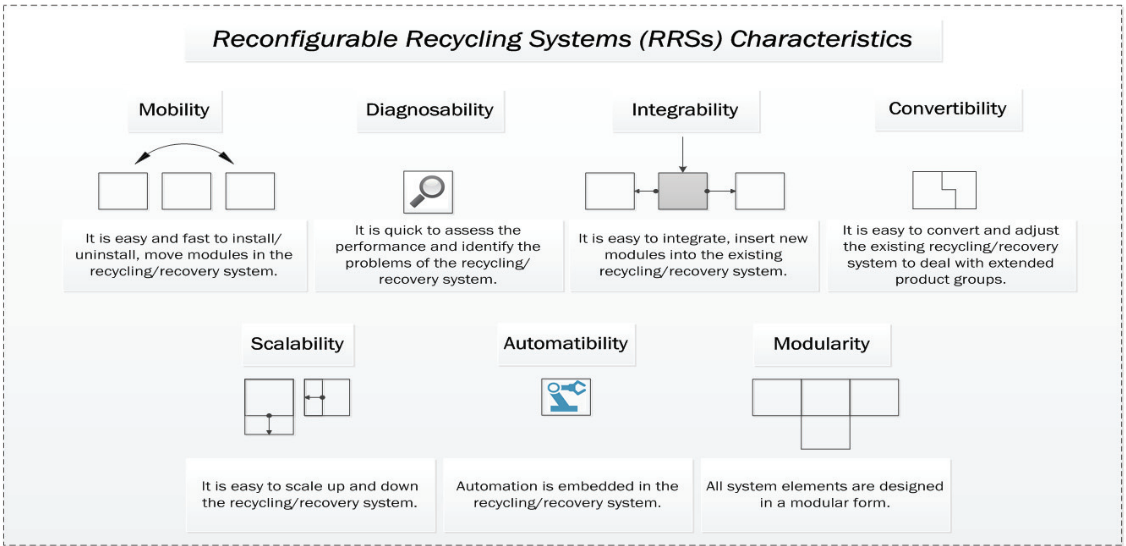

Fig. 5. Reconfigurable Recycling Systems [20]

4. Case study: A robotic disassembly cell as a reconfigurable recycling system for material recovery

In the automotive industry, as one of the potential solutions for sustainable transport, the market share of EVs is rapidly increasing. However, due to the fact that EVs involves more sophisticated technologies and complex material mixture, they cannot be recycled effectively using existing automotive recycling facilities. Therefore, this provides a great challenge for the automotive industry to meet the recycling and recovery targets set from the directive on end-of-life vehicles (ELV).

Today`s disassembly systems have to be flexible to adapt quickly to an increasing number and variety of products designs and changing demand volume for recycling. In general, manual disassembly often takes a long time which is associated with a high labour cost. In order to investigate the challenges involved in recycling of EVs, an automated robotic disassembly cell has been adopted for semi-destructive disassembly [21] of EV components i.e. electronic control units (ECUs) and separation and concentration of high value parts/sub-assemblies i.e. PCBs.

This robotic cell is setup at a lab scale level, based on the use of a standard six-axis Staübli RX160 robotic arm, a specially designed set of tools for use on the robot arm, and a standard modular fixturing platform (see Fig. 6). The tools are capable of a number of operations, including drilling/milling, cutting, and gripping using a pneumatic system. Additionally the robotic setup has the ability to diagnose error statuses of the system and respond by suspending the operation, alerting the operator and waiting for further instruction or error resolution.

This case study focused on the robots ability to undertake automated disassembly of a 'part-family' of small to medium sized ECU components, contained in EVs. It was designed to extract and improved concentration of valuable materials, PCBs, from the EVs` components in order to increase material recovery and reduce environmental impact. This robotic disassembly cell, built with an adaptable structure, provides customisation, flexibility and scalability [19], thus generating a reconfigurable system (see Fig. 7).

A series of ECUs with various material, construction design, and size contained in an EV have been disassembled. The valuable materials were successfully extracted and concentrated, while potentially environmentally damaging materials were separated for safe treatment at a later date. This experiment demonstrated this system has the capability and flexibility to adjust its setup and operational functions for different product requirements. It has the ability to integrate additional hardware and software modules, and incorporate supplementary robotic tools, which can be added when needed, while multiple dedicated programming language commands enabled both the integration of modules and facilitated the communication between software and hardware based on accumulated knowledge and understanding.

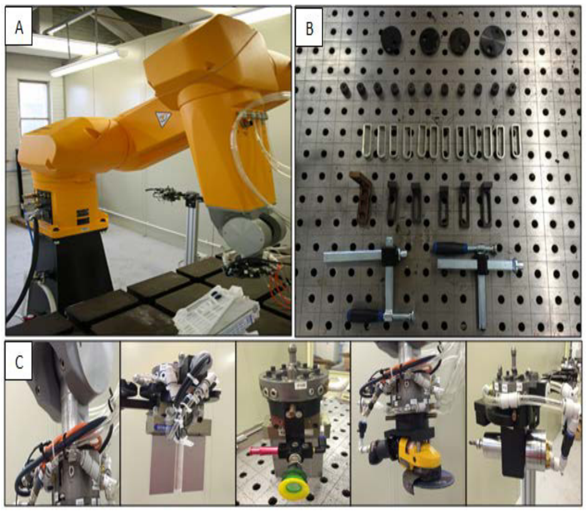

Fig. 6. Robotic disassembly cell containing A) Staübli RX160 robot, B) Divano 16 series fixturing platform with accessories and C) customised pneumatic robotic tools including (from left to right) tool changer, 2-finger gripper, air-suction gripper, circular cutting saw and the drilling/milling tool.

The scalable, convertible and modular tools can also potentially facilitate the handling of other various kinds of products with i.e. different size, shapes, materials etc. as each tool could be modified with varying sized tool bits, gripper jaws, suction cups, as well as differing saw types and blade sizes. Due to the customised flexibility offered through such a robotic disassembly cell, this system has the ability to easily transform its functionality and scalability for processing of other core products from e-waste and hence demonstrates its attribute of convertibility and scalability.

Most of the elements within this robotic cell (i.e. fixture, specially designed tools) are modular which provides the flexibility needed to process a range of components in a "similar family" and facilitate the integration and functionality transformation. If the system has modular elements (i.e. tools and components), it is easier to absorb a great range of variations in the system requirements. Most automation is embedded in the robotic operations/processes, yet due to its modular structure, this flexible cell has the potential for involving more automation, for example, conveyors which could be used as a feeder or distributor with detecting sensors and/or vision systems linked to the robot arm.

Presently the robot arm, fixturing platform and robotic tools are optimized for lab scale experiments capable of a number of operations, including drilling/milling, cutting and gripping of small to medium parts and components. In order to deal with more complex or larger component types, this system can be rearranged and customised with expanded functionality by adding greater processing capability, auxiliary devices and equipment, new modular tools and dynamic sensor systems.

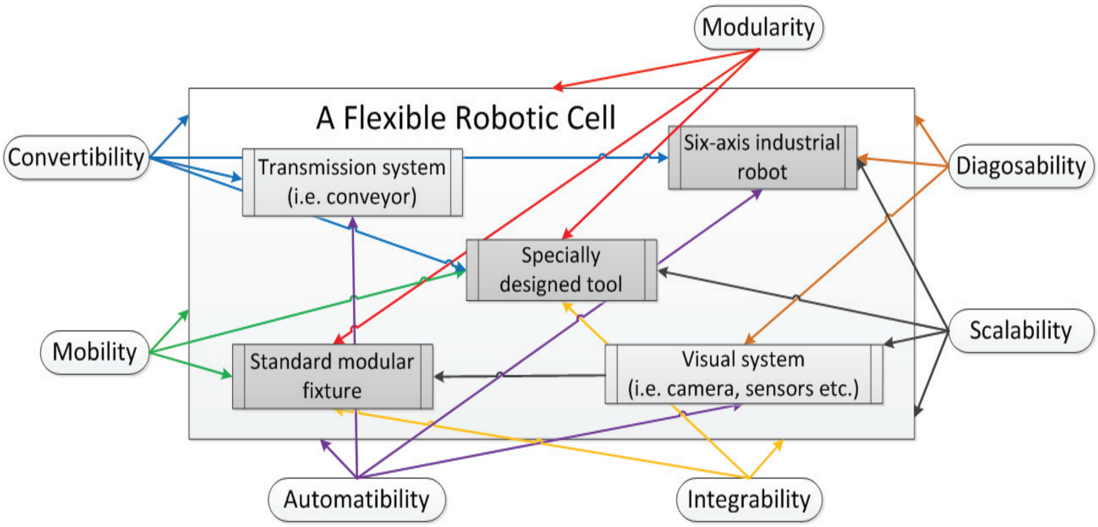

Fig. 7. Relationship between core reconfigurability characteristics and the flexible robotic cell.

5. Conclusions

The paper presents a strong case for an urgent need for a shift towards flexible and reconfigurable recycling systems that can keep pace with the technological changes and advancements in EEE products and their material content. In addition, it is argued that to ensure the realisation of a true circular use of resources, there is a need to achieve significant improvements in yield and quality of materials that are recovered from EoL products. The specific attributes of reconfigurable systems have been examined in the context of recycling applications. These have been recognised as the necessary attributes to meet the requirements of future recycling activities, and hence it is concluded that RRS has a substantial role to play in the sustainable recovery and recycling of modern complex products.

6. Future work

Currently research is being undertaken to look at developing control flexibility in both hardware and software systems for RRS to increase their process capabilities to deal with increasing product variety in e-waste.

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