Life Cycle Impact of Different Joining Decisions on Vehicle Recycling

Vi Kie Soo

May 2018

A thesis submitted for the degree of
Doctor of Philosophy of
The Australian National University

I declare that this thesis is my original work and that to the best of my knowledge, it contains no material previously published or written by another person except where due reference is made in the text. All substantive contribution by others to the work presented, including jointly authored publications, are clearly acknowledged.

Vi Kie Soo
May 2018

Acknowledgements

I would like to express my deepest gratitude to the following individuals who made this thesis possible:

My supervisory panel, Dr. Matthew Doolan, Prof. Paul Compston, and Prof. Aleksandar Subic, for all the mentoring and guidance throughout the development of this thesis. Their infallible support, encouragement, and advice were key to the successful delivery of this work.

My acting supervisor and work colleagues from the University of Leuven, Prof. Joost Duflou, Dr. Jef Peeters, and Dr. Dimos Paraskevas, who connected me to their industry partner and provided full access to the facilities in the Centre for Industrial Management. Their guidance and warm welcome facilitated my experimental work in Belgium.

The Australian and Belgian recycling facilities, who willingly participated in the industrial experiments, and made it possible to collect vital information for this research. The supply of research materials, and access to industrial recycling facilities are very much appreciated.

My fellow work colleagues, particularly Brendan Moloney, Yimeng Jiang, Brendan Voss, Tegan McAnulty, Cameron Summerville and Dr. David Adams, for the brainstorming sessions and the stress-relieving conversations.

My family and friends, especially my parents and sisters, for their relentless encouragement to pursue knowledge and moral support. Despite the distance, they have always been there for me, and are the driving force behind my achievements.

Last but not least, Terence Lai Man Chun, who has been by my side through the good and, more importantly, bad times. I cannot thank you enough for the brainstorming sessions, helping me with software-related problems, and assisting in editing and proofreading my work. I deeply appreciate your patience, care and all the things you do to alleviate my burden.

This work is financially supported by the Commonwealth of Australia, through the Cooperative Research Centre for Advanced Automotive Technology (AutoCRC) and the Australian Government Research Training Program (RTP).

Abstract

Stricter vehicle emission legislation has driven significant reduction in environmental impact of the vehicle use phase through increasing use of lightweight materials and multi-material concepts to reduce the vehicle mass. The joining techniques used for joining multi-material designs has led to reduction in efficiency of the current shredder-based recycling practices. This thesis quantifies this reduction in efficiency using data captured from industrial recycling trials.

Life Cycle Assessment has been widely used to assess the environmental impact throughout the vehicle life cycle stages. Although there is significant research on material selection or substitution to improve the vehicle's carbon footprint, the correlation between multi-material vehicle designs and the material separation through commonly used shredding process is not well captured in the current analysis. This thesis addresses this gap using data captured from industrial trials to measure the influence of different joining techniques on material recycling efficiencies. The effects of material degradation due to joining choices are examined using the life cycle analysis including exergy losses to account for a closed-loop system. The System Dynamics approach is then performed to demonstrate the dynamic life cycle impact of joining choices used for new multi-material vehicle designs.

Observations from the case studies conducted in Australia and Europe showed that mechanical fasteners, particularly machine screws, are increasingly used to join different material types and are less likely to be perfectly liberated during the shredding process. The characteristics of joints, such as joint strength, material type, size, diameter, location, temperature resistance, protrusion level, and surface smoothness, have an influence on the material liberation in the current sorting practices. Additionally, the liberation of joints is also affected by the density and thickness of materials being joined.

The life cycle analysis including exergy losses shows a significant environmental burden caused by the amount of impurities and valuable material losses due to unliberated joints. By measuring the influence of joints quantitatively, this work has looked at the potential of improving the quality of materials recycled from ELV to be reused in a closed-loop system. The dynamic behaviours between the joining choices and their delayed influence on material recycling efficiencies from the life cycle perspective are performed using the data from case studies. It shows that the short-term reduction in environmental impact through multi-material structures is offset over the long-term by the increasing impurities and valuable material losses due to unliberated joints. The different vehicle recycling systems can then be resembled using two widely known system archetypes: “Fixes that Fail” and “Shifting the Burden”. Despite the adoption of more rigorous recycling approaches, the life cycle impact of different joining techniques on vehicle recycling continue to exist. The enactment of strict regulations in current ELV recycling systems is unable to solve the underlying ELV waste problem, and only prolongs the delay in material degradation due to joining choices. This work shows that the choice of joining techniques used for multi-material vehicle designs has a significant impact on the environmental performance during the ELV recycling phase.

Publications

The following publications were developed during my PhD candidature.

Soo VK, Compston P, Doolan M. The Impact of Joining Choices on Vehicle Recycling Systems. *Procedia CIRP* 2018; 69:843-848.

Soo VK, Peeters J, Paraskevas D, Compston P, Doolan M, Duflou JR. Sustainable Aluminium Recycling of End-of-Life Products: A Joining Techniques Perspective. *Journal of Cleaner Production* 2017; 178:119-132.

Soo VK, Compston P, Doolan M. The Influence of Joint Technologies on ELV Recyclability. *Waste Management* 2017; 8:421-433.

Soo VK, Peeters J, Compston P, Doolan M, Duflou JR. Comparative Study of End-of-Life Vehicle Recycling in Australia and Belgium. *Procedia CIRP* 2017; 61:269-274.

Soo VK, Compston P, Doolan M. Is the Australian Automotive Recycling Industry Heading towards a Global Circular Economy? – A Case Study on Vehicle Doors. *Procedia CIRP* 2016; 48:10–15.

Boyden A, Soo VK, Doolan M. The Environmental Impacts of Recycling Portable Lithium-Ion Batteries. *Procedia CIRP* 2016; 48:188–193.

Yu ZY, Soo VK, Doolan M. The Effect of Consumer Behaviour on the Life Cycle Assessment of Energy Efficient Lighting Technologies. *Procedia CIRP* 2016; 40:185-190.

Soo VK, Compston P, Doolan M. Interaction between New Car Design and Recycling Impact on Life Cycle Assessment. *Procedia CIRP* 2015; 29:426–31.

Soo VK, Compston P, Subic A, Doolan M. The Impact of Different Joining Decisions for Lightweight Materials on Life Cycle Assessment. *AutoCRC 3rd Technical Conference* 2014.

Soo VK, Doolan M. Recycling Mobile Phone Impact on Life Cycle Assessment. *Procedia CIRP* 2014; 15:263-271.

Table of Contents

List of Figures

List of Tables

Acronyms and Nomenclature

AAMA	American Automobile Manufacturers Association
ABS	Acrylonitrile Butadiene Styrene
AHSS	Advanced High Strength Steel
Al	Aluminium
AP	Acidification
ASA	Acrylonitrile Styrene Acrylate
ASR	Automotive Shredder Residues
B1	Bale 1
B2	Bale 2
B3	Bale 3
BITRE	Bureau of Infrastructure, Transport and Regional Economics
BIW	Body-in-White
CC	Climate Change
CFRP/CRP	Carbon Fibre Reinforced Polymer
CLD	Causal Loop Diagrams
CO_2	Carbon Dioxide
CP	Complex Phase
Cu	Copper
DfR	Design for Recyclability
DP	Dual Phase
E.g.	For Example
EDIP	Environmental Design of Industrial Products
EF	Freshwater Eutrophication
ELCA	Exergetic Life Cycle Assessment
ELV	End-of-Life Vehicles
EM	Marine Eutrophication
EoL	End-of-Life
EPP	Expanded Polypropylene
ET	Terrestrial Eutrophication
Etc.	Et Cetera
EU	European Union
EUCAR	European Council for Automotive Research & Development
Fe	Ferrous
FET	Freshwater Ecotoxicity
GFRP	Glass Fibre Reinforced Polymer

GWP	Global Warming Potential
HDPE	High-density Polyethylene
HTc	Human Toxicity, Cancer Effects
HTn	Human Toxicity, Non-cancer Effects
I.e.	That Is
ILCD	International Reference Life Cycle Data System
IR	Ionising Radiation
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
MAG	Metal Active Gas
MFRD	Resource Depletion, Mineral, Fossils and Renewables
Mg	Magnesium
MIG	Metal Inert Gas
Mn	Manganese
MS	Martensitic Steels
n.d.	No date
ND:YAG	Neodymium-doped Yttrium Aluminium Garnet
NEDC	New European Driving Cycle
NF	Non-ferrous
OD	Ozone Depletion
PA	Polyamide
Pb	Lead
PBT	Polybutylene Terephthalate
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene Terephthalate
PM	Respiratory Inorganics
PMMA	Poly-methyl-methacrylate
POF	Photochemical Ozone Formation
POM	Polyoxymethylene
PP	Polypropylene
PPE	Polyphenylene Ether
PP-EPDM	Blend of Polypropylene and Polyethylene-Popylenediene

PS	Polystyrene
PU	Polyurethane
PVC	Poly-vinyl-chloride
PWB	Printed Wiring Board
RQ	Research Question
SD	System Dynamics
SETAC	Society of Environmental Toxicology and Chemistry
Si	Silicone
SLCA	Social Life Cycle Assessment
SMA	Styrene Maleic Anhydride
SMC	Sheet Moulding Compound
SS	Stainless Steel
THEMA	Thermodynamic Evaluation of Material Combinations
TIG	Tungsten Inert Gas
TRIP	Transformation Induced Plasticity
U.S.	United States
UK	United Kingdom
UP	Unsaturated Polyester
USAMP	United States Automotive Materials Partnership
USEPA	United States Environmental Protection Agency
WD	Water Depletion
Zn	Zinc

Chapter 1

Introduction

1.1 Overview

This introductory chapter presents the context, problem statement, and scope of this research. A summary of the current automotive industry focusing on the environmental impacts associated with the increasing use of multi-material designs on the end-of-life (EoL) phase is provided. The specific area of interest in sustainable vehicle recycling is identified, and a clear problem statement is defined. The aim of this study is then discussed followed by the description of main terminologies used in this thesis. Next, the contribution of this research towards sustainability in the automotive industry is highlighted. Finally, an outline of the thesis structure is presented.

1.2 Context of the Study

Environmental concerns have instigated the need for reducing vehicle fuel consumption, and increasing material recycling at the EoL stage. To produce more sustainable vehicles, manufacturers have been designing different vehicle powertrain technologies, and using more lightweight materials in vehicle design. Many of the design decisions have targeted a reduction in overall vehicle mass, and a decrease in the negative environmental impacts during the use phase. The adoption of lightweight materials in vehicle design has thus become widespread. Nevertheless, the choice of materials used in vehicle design has several crucial impacts on cost, safety, and the recyclability of materials.

Combinations of lightweight materials are widely used in the mass-optimised vehicle designs. Multi-material designs have been increasingly adopted to further optimise the vehicle mass, fuel efficiency, safety, comfort, and environmental performance. This has led to the introduction of various joining techniques. However, the joining of dissimilar materials, particularly between metals and non-metals, is limited to choices such as adhesive bonding and mechanical fastening. Consequently, material recycling at the EoL using traditional techniques, such as shredder-based recycling processes, is difficult due to the complexity of separating the different material types while maintaining a high level of material purity. This is a concern due to the increasing amount of valuable materials entering the waste stream.

ELV are one of the fastest growing waste streams in the world due to the rapid pace of automotive technology development. In 2010, there were about 40 million ELV globally (Sakai et al., 2014). The number of ELV is projected to increase continuously over the next 20 years (Andersen et al., 2008). ELV recycling plays an important role in maximising recovery of high quality materials that can eventually be reused in a closed-loop vehicle manufacturing system. It is crucial to choose the proper combination of materials and joining techniques to achieve optimal recycling from the economic and technological perspectives. However, the lack of interaction between vehicle manufacturers and auto recyclers has resulted in more waste entering landfill. Most of the current recycling facilities are only capable of recovering steel cost-effectively (Sakai et al., 2014), and the trend of new vehicle designs is showing an increasing use of light metals, plastics, and composites that are either not recovered efficiently or landfilled.

To assist in designing and manufacturing vehicles aligned with the emission and recycling standards, manufacturers have been using Life Cycle Assessment (LCA) to assess the environmental impact of the entire vehicle life cycle. In LCA, the use phase is often the focus due to its significant contribution to global warming potential (GWP). However, LCA is often limited by temporal delays and the inability to account for material degradation in a closed-loop system (Castro et al., 2007). The materials and processes used to improve the quality of recovered materials need to be included in the recycling phase rather than only accounting for the environmental offset of virgin material production. This is crucial to ensure the resultant environmental performance from the life cycle analysis is targeted towards a realistic cradle-to-cradle approach. It is therefore critical to quantitatively assess the effects of materials and their associated joining methods to attain the optimal ELV recycling from a closed-loop perspective.

1.3 Problem Statement

Multi-material vehicle structures and their associated joining techniques used are the two aspects that need to be examined closely from the perspective of ELV recycling. The choice of materials, and the joining decisions in the manufacturing phase are investigated to understand how they influence the ease of material recycling through the current industrial recycling processes. Therefore, the problem statement addressed in this research is as follows.

> The joining processes used during automotive manufacture are critical for the material recovery efficiencies particularly when recycling the increasingly complex multi-material vehicle designs over time.

1.4 Research Aim and Scope

This research aims to fill the gap between vehicle design and recycling by investigating the trends in joining processes used in vehicle manufacturing, and their delayed implications at the EoL phase. The specific aims of this work are as follows.

- Assess the influence of joining choices for lightweight materials and their effects on vehicle recyclability through current recycling practices.
- Determine a method to quantify the impact of joints during the recycling phase towards a closed-loop ELV recycling system.
- Demonstrate the interaction between multi-material vehicle designs and ELV recyclability through dynamical changes in vehicle life cycle environmental impacts over time from a joining techniques perspective.

The scope boundary of this thesis includes a comparison study of the vehicle recycling systems in Australia and Europe based on industrial trials. By understanding the issues addressed, recommendations for the preferred multi-material joining techniques can be provided based on the life cycle analysis and simulated dynamical models for different regions.

1.5 Definition of Terminology

This work focuses on the different joining processes used in automotive manufacturing. Additionally, joint attributes (characteristics of the joining and material parts), joint designs (e.g. butt joint, lap joint, etc.), and joint types (e.g. bolted joint, adhesive joint, etc.) are also investigated. To disambiguate the different contexts, the terms ‘join’, ‘joining’, and ‘joint’ used throughout this thesis are clarified as follows.

As illustrated in Figure 1-1(a), *join* and *joining* are defined as the act of bringing two or more parts into contact to become a single unit. The terms ‘joining processes’, ‘joining methods’, or ‘joining techniques’ are used interchangeably in this thesis to describe the act of joining one vehicle part or material to another using different techniques, such as welding, adhesive bonding, mechanical fastening, and brazing. ‘Joining choices’ refers to the choice of two or more joining techniques.

Joint is defined as the section where two or more materials have been joined together, as illustrated in Figure 1-1(b). A joint can be either permanent or temporary. In this thesis, ‘joint designs’ refers to the shape or structure of the joint, such as butt joint, lap joint, T joint, and others. On the other hand, the term ‘joint types’ is used to describe the different joining processes used at the joint. Take for example, bolted joints and riveted joints are used to describe the joint types for different mechanical fastening techniques. The choice of joint designs often corresponds to the joint types; for instance, the joining of thin materials through adhesive bonded lap joints are preferred in comparison to mechanically fastened lap joints because they develop smoother load transfer, and have fewer points of stress concentration. 'Unliberated joints' or 'partially liberated joints' refers to material collected at the output stream of the recycling facility, as shown in Figure 1-1(c) and Figure 1-1(d). This term is used to reflect the separability of different material types at the joints including the materials being joined, and the additional materials introduced during the joining processes (e.g. fastener, adhesive, filler metal, etc.).

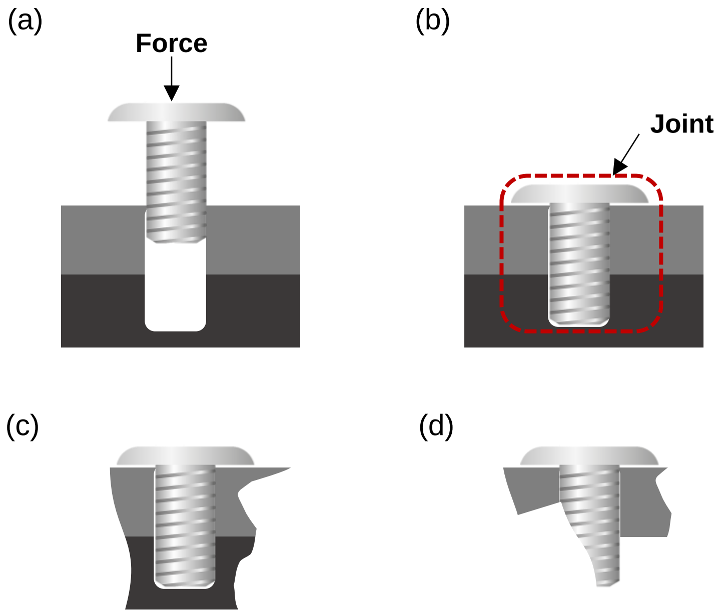


Figure 1-1: Differentiation of the terms *joining* and *joint* using the mechanical fastener as an example. (a) The joining of two parts using a machine screw; (b) Mechanically fastened lap joint using a machine screw; (c) Shredded particle consists of unliberated joint; (d) Shredded particle consists of partially liberated joint.

1.6 Significance of the Study

This research provides new insights into which joining techniques could be used or avoided during vehicle design phase to assist in vehicle recycling efficiency. In addition, the characteristics of joints that have an influence on material recyclability are investigated. The mass of impurities and material losses due to joints are integrated into the sustainable vehicle life cycle analysis emphasising on the closed-loop material recycling. This allows for a better understanding on how different joining techniques used in vehicle manufacturing have an impact on the ELV recyclability in the Australian and global context.

This work emphasises the dynamics of changing vehicle designs and its influence on the recycling phase. The investigation on the relationship between multi-material vehicle designs and the ELV recyclability provides insights into the dynamic behaviours of different recycling systems. Such comprehension allows the optimisation of the vehicle recycling systems from a systematic view. The complex interconnections between different material combinations and their joining methods can be better interpreted from the environmental and legislative perspectives.

The issues addressed are important for current and future sustainable vehicle recycling. The findings from this study can be used by various parties, including those involved in ELV waste management (recycling industry and government policies), sustainable vehicle manufacturing (vehicle manufacturers and engineers), and sustainable non-renewable resources. The outcomes of this research provide a better understanding of the influences of joints that are crucial to vehicle manufacturers, recyclers, and policy-makers in enacting effective ELV policies, and choosing appropriate vehicle designs and recycling approaches to optimise high quality material recycling for a closed-loop system.

1.7 Structure of the Thesis

This section provides an overview of the thesis structure. The chapters in this thesis can be divided into four main parts as follows.

Part One: Background and Literature Review (Chapter 2)
Part Two: Research Methodology (Chapter 3)
Part Three: Case Studies (Chapters 4 and 5)
Part Four: Synthesis (Chapters 6, 7, and 8)

Chapter 2 reviews the evolution in the automotive industry focusing on lightweight materials and multi-material designs, and their associated joining technologies in vehicle manufacturing. The challenges of recycling new vehicle designs are highlighted in line with the material and joining trends. This is followed by an overview of the approaches largely used to address the environmental impact of vehicles. The research questions aimed to address the scope of this study are provided based on the observations from literature.

Chapter 3 describes the integrated methods used in this study: LCA, exergy analysis, and System Dynamics (SD) approach. Firstly, the method used to collect case study data relevant to the research problem is explained. The data analysis techniques adopted to examine the case study observations are then outlined. Analytical tools used to analyse the results obtained from the case studies are discussed in line with the research questions addressed in Chapter 2.

Chapters 4 and 5 present the data obtained from the industrial experiments carried out in Australia and Belgium. A dynamic vehicle life cycle analysis is performed for a specific vehicle part to represent the changing vehicle structures over time based on the data collected in Australia. To investigate the influence of more advanced recycling technology, a case study on aluminium recycling from ELV is carried out in Belgium. The environmental impact of aluminium recycling phase including exergy losses is assessed to understand the effects of different impurity levels in the recovered output streams. Empirical observations on the types of joining techniques causing impurities and material losses in the different output streams are discussed. These chapters also highlight the characteristics of joints likely to affect material recyclability through different recycling approaches.

Chapter 6 interprets the dynamic behaviours of the vehicle life cycle analysis over time represented through the vehicle recycling models from a broader view. The main observations drawn from case study results and the dynamical models are discussed and concluded in Chapters 7 and 8. Recommendations for future research looking at the potential of alternative ELV recycling technologies are also briefly described in Chapter 7. The areas of further work arising from this study are explored in Chapter 8.

Chapter 2

Background
and
Literature Review

Publications relevant to this chapter:

Soo VK, Compston P, Subic A, Doolan M. The Impact of Different Joining Decisions for Lightweight Materials on Life Cycle Assessment. *AutoCRC 3rd Technical Conference* 2014.

Soo VK, Compston P, Doolan M. Interaction between New Car Design and Recycling Impact on Life Cycle Assessment. *Procedia CIRP* 2015; 29:426-431.

2.1 Introduction

This chapter reviews the literature on automotive designs, manufacturing, and recycling industries, that leads to the fundamental approach commonly used to assess vehicle sustainability based on its life cycle. The first section provides a historical trend of automotive design and manufacturing, focusing on the material composition and joining choices. The second section looks into the common recycling practices adopted in different countries or regions. Vehicle standards influencing the trends in automotive design and recycling are also discussed. Finally, the approaches widely used to assess the environmental impact of vehicles are discussed to provide some context on the chosen approaches and methodologies for this study.

2.2 Evolution in Automotive Industry

The growth in vehicle use has contributed significantly to the global carbon dioxide (CO_2) emissions (Hao et al., 2016). In 2014, 75% of the total CO_2 emissions from transportation sector was contributed by road transport. From 1990 to 2014, the CO_2 emissions from road transport have increased by 73%, from 3.3 $GtCO_2$ to 5.7$GtCO_2$ (International Energy Agency, 2016). Environmental concerns have instigated the need for understanding the key influential factors that contribute to the vehicles' CO_2 emissions, and ways to kerb this issue effectively. Past research has identified the potential benefits of vehicle mass reduction, alternative powertrain technologies, and stricter vehicle emission legislations to further reduce the vehicle CO_2 emissions during use phase (Bielaczyc et al., 2014; Offer et al., 2010; Volkswagen Group, 2009).

In recent years, vehicle manufacturers have been pressured to design and manufacture vehicles with low carbon footprint to abide by the strict vehicle emission standards. One of the most stringent vehicle emission policies was implemented by the European Commission through Regulation (EC) No 443/2009 (European Commission, 2009), which was then amended as Regulation (EU) No 333/2014 to include mandatory CO_2 emission targets by 2020 (European Commission, 2014). The mandatory CO_2 emission standards for new passenger cars are outlined as follows.

- A target value of 130g/km of CO_2 by 2015.
- A target value of 95g/km of CO_2 by 2020.

Green car concepts have been emerging to increase fuel efficiency with the vision to achieve the strict CO_2 emission regulations. Toward producing more sustainable vehicles, manufacturers have progressively invested in research and development for alternative fuels such as biodiesel, compressed natural gas, electricity, hydrogen, liquefied natural gas, and liquefied petroleum gas. New advanced powertrain technologies—fuel cell vehicle, hybrid electric vehicle, and plug-in hybrid electric vehicles—are also gaining prominence. Despite the emergence of these technologies, higher production cost (Chan, 2007) and the slow shift to new energy resources (Fouquet, 2010) have hindered widespread adoption in the industry. To overcome this barrier, manufacturers have focused on reducing the overall vehicle mass. Previous studies have shown the great potential of reducing fuel consumption through vehicle mass reduction (Friedrich and Schumann, 2001; Koffler and Rohde-Brandenburger, 2010).

There are several lightweight strategies used in the automotive industry: using high strength-to-weight ratio materials (lightweight materials) (Friedrich and Schumann, 2001; Goede et al., 2009; Sakundarini et al., 2013; Schmidt et al., 2004); lightweight by form and topology optimisation (Christensen et al., 2011; Jang et al., 2010); lightweight by manufacturing process technology (Kleiner et al., 2006, 2003; Merklein and Geiger, 2002); lightweight through secondary effect (Alonso et al., 2012; Goede et al., 2009; Redelbach et al., 2012); and others. Among these lightweight strategies, the use of lightweight materials in vehicle manufacturing is the most commonly used method. The use of high strength-to-weight ratio materials to reduce the mass in the vehicle structure is increasing. For the past several decades, the mass of the base vehicle structure has improved; however, the requirements for better safety and emissions equipment, and the demand for comfort features have contributed to the increasing overall vehicle mass, as seen in Figure 2-1. Moreover, vehicle users are increasingly demanding for fuel-efficient vehicles due to the high fuel prices (Graham and Glaister, 2002). To further optimise the mass reduction potential in vehicle structure, multi-material designs are incorporated during the vehicle design phase. The combination of different material types has an implication on the current manufacturing and recycling processes.

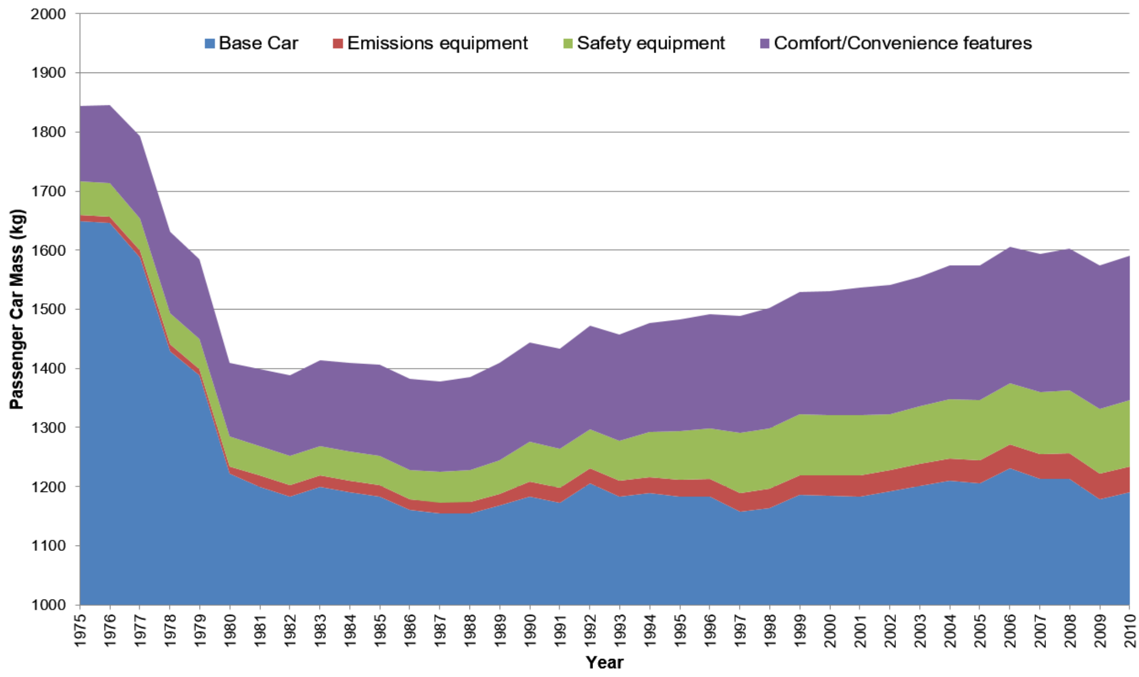


Figure 2-1: Mass of passenger cars in the United States attributed to base car, vehicle safety, emissions, and comfort/convenience features in 1975-2010 (Reproduced with permission from (Zoepf, 2011)).

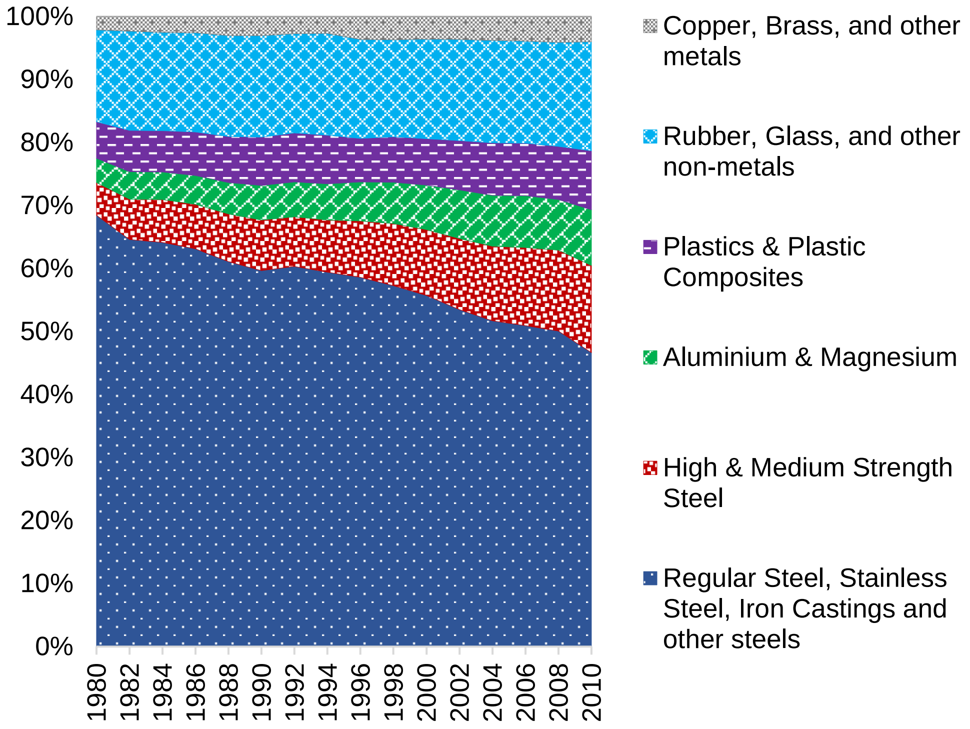
The waste generated by ELV is a growing concern; the global car production has increased by 37% from 2000 to 2013 (Davis et al., 2015), and this trend is projected to continue. It is estimated that 2 billion vehicles will be in use worldwide by 2020 (Sperling and Gordon, 2009). It is an emerging issue in many countries, particularly in the European Union (EU) due to the high amount of ELV. About 7 to 8 million tons of ELV waste is produced annually from ELV recycling in Europe (European Commission, 2016a). Due to the pervasiveness of the automotive technology, the automotive sector has cemented itself as one of the core global industries. Unfortunately, this rapid development comes with a costly environmental impact not just due to the emissions during vehicle use, but also the generation of ELV waste at the EoL stage.

2.3 Lightweight Materials in Vehicle Structure

Lightweight vehicle concept has been rising, and will continue to grow in future vehicle designs. Manufacturers have focused on producing cost-effective lightweight vehicles by introducing changes in vehicle design, reducing vehicle content, and utilising more advanced lightweight materials to replace conventional steels (U.S Department of Energy, 2013). In this context, "lightweight" refers to materials with high specific strength, or better known as high strength-to-weight ratio, which is defined by the material's strength and density.

The demand for better safety and comfort features makes it difficult to further reduce the vehicle content. The vehicle mass has been rising as a result of the additional features. To overcome these barriers, the use of lightweight materials in vehicle structure has gained prominence. The use of more advanced lightweight materials provides the opportunity to improve the performance and functionality at a competitive price without compromising the vehicle size.

Over the past four decades, the choice of materials used in vehicle structure has been greatly transformed to optimise vehicle structure. Mild steel was widely used in the automotive industry in the 1920s (Miller et al., 2000). In the late 1970s, there were major changes in the material selection for vehicles that were triggered by the global oil crisis and high fuel prices (Reynolds, 2014; Taub, 2012). Traditional steels are gradually replaced with lightweight materials such as advanced high strength steel (AHSS), aluminium (Al), magnesium, polymers, and composites (Davies, 2012; US Department of Energy, 2013; Wiel et al., 2012). These materials have been widely explored in automotive sector to optimise their potentials and feasibility in substituting traditional materials due to their high strength-to-weight ratio. The trend towards the use of more lightweight materials in the automotive industry can be observed from Figure 2-2.



Other metals: lead, zinc, powder metals, etc.

Other non-metals: coatings, textiles, fluids and lubricants, etc.

Figure 2-2: Material composition of an average passenger vehicle made in 1980-2010 in the United States (American Automobile Manufacturers Association et al., 1994; U.S Department of Energy, 2013).

The choice of lightweight materials depends greatly on the mass reduction potential, crash performance, and most importantly, the material and manufacturing costs. As shown in Table 2-1, there is potential to reduce the mass of vehicle structural parts by 10-70% when replacing conventional steels with more lightweight materials. The replacement of structural parts is based on the required physical and mechanical properties. For instance, lightweight materials with high torsion and bending stiffness are required to replace the vehicle’s longitudinal structural rails to ensure crashworthiness (Cui et al., 2011; Goede et al., 2008). The relative material cost, however, has caused a major setback for high volume production. For instance, the use of lightweight materials with relative high material cost, such as carbon fibre composites to replace traditional materials, is limited to niche vehicles despite a 50 to 70% mass reduction for a comparable steel design. The mass reduction potential for different lightweight materials, and their relative costs per part to replace conventional steels are shown in Table 2-1.

Table 2-1: Materials' mass reduction potential and relative cost (Adapted from (Joost, 2015; Lutsey, 2010; US Department of Energy, 2013)).

Lightweight Material	**Material Replaced**	**Mass Reduction (%)**	**Relative Cost Per Part**
Carbon fibre composites	Steel	50-70	2-10+
Magnesium	Steel, cast iron	30-70	1.5-2.5
Aluminium	Steel, cast iron	30-60	1.3-2
Glass fibre composites	Steel	25-35	1-1.5
Advanced materials(i)	Steel	10-30	1.5-10+
Advanced high strength steel	Mild steel, carbon steel	10-30	1-1.5
High strength steel	Mild steel	0-15	1

(i) Advanced materials include titanium alloys, metal matrix composites, nickel-based alloys, etc.

There are many studies carried out focusing on the material selection for lightweight vehicles. According to the U.S. Department of Energy, an improvement of 6-8% in fuel economy is shown by reducing the vehicle's mass by 10% (Shea, 2013). The types of lightweight materials commonly used in the lightweight automotive manufacturing are AHSS, aluminium, magnesium, polymers, and composites. The benefits and limitations of each material are summarised in Table 2-2. These materials have been the main focus due to their high strength-to-weight ratio, stiffness and durability, energy absorption ability in crush zones, design feasibility, and manufacturability (US Department of Energy, 2013). Various organisations within the automotive sector have forecasted the leading material that will be used in the future automotive manufacturing industry (Schultz and Abraham, 2013; Shaw et al., 2010; The Aluminium Association, Inc., 2011). These predictions might be biased and influenced by factors such as economic benefits and self-interest. According to the Ford spokesman, Alan Hall, the choice of materials that will prevail in car-making industry is still not obvious (Motavalli, 2012). However, it is appropriate to say that advanced steel, aluminium, magnesium, and polymer composites are the four major materials largely researched and applied in current lightweight vehicles. An overview of these lightweight materials is discussed in the following sections.

2.3.1 Steel

Conventional steels, such as iron and mild steel, commonly used in the car industry are slowly replaced by better lightweight steels for vehicle mass reduction purposes. High strength steel is a popular alternative to conventional steels in the near term due to accessibility, and the relative low cost compared to other lightweight materials. In the quest to maintain its dominance in the car industry, steel manufacturers have been exploring new steel types and grades that are affordable, implementable, structurally robust, easily formable and most critically, lightweight in nature. These criteria are fulfilled by the AHSS steel group that includes Dual Phase (DP), Transformation Induced Plasticity (TRIP), Complex Phase (CP), and Martensitic Steels (MS) (Center for Automotive Research, 2011; Keeler and Kimchi, 2014). These types of steels provide better performance in energy absorption during collision, and higher tensile strength in comparison to conventional and low strength steels.

Table 2-2: Comparison for different lightweight materials used in automotive industry (Adapted from (Center for Automotive Research, 2011; Davies, 2012)).

Material	Benefits	Limitations
High strength steel	• Low cost • Ease of forming • Consistency of supply • Corrosion resistance with zinc coatings • Ease of joining • Well established infrastructure • Good crash energy absorption • Well known material properties • Recyclable	• Corrode if uncoated • Lower strength-to-weight ratio than other • Reducing thickness decreases material stiffness
Aluminium	• Low density • Corrosion resistance • Strong supply base • Well established casting technology • Recyclable	• High fluctuating cost • Poorer formability than steel • Less readily welded than steel
Magnesium	• Low density • Ability to cast thin walls • Possible to integrate components in castings • Recyclable	• High cost at medium to high volumes • Only viable as cast components • Limited stock for product manufacturing • Limited familiarity within the industry
Glass fibre reinforced plastics	• Handle harsh chemical environment • Excellent damping capabilities • Accommodate complex designs	• Slow cycle times • Limited strength • Not recyclable
Carbon fibre reinforced plastics	• Highest strength-to-weight ratio of all materials • Greatest potential for weight reduction	• High cost • Slow cycle times • Limited familiarity within the industry

AHSS provides many benefits to the automotive industry. The strength of different types of AHSS can be applied to different parts of the vehicle to improve overall performance. For instance, the DP and TRIP steels are more stretchable but not bendable compared to the conventional steels (Keeler and Kimchi, 2014). These steels are highly appropriate to build the B-Pillar—the vertical support between a car's front door window and rear side window—for high crashworthiness performance (Cooman et al., 2011; Peixinho et al., 2005). Alternatively, the CP and MS steels have wider strength range in comparison to traditional steels while maintaining the same formability (Keeler and Kimchi, 2014). Therefore, CP and MS are mostly used for side impact protection bars—bars at the passenger doors—of vehicles (Maggi and Murgia, 2008).

2.3.2 Aluminium

The demand for eco-friendly and lightweight materials has placed aluminium as one of the best options to substitute conventional steel and iron for automotive body parts. Aluminium sheet panels have the same strength in comparison to steel body panels, meaning that the same force is needed to deform or break the respective panel. Some car manufacturers are using aluminium to construct the full car bodies such as Audi's A8, Honda's NSX, BMW Z8, and the Lotus Elise (Hirsch, 2014). Aluminium has low density, high resistance to corrosion, strong supply base, and high recyclability that place it at a major advantage to be used as auto-body materials (Davies, 2012). Nevertheless, aluminium is not as stiff as steel because of its lower modulus of elasticity property. Furthermore, its poorer formability, lower weldability compared to steel, and higher cost have limited the wide application of this material (Davies, 2012). These disadvantages can be overcome by increasing the thickness and optimising the cross section designs of parts to influence the deformation behaviour and crashworthiness (Carle and Blount, 1999); however, the raw material cost will also increase. Research and development for this material has led to the formation of different aluminium alloys to improve formability and surface quality (Miller et al., 2000), as well as making them more cost-effective for automotive application.

2.3.3 Magnesium

The potential use of magnesium in vehicle structure has been explored due to its high strength-to-weight ratio. It has very low density, 1740 kg/m^3 in comparison to iron, 7874 kg/m^3, and aluminium, 2712 kg/m^3 (Luo, 2002). This characteristic has encouraged car manufacturers to replace steel, cast iron, copper, and aluminium alloys with magnesium or magnesium alloys (Mordike and Ebert, 2001). Moreover, magnesium has many advantages for automobile application such as high specific strength, good castability

(ability to be cast without formation of defects), great weldability, and better corrosion resistance by using high purity magnesium (Kulekci, 2008; Mordike and Ebert, 2001). The disadvantages, such as low elastic modulus, limited creep resistance, and high chemical reactivity, have further advanced the alloy development for this material (Mordike and Ebert, 2001). Aluminium, manganese, and zinc are commonly added to magnesium to form magnesium alloys that can overcome the poor mechanical properties (Davies, 2012). Nevertheless, magnesium is proven to be the lightest structural metal, with a density only slightly higher than the plastics (Luo, 2002). Magnesium is much stiffer in comparison to plastics with almost 20 times higher elastic modulus, which makes it a promising material that can be used to further optimise the vehicle mass reduction potential (Kulekci, 2008; Luo, 2002). Despite the suitability for lightweight car manufacturing, the use of magnesium is limited in car production due to its high material cost.

2.3.4 Polymers and Composites

Polymers used in the automotive industry can be divided into two categories: thermoplastics and thermosets. Thermoplastics melt and soften with the application of heat, whereas thermosets are non-reversible polymerised structure which cannot be reformed and remelted. Polypropylene (PP), polyurethane (PU), and poly-vinyl-chloride (PVC) are examples of thermoplastics widely used in car manufacturing, contributing about 66% to the total plastics used in an average vehicle (Szeteiová, 2010). A typical car consists of up to 13 different types of polymers, as seen in Table 2-3. Thermosets that are commonly used in automotive are epoxies, polyester, silicones, and phenolics (Happian-Smith, 2001). These materials consist of a resin and a hardener that react chemically and harden when combined at room temperature or heated. They are brittle, and most of the time, require reinforcement to form polymer composite materials for specific automotive application.

Table 2-3: Types of polymers used in the automotive industry (Adapted from (Gerard, 2014; Szeteiová, 2010)).

Vehicle Component	**Types of Polymers**	**Mass in Average Vehicle (kg)**
Bumpers	PS, ABS, PC/PBT, PP	10
Seating	PU, PP, PVC, ABS, PA	13
Dashboard	PP, ABS, SMA, PPE, PC	7
Fuel systems	HDPE, POM, PA, PP, PBT	6
Body including panels	PP, PPE, UP, ABS, PS	6
Under bonnet components	PA, PP, PBT	9
Interior trim	PP, ABS, PET, POM, PVC, ASA	20
Electrical components	PP, PE, PBT, PA, PVC	7
Exterior trim	ABS, PA, PBT, POM, ASA, PP, PU	4
Lighting	PC, PBT, ABS, PMMA, UP	5
Upholstery	PVC, PU, PP, PE	8
Liquid reservoirs	PP, PE, PA	1

Most of the polymer composite materials are made of two or more components, such as fibres of glass or carbon, to reinforce the matrix of thermoset or thermoplastic polymer materials (Das, 2001). Carbon fibre reinforced polymer (CFRP/CRP) is one of the most promising materials used for reducing vehicle mass (Troy, 2012; Wiel et al., 2012). It is costly and often used in high-performance vehicles. This material has high strength and stiffness, low mass, and good corrosion resistance in comparison to conventional steels. Moreover, it can be used to construct the Body-in-White (BIW)—the frame structure welded together where components are attached—that can substantially reduce the vehicle mass (Van Acker et al., 2009). Glass fibre reinforced plastic is a type of composite which is largely used by a few car manufacturers such as BMW, Peugeot, Maybach, and Volvo. It has lower stiffness, less strength, and higher density compared to carbon fibre composites which makes it typically thicker and heavier than an equivalent carbon fibre-reinforced part (Fuchs et al., 2008). The main drawback of carbon or glass fibre reinforced plastic is the relatively high cost of manufacturing. Thus, it is mostly used in luxury and sport cars (Wiel et al., 2012).

Composite materials that consist of natural elements, such as wood and plant fibres, have been widely researched in recent years to be used in automotive body parts. For instance, wood-plastic composites made of plant fibre and thermosets or thermoplastics have the potential to reduce vehicle mass while providing high strength and stiffness. Natural fibre reinforcements for composites result in slightly higher density, but have better tensile strength compared to traditional polymers. The natural fibre composites have relatively higher Young’s modulus which indicates higher stiffness in comparison to most of the polymers except polystyrene (Ashori, 2008). These composites are inexpensive, can withstand high temperatures, and most importantly, are able to improve the recyclability of auto interior parts (Ashori, 2008) that are largely landfilled.

2.4 Multi-Material Vehicle Designs

Multi-material designs are introduced to further optimise the mass reduction potential for vehicle (Cui et al., 2011, 2008; Ramani and Kaushik, 2012). Lightweight multi-material designs have been progressively used to replace reinforcement structures while ensuring crashworthiness. Multi-material structures allow optimal material selection for each structural component by targeting the ideal material type for the desired functionality. For instance, materials with greater strength-to-weight ratio are often selected to replace material parts at localised areas of high load.

For many years, different manufacturers have designed new multi-material concepts based on their reference cars such as BMW 7-Series, Jaguar XJ Mark III, Audi A8 (D3), Ford P2000 Sedan, Ford AIV, etc (Wallentowitz et al., 2006). The most prominent collaboration project, SuperLIGHT-CAR, involving high-profile organisations from renowned car manufacturers and material suppliers to leading automotive researchers has achieved great success in mass reduction for the Volkswagen Golf V (Volkswagen Group, 2009). This project was largely subsidised by the European Commission under the 6th Framework Program through European Council for Automotive R&D (EUCAR) (European Commission, 2006). Examples of government funded collaboration projects involving manufacturers and research institutions that focus on lightweight vehicle concepts are listed in Table 2-4. The consideration for lightweight multi-material concepts has gained increasing prominence within the automotive industry.

Table 2-4: List of European and U.S. funded lightweight vehicle projects.

Project	**Duration**	**Objective**
SuperLIGHT-CAR (Goede et al., 2008)	2005-2009	To reduce the mass of BIW structure of a compact car by at least 30% while retaining high manufacturability
MMV-USAMP (MMV701, MMV702, MMV703, MMV704) (USAMP, 2011)	2007-2010	Support the delivery of FreedomCAR goals To investigate vehicle mass reduction potential and issues associated with multi-material designs To address lightweight technology improvements using the General Motors' vehicle structure as baseline To investigate feasible joining technologies for aluminium cast and steel, and magnesium cast and steel while remaining low manufacturing cost
e-Light (European Commission, 2016b)	2011-2013	To develop suitable and feasible joining technologies and manufacturing processes for multi-material urban electric vehicles
MMLV (Skszek et al., 2015)	2012-2015	To design and build lightweight Ford Mustang Mach-I prototype vehicle and Mach-II concept vehicle to be compared with the 2002 baseline vehicle
EVolution ("EVolution," n.d.)	2012-2016	To develop new advanced materials to reduce the mass of hybrid and electrical vehicles by 40% through sustainable production
ALIVE ("ALIVE," n.d.)	2012-2016	To develop key vehicle lightweight technologies for mass production in future electric vehicles To reduce the mass of BIW structure by a further 20% in comparison to the 30% mass reduction in recent EU funded projects
ENLIGHT ("ENLIGHT," n.d.)	2012-2016	To enhance lightweight materials, particularly for thermoset, thermoplastic, bio-based and hybrid materials for vehicle structural parts To explore lightweight materials with great potential to reduce mass and overall CO_2 emissions for medium-high volume electric vehicles production

Materials with greater strength-to-weight ratio are increasingly used to replace enforcement structures. The BIW structure is one of the core body structures of a vehicle. The evolution of the automotive body structure can be seen in Figure 2-3.

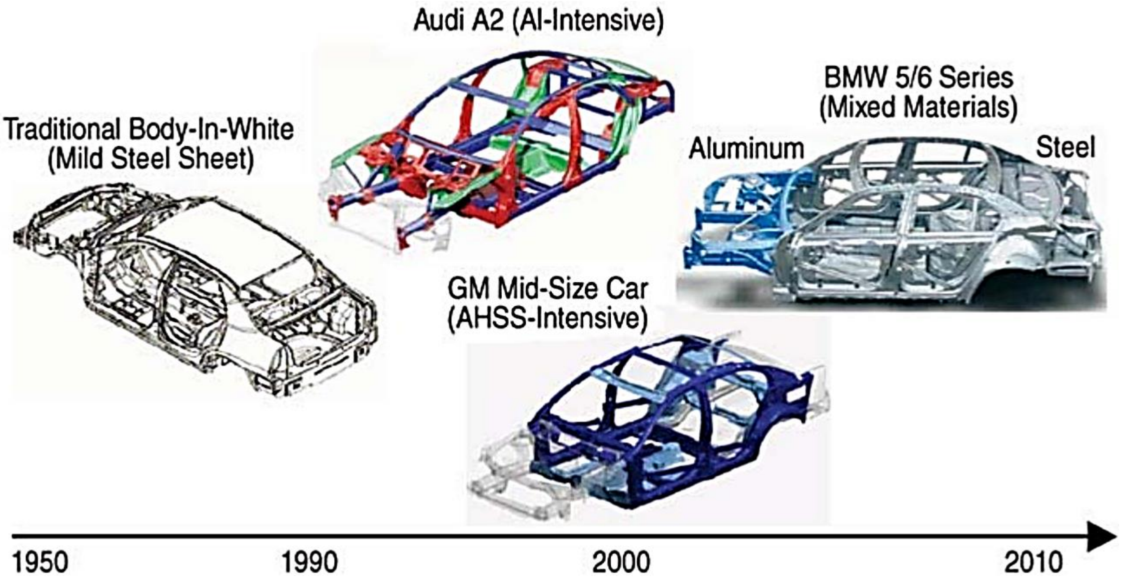


Figure 2-3: The evolution of automotive BIW structure, 1950-2010 (Reproduced with permission from (Taub et al., 2007)).

Many studies have been carried out to optimise the mass reduction potential for the BIW structure (Carle and Blount, 1999; Cole and Sherman, 1995; Das, 2000; Mayyas et al., 2012; Miller et al., 2000; Stasinopoulos et al., 2012b). The optimisation of BIW mass is crucial due to its potential to reduce the overall vehicle mass by 30-50% (Jambor and Beyer, 1997). Nevertheless, the crashworthiness and safety features should not be compromised. For example, the Lotus Engineering Inc.—an engineering consultancy and car manufacturer in America—has investigated the mass reduction potential for the BIW structure of Toyota Venza 2009 model without compromising the crashworthiness performance (Lotus Engineering Inc., 2012). The BIW car structure modelling focused on optimising the use of lightweight materials such as aluminium (75%), magnesium (12%), high-strength steel (8%), and composites (5%) (Lotus Engineering Inc., 2012).

The focus on designing lightweight vehicles has led to the growing complexity of vehicle designs over time. The Golf car, for instance, has experienced significant vehicle design changes from 1974 to 2008 to optimise the vehicle mass, as shown in Figure 2-4. Furthermore, the combination of different lightweight materials, such as aluminium, AHSS, magnesium, composites, and fibre reinforced polymers, is widely used in the mass-optimised design approach in vehicles, that further introduce a variety of joining techniques (Davies, 2012; Omar, 2011; Rowe, 2012). Consequently, the development for multi-material vehicle designs affects not only the choice of material combinations, but also the feasibility of joining methods used to combine them.

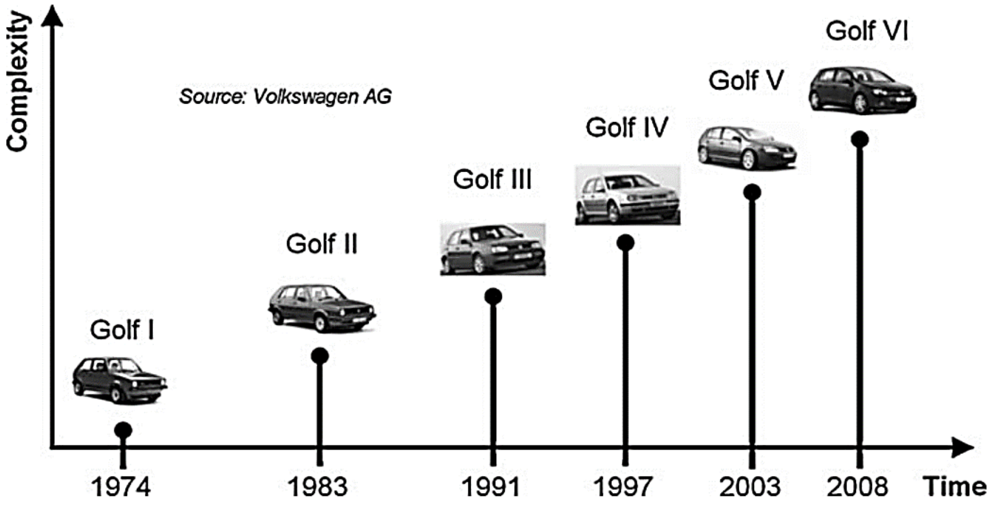


Figure 2-4: The growing complexity of Golf car (Reproduced with permission from (Juehling et al., 2010)).

2.5 Material Joining Technologies

The choice of joining techniques used for multi-material vehicle designs is facing increasing challenges due to the requirement for thinner and lighter components made of different material combinations. From the design perspective, it is best to minimise the use of joints to reduce potential weak points (Campbell, 2011). This is, however, impractical for new vehicle designs with increasing variety both in material types and structural components. In recent years, joining processes used for vehicle manufacturing have had to adapt to changing material designs while retaining the vehicle structural bonding strength (Martinsen et al., 2015). Moreover, the quality of joint contributes to the durability and structural performance of the vehicle body. The choice of joining processes is becoming critical as a consequence of the evolution in automotive materials.

Joining processes can be classified to four major types: welding, brazing or soldering, mechanical fastening, and adhesive bonding, as seen in Figure 2-5. Welding and brazing techniques are used largely for the joining of similar metals, whereas mechanical fastening and adhesive bonding techniques are more widely applicable for a varied range of materials including metallic to non-metallic material combinations. These joining techniques can be further categorised as permanent or temporary joints. Welding, brazing and adhesive bonding provide permanent joints that are more suited for parts that do not require disassembly for operational and maintenance purposes. On the other

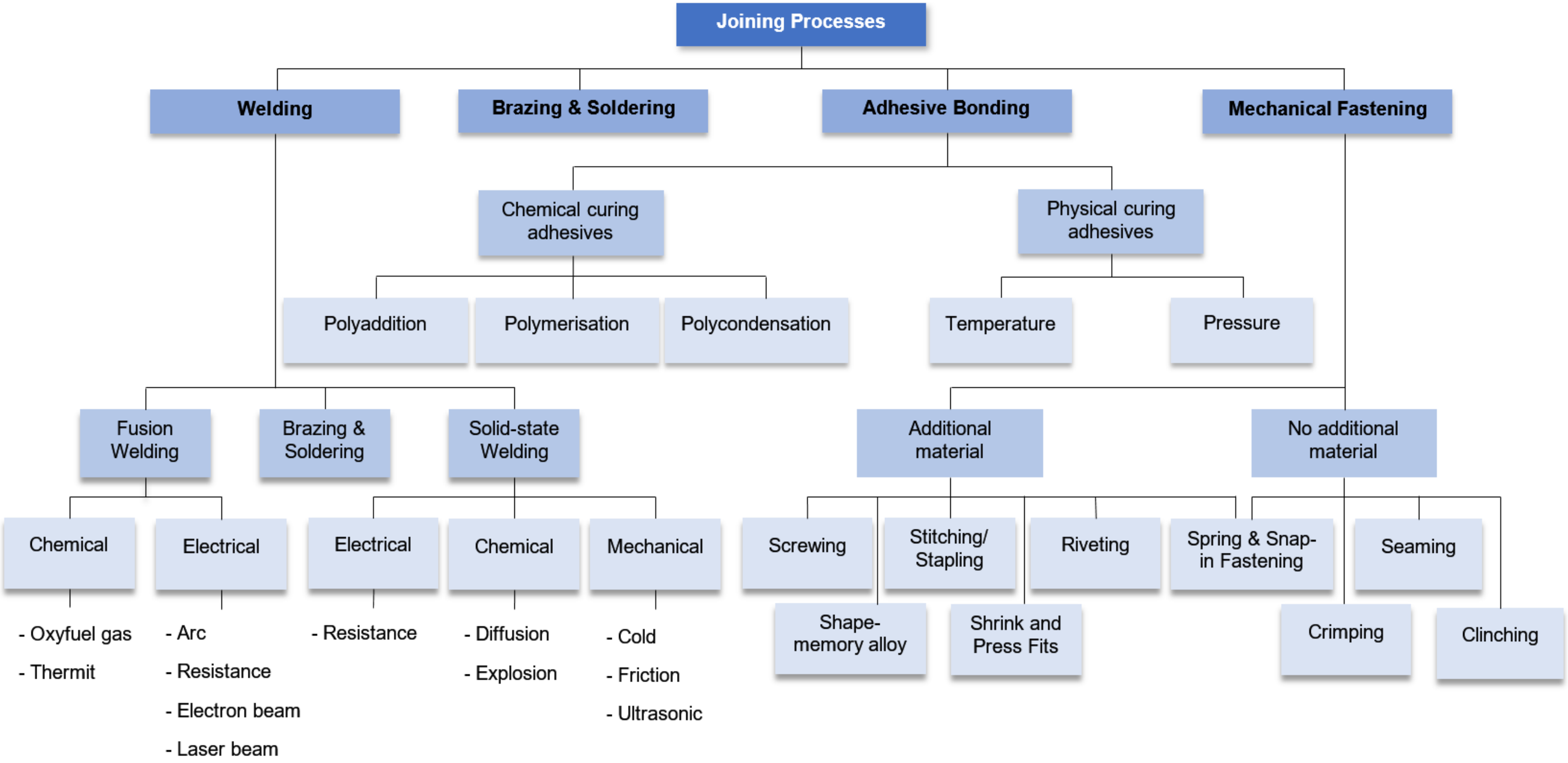


Figure 2-5: Classification of joining processes based on bonding mechanisms (Adapted from (Grote and Antonsson, 2009; Habenicht, 2008; Kalpakjian and Schmid, 2013)).

hand, mechanical fastening can produce either permanent or temporary joints (Campbell, 2011). Rivets are an example of permanent joints, and screws are temporary joints that allow repeated fastening and unfastening to cater for repair and maintenance.

To select the appropriate joint design, criteria relating to the material and joining parts need to be considered to conform to the joint specifications. The joint requirements associate to the material and joining parts are listed in Table 2-5. The five basic joint designs that can be used for various joining processes are butt joint, corner joint, T joint, lap joint, and edge joint (Campbell, 2011; Kalpakjian and Schmid, 2013). Based on the joint specifications, the choice of joining processes and their respective joint designs are selected to provide optimal structural loading while remaining cost-effective. Moreover, the types of material combinations play an essential role in determining better suited joint designs to allow force to distribute evenly between joint and material structural parts (Rowe, 2012). For instance, lap joint is preferable for adhesive bonding to allow even loading, and to reduce localised stress (Matthews et al., 1982; Moya-Sanz et al., 2017).

Table 2-5: Joint specifications to select appropriate bonding design (Campbell, 2011; Kalpakjian and Schmid, 2013; Michalos et al., 2010).

Material Part	**Joining Part**
Material type	Joint strength
Material thickness	Joint geometry
Material cost	Joint location
	Accessibility
	Distortion control
	Manufacturing cost

The selection of joining processes based on the characteristics of joints is critical to meet the required specifications (Campbell, 2011). There are usually multiple joining methods that can be chosen for a specific task. The choice of joining technique often relies on economic factors; the material and manufacturing costs of the joining technique is compared to low-cost options where performance is not compromised. There is a wide range of joint attributes considered by the vehicle manufacturers. An overview of the characteristics of different joining processes from the perspectives of joint and production are summarised in Table 2-6 and Table 2-7.

Table 2-6: General comparison of characteristics for different joining processes relating to joint features (Adapted from (Petrie, 2000)).

Joint Features	**Welding**	**Brazing and soldering**	**Mechanical fastening**	**Adhesive bonding**
Permanence	Permanent joints	Usually permanent (soldering may not be permanent)	Threaded fasteners permit disassembly	Permanent joints
Stress distribution	Local stress points in structure	Fairly good stress distribution	Points of high stress at fasteners	Good uniform load distribution over joint area (except in peel)
Appearance	Joint appearance usually acceptable. Some dressing necessary for smooth surface	Good appearance joints	Surface discontinuities sometimes unacceptable	No surface marking. Joint almost invisible
Materials joined	Generally limited to similar material groups	Some capability of joining dissimilar materials	Most forms and combinations of materials can be fastened	Ideal for joining most dissimilar materials
Temperature resistance	Very high temperature resistance	Temperature resistance limited by filler metal	High temperature resistance	Poor resistance to elevated temperatures
Mechanical resistance	Special provision often necessary to enhance fatigue resistance	Fairly good resistance to vibration	Special provision for fatigue and resistance to loosening at joints	Excellent fatigue properties. Electrical resistance reduces corrosion

Table 2-7: General comparison of characteristics for different joining processes relating to production aspects (Adapted from (Petrie, 2000)).

Production Aspects	**Welding**	**Brazing and soldering**	**Mechanical fastening**	**Adhesive bonding**
Joint preparation	Little or none on thin material. Edge preparation for thick plates	Prefluxing often required (except for special brazing processes)	Hole preparation and tapping for threaded fasteners	Cleaning often necessary
Post-processing	Heat transfer sometimes necessary	Corrosive fluxes must be cleaned off	Usually no post-processing —occasionally re-tightening in service	Not often required
Equipment	Relatively expensive, bulky and often required heavy power supply	Manual equipment is cheap. Special furnaces and automatic unit are expensive	Relatively cheap, portable, and on-site assembly	Only large multi-feature, multi-component dispensers are expensive
Consumables	Some require wire, rods, etc. Fairly cheap	Some special brazing fillers are expensive. Soft solders are cheap	Quite expensive	Structural adhesives somewhat expensive
Production rate	Can be very fast	Automatic processes quite fast	Slow joint preparation and manual tightening. Mechanised tightening is fairly rapid	Seconds to hours, according to type
Quality assurance	Non-destructive testings well established	Inspection difficult, particularly on soldered electrical joints	Reasonable confidence in torque control tightening	Non-destructive testings are limited

2.5.1 Welding

Welding is the most common joining technique used in automotive industry, and it can be broadly divided into two categories: fusion welding and solid-state welding. Fusion welding joins two materials by melting and fusing the interface through the application of heat generated by chemical or electrical sources. This technique may also use additional consumables, better known as filler metals, at the weld area such as in metal inert gas (MIG) welding. In contrast, solid-state welding creates material bonding under pressure, through relative interfacial movements or heat below the melting point of base materials being joined without the presence of consumables (Kalpakjian and Schmid, 2013). The bonding mechanism for solid-state welding can be induced through electrical, chemical or mechanical sources. Resistance spot welding is an example of solid-state welding commonly used for lap joint design. It is used to bond metallic structure by generating electrical resistance across the materials being joined.

2.5.1.1 Resistance Welding

The types of resistance welding largely used for automotive application include spot welding, projection welding, and seam welding. Of these welding techniques, spot welding is the most widely used in automotive industry (Barnes and Pashby, 2000b; Janota and Neumann, 2008) due to its low cost for large-scale production. There are about 2000-5000 welds in a typical BIW structure which signify the importance of high quality resistance spot welding (Chao, 2003). Most metals can be joined using this method; however, the weld quality varies for different material types, material thickness, and surface coating (Campbell, 2011). Table 2-8 shows that resistance spot welding produces good to excellent weldability for steel, stainless steel, galvanised iron, and aluminium that are commonly used for automotive vehicle structure and body. The basic principles of bonding for projection welding and seam welding are very similar to spot welding; thus, the weldability rating in Table 2-8 is also applicable. Seam welding is a series of overlapping spot welds produced by a rolling resistance weld to form a continuous bonding between the materials, whereas projection welding localises the electrical resistance through the use of projection, embossments or intersections on one or both material surfaces. Examples of automotive components that are joined through projection welding and seam welding are weld nuts and leak proof petrol tank respectively (Davies, 2012). The advantages and disadvantages of spot welding, projection welding, and seam welding are highlighted in Table 2-9.

Table 2-8: The weldability rating of resistance spot welding used for different metals and alloys (Davis, 1998).

Metals	Steel	Stainless steel	Galvanised iron	Aluminium	Copper	Brass	Zinc	Nickel	Lead
Steel	A	A	B	D	E	D	F	C	E
Stainless steel		A	B	F	E	E	F	C	F
Galvanised iron			B	C	E	D	C	C	D
Aluminium				B	E	D	C	D	E
Copper					F	D	E	D	E
Brass						C	E	C	F
Zinc							C	F	C
Nickel								A	E
Lead									C

A: Excellent, B: Good, C: Fair, D: Poor, E: Very poor, F: Impractical

Table 2-9: The benefits and limitations of spot welding, projection welding, and seam welding (Adapted from (Campbell, 2011; Davies, 2012)).

	Spot welding	**Projection welding**	**Seam welding**
Advantages	Consistent and uniform joint is produced Highly automated process with high production rates Does not require special skill Low labour costs	Multiple spot welds can be produced at a single operation Can be used to weld metals that are too thick for spot welding	Ability to make gas tight and liquid tight joints (not possible for spot welding or projection welding) Less material overlap is required in comparison to spot welding or projection welding
Disadvantages	Only create localised joint Metal sheet with thickness more than 3mm can cause problem during welding Certain metal requires special surface preparation	Not suitable for thin work pieces due to electrode pressure Equipment is costlier	Welding process is restricted to straight line or uniformly curved line Metal sheet with thickness more than 3mm can cause problem during welding Require changes to the design of electrodes when there is obstruction to weld metal sheets

2.5.1.2 MIG Welding

MIG welding is one of the traditional welding techniques that is still largely used in current automotive manufacturing. It is a type of arc welding that utilises electric arc to generate heat to melt and join metals with a consumable wire. A shielding gas, such as argon, is used to protect the molten metal from oxygen and water vapour, and produce a uniform metal transfer (Campbell, 2011). Under suitable welding conditions, all types of metals can be joined through MIG welding, particularly the main metals used in automotive production. It is typically used to combine the different vehicle structural parts to form a vehicle spaceframe. Some of the advantages and disadvantages of MIG welding are listed as follows (Campbell, 2011).

Advantages of MIG welding:

- Simple while producing reliable welds.
- Welding is possible in all positions.
- Welding is possible for different metals.
- Can be used to weld thicker materials through multiple passes.
- High production rates.
- Low consumable cost.

Disadvantages of MIG welding:

- Welding process is sensitive to contaminants and wind.
- Complexity of welding equipment.
- Welding is more difficult at places that are hard to reach.

2.5.1.3 Laser Beam Welding

Laser beam welding is an emerging welding technique used for high-volume automated production, such as in the automotive industry. Materials are joined through a concentrated heat source generated by an intense laser on the material surface. The joining of different material combinations is possible, particularly for lightweight materials such as high strength steels, aluminium, and magnesium (Schubert et al., 2001). Therefore, the increasing complexity in vehicle multi-material designs has significantly contributed to the development of laser welding technologies (Kah et al., 2014). This welding method has the potential to overcome the difficulties of joining a variety of materials faced by traditional welding techniques (Cao et al., 2006; Dawes, 1992). The two main types of lasers largely used in automotive manufacturing are CO_2 and Nd:YAG lasers. Their benefits, such as high average power and beam stability, are used to resolve the welding problems faced in aluminium alloys (Ahmed, 2005). In recent years, laser welding has been widely used in vehicle structures such as new Audi A2 and A8, VW Golf V, and BMW 6 Series (Ahmed, 2005; Davies, 2012). The advantages and disadvantages of laser welding are as follows (Barnes and Pashby, 2000b; Ribolla et al., 2005).

Advantages of laser welding:

- Welding is possible for dissimilar metals.
- Highly focused beam with little heat deformation.
- Highly automated process with high production rates.
- High quality welds.
- High flexibility during welding processes.

Disadvantages of laser welding:

- May cause metal cracking due to rapid cooling rate.
- High equipment and maintenance costs.
- Low material gap toleration due to the small weld spots produced by highly focused beam.

2.5.1.4 Friction Welding

Friction welding is a solid-state welding process that can be used to join different types of metals and thermoplastics that are widely used in automotive application (Campbell, 2011; Elmer and Kautz, 1993; Mori et al., 2013). This welding technique converts the mechanical energy to thermal energy at the interface of the materials being joined without the application of energy or heat (Bay, 2011). A non-rotating workpiece is in contact with another rotating workpiece with gradual pressure until a friction weld is formed (Bay, 2011; Elmer and Kautz, 1993). The joining of different materials or parts is based on the relative motion between the parts. This welding technique is very similar to friction stir welding, wherein a friction stir tool is utilised to join the different materials along the contact point. The advantages and disadvantages of friction welding is very similar to friction stir welding except for the lack of friction stir tool. The friction stir welding technique will be discussed in Section 2.5.1.5.

2.5.1.5 Friction Stir Welding

Friction stir welding is another welding technique that is gaining prominence in joining multi-material vehicle designs. Materials are combined when heat is generated through the friction between the rotating tool and the material surface that causes a deformation along the contact point. This welding technique is developed by The Welding Institute (Cambridge, UK) in 1991 (Campbell, 2011), and its application is initially focused on aluminium alloys due to the issues in producing high strength and fracture resistant welds through traditional welding methods. Nevertheless, its application has been extended for joining harder metals and dissimilar metal combinations (Mori et al., 2013). Previous research has shown that friction stir welding can be used to produce good quality weld for aluminium alloys to high strength steel or stainless steel (Coelho et al., 2012; Uzun et al., 2005). The benefits and limitations of friction stir welding are provided as follows (Campbell, 2011; Mori et al., 2013).

Advantages of friction stir welding:

- Welding is possible for dissimilar metals.
- High quality welds.
- Metal cracking and heat-affected zone are eliminated.
- Does no require consumable or shielding gas.
- Environmental safety.

Disadvantages of friction stir welding:

- Need reliable clamps to hold the materials being joined.
- Need high precision for fix tool penetration.
- Produces uneven joint surface.
- High equipment and maintenance costs.

2.5.1.6 Ultrasonic Welding

Ultrasonic welding is one of the well-researched welding technologies to join dissimilar materials including metal and non-metallic combinations (Balle et al., 2007; Tsujino et al., 1996). Materials are joined in solid-state through the application of high-frequency vibrations to disrupt the metallic or non-metallic atoms at the surface area and form a mechanical joint (Campbell, 2011). The material trends in automotive industry have shown a significant increase in the use of polymers and composites for multi-material vehicle designs to optimise the mass reduction potential. As a consequence, high quality weld bonding between metals and non-metals using ultrasonic welding is increasingly explored for large-scale production. Some of the advantages and disadvantages of ultrasonic welding are listed below.

Advantages of ultrasonic welding:

- Welding is possible for dissimilar metals, as well as metal to non-metal combinations.
- Suitable for high thermal conductivity materials, such as aluminium and copper, that cannot be easily welded through the fusion processes.
- Welding is insensitive to contaminants.
- Low power consumption.
- Highly automated process.

Disadvantages of ultrasonic welding:

- Limited to lap joint design.
- Cannot easily weld materials with high strength and hardness.
- Power usage increases with the material thickness.
- Welding process is not well-known to vehicle manufacturers.

2.5.2 Brazing

Brazing techniques are used in automotive manufacturing particularly for exterior vehicle body due to the good aesthetic joint finish. Brazing is used to join different materials by melting filler metals between the materials being joined. The type of filler metal used typically has lower melting point compared to the base metals and thus, forms a bond without fusing the materials being joined (Campbell, 2011). The bonding principles through this method allow the joining of dissimilar metals (Dilthey and Stein, 2006). This method has a small heat dispersion, and is commonly used for joining exterior vehicle parts with visible seams (Koltsov et al., 2010). Laser brazing, for example, is utilised in trunk lids, roof seams, and doors. The benefits and limitations of brazing are summarised as follows (Campbell, 2011; Michalos et al., 2010).

Advantages of brazing:

- Less damage to galvanised coating.
- Less thermal distortion on base metals.
- Brazing is possible for dissimilar metals.
- Utilises simple tool and equipment.
- Facilitates repair and maintenance since the brazed bonding can be disconnected.
- Process can be easily automated.

Disadvantages of brazing:

- Lower joint strength compared to welded joints.
- Require high degree of cleanliness for base metal.
- High service temperature can easily damage the joint.

2.5.3 Mechanical Fastening

Mechanical fastening methods can be classified broadly into two categories: mechanical joining with additional material and mechanical joining without additional material. Mechanical joining with additional material uses external components, such as screws, rivets, clips, etc., that are made of either the same or dissimilar material types from the base materials being joined. In contrast, mechanical joining without additional material creates a bond for different materials through material deformation without using fasteners. Examples of fastening methods without additional material include clinching, seaming, and crimping. Mechanical fasteners are one of the most versatile joining methods used to join different material types and, most importantly, they can produce semi-permanent and temporary joints to ease part disassembly. The most widely used types of fasteners for complex products, such as vehicles, are machine screws, bolts, and rivets. These mechanical fasteners can be removed manually or through partial destruction to cater for repair and maintenance.

2.5.3.1 Threaded Fastening

Screwing is one of the most established joining techniques that uses additional material in the form of threaded fasteners with helical structure. It is widely applied for modular design to join different subassembly parts. There is a variety of threaded fasteners with different standards and specifications to suit the required strength to bond different materials together (Robert Bosch GmbH, 2011). The different types of screws commonly seen in automotive application are hex bolts, machine screws, sheet metal screws, and socket screws. The selection of fastener is based on the design requirements and the required bond strength, that are affected by the types of material being joined, thickness of parts, length and diameter of fasteners, fastener material types, thread characteristics, and others (Campbell, 2011; Robert Bosch GmbH, 2011). The advantages and disadvantages of screw joints are summarised as follows (Kalpakjian and Schmid, 2013).

Advantages of screw joints:

- Can be fastened and unfastened for repair and maintenance.

- Joint is possible for dissimilar metals, as well as metal to non-metal combinations.
- Low material cost.
- Insensitive to the base metal condition.

Disadvantages of screw joints:

- Exposure to vibration can cause the loosening of joint.
- Variability of stress concentration for different conditions.
- Most of the fasteners require threading process or pre-drilled holes.

2.5.3.2 Riveting

Another commonly used mechanical joining method that can overcome some of the limitations of screw joints is riveting. Rivet joints are more resistant to vibrations due to their permanent or semi-permanent bonding that can only be disassembled through partial joint destruction. A rivet consists of a head on one end, and a smooth cylindrical shaft on the other end (tail) which can be either solid or hollow. Rivet bonding is produced by deforming or upsetting the tail after it is placed in the punched or pre-drilled hole. Self-pierce rivets and blind rivets are two of the rivet types largely used in automotive production.

Self-pierce riveting is often chosen as an alternative to spot welding when dissimilar material combinations are required (Davies, 2012; Fu and Mallick, 2003). This technique caters well for the joining of lightweight materials and multi-material structures, and is increasingly used in the automotive industry (Abe et al., 2009; He et al., 2008). The aesthetic appearances of riveting and spot welding are very similar since the rivet head sinks into the material creating a flat surface. The joint is produced by punching the rivet into the materials being joined in single operation without the need for pre-drilled hole. The benefits and limitations of self-pierce riveting are as follows (Campbell, 2011; He et al., 2008).

Advantages of self-pierce riveting:

- Joint is possible for dissimilar metals, as well as metal to non-metal combinations in multiple stacks.
- Does not require pre-drilled hole.
- Process can be easily automated.
- Produces joint with high fatigue properties.

- Low material cost.

Disadvantages of self-pierce riveting:

- Process requires access from both sides of the joint.
- Not suitable for brittle materials.
- High force is required during the forming process.

Blind rivets are used when the materials or parts that need to be joined during manufacturing and assembly are only accessible from one side of the joint (Min et al., 2015). Similar to self-pierce riveting method, it can be used to join dissimilar materials, particularly for lightweight materials. Blind rivet, also known as pop rivet, consists of a head on one end, and a built-in mandrel to deform the other end of the rivet during the joining process (Gould, 2012). This bonding technique is as strong as spot welding, and produces high bonding strength for dissimilar metals such as steel and aluminium alloy. For example, blind rivets are used to bond the steel beam structure and the aluminium alloy of Mazda RX-8 vehicle doors (Sakiyama et al., 2013). The advantages and disadvantages of blind rivet joints are listed as follows (Grote and Antonsson, 2009).

Advantages of blind riveting:

- Joint is possible for dissimilar metals, as well as metal to non-metal combinations in multiple stacks.
- Produces joint without deforming the materials being joined.
- Process requires access from one side of the joint only.

Disadvantages of blind riveting:

- Requires pre-drilled holes.
- Disassembly is only possible through the destruction of rivet.
- Lower shear strength compared to punch rivets.

2.5.3.3 Clinching

Materials can be joined through deformation without the use of additional fasteners to bond them together. Clinching is an example of such bonding technique that has been widely applied in the automotive industry to join two or more metal sheets in car bonnets, BIW structures, and others (Busse et al., 2010; Carboni et al., 2006). The clinching process is very similar to self-pierce riveting process, except for the presence of a rivet or fastener. The mechanical joining between materials is formed through the use of a die and punch (Meschut et al., 2014). The bonding is highly dependent on the material deformability and is thus more suitable for hardened metals such as steel and aluminium alloy. The advantages and disadvantages of clinching method can be summarised as follows (Grote and Antonsson, 2009).

Advantages of clinching:

- Joint is possible for dissimilar metals.
- Does not require pre-drilled hole.
- No cost associated with additional fasteners.
- Process can be easily automated.

Disadvantages of clinching:

- Limited by the formability of sheet material.
- Low torsional stress.
- Only suitable for joint thickness up to 6mm.
- Joint strength is lower compared to spot welding and self-pierce riveting.

2.5.4 Adhesive Bonding

The types of adhesive bonding can be broadly divided based on their curing methods: chemical curing adhesives and physical curing adhesives (Staff, 2008). Chemical curing adhesives create adhesion when there is chemical reaction, also known as polyreactions, between the polymer chains. The chemical reaction can be classified into polyaddition—two or more monomers are bonded together without the loss of any molecule; polycondensation—monomers are bonded together through condensation reaction; and polymerisation—monomers are bonded together through the formation of polymer chains (Wypych, 2001). Examples of adhesive types for the different chemical-cured adhesives are shown in Figure 2-6.

In contrast, physical curing adhesives already have the polymer to form adhesion when they are exposed to different physical conditions such as temperature or pressure. The list of different physical curing adhesives is provided in Figure 2-7.

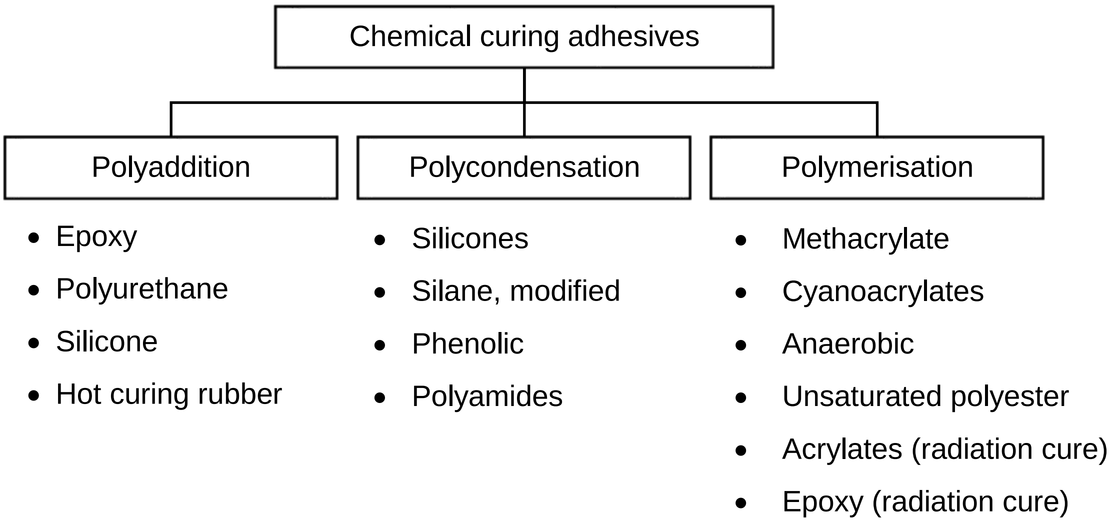


Figure 2-6: The types of chemical curing adhesives (Ebnesajjad and Landrock, 2014).

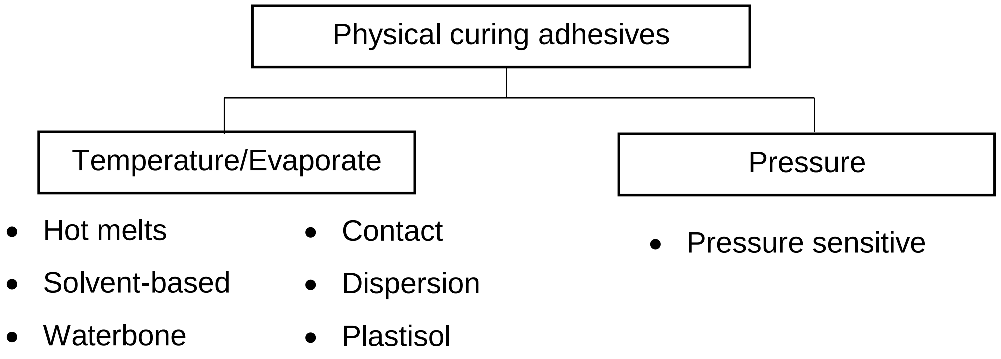


Figure 2-7: The types of physical curing adhesives (Ebnesajjad and Landrock, 2014).

The characteristics of adhesions formed through chemical and physical curing are crucial to determine the right choice of adhesion based on the required bonding strength, and physical conditions. Generally, the bonding strength and longevity for chemical curing adhesives are higher in comparison to physical curing adhesives. Table 2-10 shows the major differences of the characteristics of joints based on their curing properties.

The types of adhesive bonding commonly used in automotive application are epoxies and rubber-based adhesives (Davies, 2012; Robert Bosch GmbH, 2011). Their initial application focus on vehicle assembly and vibration damping, such as windshield and inside of doors; nevertheless, the use of adhesion for structural bonding of metal or non-metal parts are gaining prominence. For example, there is an increasing use of adhesion to join the parts in BIW structure due to good force distribution, and resistance to sudden material deformation during crash (Davies, 2012). The choice of adhesive types used is highly dependent on the required load-bearing, tensile-shear strength, and durability under different operating conditions such as temperature, waterproof, and others. Epoxies are widely used for the seam of components and material structural bonding. On the other hand, rubber-based adhesives such as silicone are used for door frames, windshields, and most interior parts for vibration absorption. The main advantages and disadvantages of epoxy and silicone adhesives are shown in Table 2-11.

Table 2-10: General comparison of bonding characteristics for chemical and physical curing adhesives.

Characteristics	**Chemical curing adhesives**	**Physical curing adhesives**
Bond strength (Ebnesajjad and Landrock, 2014; Kalpakjian and Schmid, 2013)	High shear strength (e.g. modified acrylic can hold strength up to 22MPa)	Moderate-low shear strength (e.g. hot melt adhesives can hold strength up to 3.4MPa)
Temperature resistance (Campbell, 2011)	Moderate-high (e.g. silicone can reach up to 371^{o}c)	Low-moderate (e.g. Hot melt adhesives generally can reach up to 149-188 ^{o}c)
Moisture and environmental resistance (Petrie, 2000)	Moderate-high	Low-moderate (degrade over time)

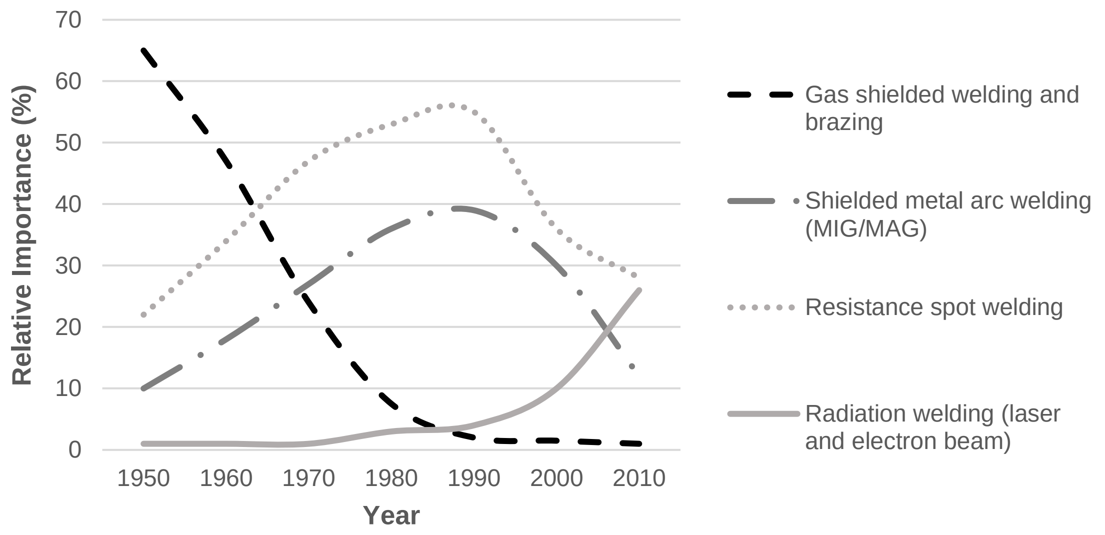
Table 2-11: Comparison between epoxy and silicone adhesives used for automotive application (Davies, 2012).

	Epoxy	**Silicone**
Advantages	Create high bonding strength with high temperature and moisture resistance	Rubberlike texture with good anti-vibration properties.
Disadvantages	Require careful application and difficult to use	Cannot meet higher structural strength requirements
	Health and safety hazards	Slow curing time

2.6 Trend of Automotive Joining Methods

With the increasing complexity of vehicle structures, it is a challenge to choose the most suitable joining techniques for the desired vehicle design requirements (Martinsen et al., 2015). Moreover, the increasing use of multi-material designs has limited the choice of automotive joining processes. In recent years, there has been a growing development in new joining technologies that cater for the joining of different materials with diverse properties, particularly metal to non-metal combinations. A comparison of the joint characteristics, benefits, and limitations for a variety of joining techniques discussed in Section 2.5 can assist in decision-making for vehicle design from the perspectives of manufacturability, reliability, and cost efficiency.

Traditional welding methods, such as tungsten inert gas (TIG) welding, metal inert gas (MIG) welding, and resistance welding, no longer cater well for multi-material designs (Dilthey and Stein, 2006). The trends of commonly used welding techniques for BIW structure can be seen in Figure 2-8. Resistance spot welding, one of the widely used joining techniques for steels, is mostly used for similar steel combinations. It can be challenging to join dissimilar materials using spot welding method due to the differences in physical and chemical properties of materials' structure (Avalle et al., 2010; Briskham et al., 2006; Radaj and Zhang, 1992). For instance, same material joining of aluminium or steel is feasible using this technique; it would however be inappropriate for aluminium-steel joint since both materials have different mechanical structures (Radaj and Zhang, 1992). Friction stir spot welding is slowly replacing the resistance spot welding to further improve the bonding quality. Moreover, this joining technique only requires simple equipment and working conditions to weld (Matsuyama, 2007; Zhang et al., 2011). Laser welding is increasingly used to replace TIG, MIG, and resistance welding in the automotive manufacturing production. Its ability to join different light metals to cater for multi-material designs with high-volume manufacturability has seen growing application in the automotive assembly plants (Ribolla et al., 2005). Recently, ultrasonic spot welding has been researched and proven to be able to join aluminium to CFRP (Bakavos and Prangnell, 2010; Balle et al., 2007; Tsujino et al., 1996). However, this method has yet to be implemented in large volume.



Relative importance indicates the frequency of joining methods used for BIW assembly disregarding the conception type (steel, aluminium, or multi-material concepts)

Figure 2-8: Trends of welding processes used in automotive BIW assembly (Reproduced with permission from (Neugebauer, 2003; Ribolla et al., 2005)).

Another alternative to resistance spot welding is mechanical fastening, such as clinching method (He, 2010) and self-pierce riveting (Carle and Blount, 1999; He et al., 2008), which are used extensively in current vehicle manufacturing. Mechanical fasteners can be used to join dissimilar metallic materials to produce multi-material joints such as steel-aluminium (Lotus Engineering Inc., 2012), magnesium-aluminium and magnesium-steel joints (Shaw et al., 2010). Self-piercing rivets are largely used to join lightweight sandwich sheet and aluminium (Pickin et al., 2007) due to the limited joining methods feasible for aluminium materials (Barnes and Pashby, 2000a; Davies, 2012). Moreover, this technique is used to join material combinations that cannot be easily welded, such as paint-coated steels (Davies, 2012). This method has been used in large volume together with adhesive bonding to join dissimilar materials.

Adhesive bonding is one of the most crucial joining methods especially in joining dissimilar lightweight materials (Zhang et al., 2013), polymers, and composite materials such as fibre reinforced plastic (Lupton, 1983). It is also commonly used for new hybrid joining procedures such as the combination of resistance welding with adhesive bonding, and mechanical joining with adhesive bonding (Kaščák and Spišák, 2013). This technique offers advantages that can overcome the drawbacks of each joining technique. For instance, riv-bonding joint protects the material’s surface from corrosion through adhesive bonding, whereas, the rivet provides a better shear force to improve the material's adhesion (Barnes and Pashby, 2000a; Briskham et al., 2006). The existence of new hybrid joining processes further strengthen the joints with multi-material combinations particularly for metallic and non-metallic materials. Moreover, the joints produced have better mechanical performances such as good formability, high rigidity, and low sensitivity to drilling. The main advantages of hybrid joining are the high-quality bonding and the high-applicability for superlight materials. However, disassembling materials for maintenance or recycling could be complicated.

To join the increasing variety of materials, manufacturers are limited by the choice of joining methods. There has been a rapid increase in non-welding techniques to accommodate multi-material designs particularly for joining metallic to non-metallic materials or hybrid structures (Groche et al., 2014). It can be seen from Table 2-12 that the use of more light metal and non-metal combinations limits the choice of joining techniques to mechanical fasteners, adhesive bonding or a combination of both joining methods. Although there are new emerging joining technologies to cater for multi-material combinations (Amancio-Filho and dos Santos, 2009; Huang et al., 2013), they have not been adopted in large-scale production due to the high initial investment cost for new tooling and equipment installation (Davies, 2012).

Table 2-12: Multi-material joining matrix.

		Light metal			**Non-metal**	
		AHSS	Aluminium	Magnesium	PP	CFRP
Light metal	AHSS	a b c d e* f g*	a b c d* e* f* g	a b c d* e* f* g*	b c e*	b c e*
	Aluminium		a b c d e* f g	a b c d* e* f* g*	b c e*	b c e*
	Magnesium			a b c d* e* f g*	b c e*	b c e*
Non-metal	PP				b c e*	b c e*
	CFRP					b c e *

a	TIG, MIG welding	d	Resistance welding	g	Friction stir spot welding
b	Adhesive bonding	e	Ultrasonic spot welding	*	Not in large production
c	Mechanical fastening	f	Laser welding		

The overall joining trends in Table 2-13 are observed based on the changing vehicle BIW designs for the same vehicle model (Audi A6 and Audi A8) manufactured over a number of years. Most of the joining techniques that introduce additional materials, such as screwing, riveting and adhesive bonding, are becoming more common in newer vehicle designs. Traditional welding techniques including spot welding and MIG welding no longer cater well for multi-material joints. The observed trends in joining techniques are based on the feasibility of large-scale vehicle manufacturing, and are supported by the manufacturers' perspective on the development of joining processes (Grote and Antonsson, 2009). Moreover, it is predicted that new laser beam welding technology is emerging to replace traditional welding techniques.

Table 2-13: Joining trends observed from literature data based on the percentage of point and linear joints for the BIW of different vehicle models (European Aluminium Association, 2013; Mirdamadi and Korchnak, 2006).

Joint Type	**Audi A6**		**Trend**	**Audi A8**		**Trend**
	2001-2004	**2005-2008**		**1994-2002**	**2009-2016**	
Share of point joints (%)						
Spot welding	91.5	81.0	↓	28.1	7.5	↓
Stud welding	3.3	6.5	↑	0	0	
Clinching	0.9	1.3		10.0	0	↓
Screw joints	0	0		0	23.6	↑
Rivets	0	5.8	↑	61.9	68.9	↑
Share of linear joints (%)						
Laser welding	8.3	3.3	↓	0	8	↑
MIG welding	6	4.3	↓	100	33.3	↓
Laser brazing	0	3.1	↑	0	0	
Adhesive bonding	85.7	89.3	↑	0	58.7	↑

The types of joining methods used is becoming critical due to its significance on ELV recycling efficiency. The combination of different material types is limiting the choice of joining techniques during vehicle manufacturing (Meschut et al., 2014). Moreover, the choice of joining methods used is influenced by other factors such as joint strength, large-scale production, manufacturing cost, and repairability (Davies, 2012; Larsson and Hanicke, 1999). Despite efforts to improve ELV recycling, the focus has been on the material selection of new vehicle designs. The lack of consideration for the impact of joining choices during vehicle manufacturing on EoL phase has reduced the effectiveness of current vehicle sorting practices. Therefore, the gap between vehicle design and manufacturing, and the ELV recyclability through industrial recycling scenarios need to be addressed.

2.7 ELV Recycling Systems

The adoption of different ELV management systems can lead to different EoL treatment strategies. In Europe, the strict legislative framework outlined in the ELV Directive has forced recyclers to progressively improve their processes and ensures vehicle manufacturers take responsibility for the EoL treatment of their products. In this context, ASR have been targeted for further recycling of valuable metals and non-metallic materials to meet the strict legislation. On the contrary, there are only voluntary based ELV recycling guidelines for Australian recyclers that are based on the European Union’s ELV Directive. This leads to ASR entering landfill without further treatment to reduce recycling cost.

The choice of EoL treatment strategies has a major influence on the ELV environmental performance and recycling costs. For many years, high steel content in ELV has made them attractive to be acquired by recyclers. Shredder, also known as the Newell Shredder (Newell, 1965), and magnetic separator are commonly used to retrieve steel with high efficiency and low cost. However, the increasing use of lightweight materials in vehicle design has led to the importance of recovering other materials such as plastics. In Europe, the market for high quality secondary plastics is developed, and has encouraged recyclers to improve their post-shredder treatment technologies while restricted by the recycling costs. The lack of market for secondary plastics in countries such as Australia has discouraged further ASR treatment.

2.7.1 ELV Regulatory Framework

The management of ELV waste is restricted by a wide variety of national legislations. Countries and regions such as the European Union, Japan, and Korea have specific ELV related legislation to manage waste disposal. However, certain industrialised countries with high vehicle penetration rate, such as Australia, Canada, and the U.S., have no specific mandatory legislation (Jha, 2015; Sakai et al., 2014). The ELV legislations in

Europe is one of the most established laws, and they are used as reference by other countries in curbing ELV waste issues (Gerrard and Kandlikar, 2007). The stricter legislations can have a significant impact on the adoption of recycling technologies when compared to countries with no specific ELV laws, like Australia. The comparison of ELV management systems from the legislative perspective focusing on the European and Australian scenarios are discussed as follows.

The ELV management in Australia is driven by economic mechanisms, with no existing national legislation related to ELV disposal (McNamara, 2009; Soo et al., 2016). ELV are acquired by recyclers due to the value of metal scrap, and they are responsible for the disposal of ELV waste at their own expense. The amount of waste generated from ELV is significant and can be costly. Despite the lack of ELV legislation in Australia, the disposal of certain toxic substances is captured under different and more broadly defined voluntary product stewardship arrangements bound by the Product Stewardship Act 2011 (The Parliament of the Commonwealth of Australia, 2011). Voluntary product stewardship involves parties voluntarily seeking accreditation for their product stewardship arrangement from the Australian Government, as is the case for the Australian Battery Recycling Initiative, the Product Stewardship for Oil Program, and the Tyre Stewardship Australia (ABRI, n.d.; Department of the Environment and Energy, Australia, n.d., n.d.). Therefore, the recycling of certain vehicle parts, such as batteries, fluids, and tyres, are captured under these organisations. The National Waste Policy is responsible for the product stewardship framework (Department of the Environment, Australia, 2009). One of the major consequences arising from voluntary based waste policy is the competition between legitimate and illegitimate recycling sectors. The illegitimate recycling sectors do not adhere to the environmental standards, and often provide competitive prices during the ELV collection process due to their low recycling costs (McNamara, 2009). This has consequently led to the disposal of large amounts of ELV waste without proper treatment. About 25% of the ELV is ASR that ends up in landfills (Vermeulen et al., 2011). ASR landfills contain hazardous waste that is constrained by the landfill standards covered in the waste management strategies (Wright Corporate Strategy, 2010). A landfill levy is imposed to deter landfill and promote alternative waste treatment options that increase material recycling such as plastics (Dawkins and Allan, 2010; Department of Environment and Heritage, 2002). Nevertheless, the landfill costs are still low in comparison to other countries (Kanari et al., 2003).

The ELV management system in Europe is driven by ELV Directive 200/53/EC enacted in the year 2000 (E. U. Directive, 2000). It covers different aspects involving all parties from vehicle production to recycling stages based on the subsidiarity principle (Smink, 2007) and extended producer responsibility policy (Sakai et al., 2014). The subsidiarity principle is defined as the fulfilment of the Directive’s guidelines based on individual approaches of the Member States in their countries (Smink, 2007). This has led to slight differences in the approach taken to comply with the regulatory requirements (Sander et al., 2002). For instance, in Belgium, the ELV Directive is implemented at regional level and monitored by Febelauto, a non-profit organisation. Febelauto manages the collection, treatment and recycling of ELV. They also inform and support different parties involved in the ELV management system, such as last vehicle owners, recycling operators, authorised treatment facilities, and authorities (“Febelauto,” n.d.). The most pertinent legislation to vehicle recyclers are the strict quantified targets to be achieved for reuse, recycling, and recovery of ELV. Recycling refers to the retrieval of waste materials for reuse in a closed-loop or open-loop system, whereas recovery refers to the use of waste materials to generate energy. As shown in Equation (1) and (2), recycling and recovery efficiencies (η) are defined as the total mass (kg) of material output from the recycling processes, either for reuse or energy recovery, divided by the input, taking into consideration material losses during processing. Based on the ELV Directive, by 2015 85% of ELV mass needs to be reused and recycled. A further 10% can be used in energy recovery (Gerrard and Kandlikar, 2007). Therefore, the targets for reuse and recovery combined amount to 95% by mass (E. U. Directive, 2000). This has consequently pressured vehicle recyclers to continuously improve their recycling techniques and post-shredder treatment technologies while generating revenue for their companies. Moreover, the amount of ASR landfilled has decreased and been minimised due to the lack of landfill space, charges for landfill disposal, and strict landfill waste legislation (Bellmann and Khare, 2000; Mazzanti and Zoboli, 2006).

$$Recycling\ efficiency\ (\eta) = \frac{material\ recycling\ output\ (kg)}{recycling\ input\ (kg)} \tag{1}$$

$$Recovery\ efficiency\ (\eta) = \frac{material\ recycling\ output + energy\ recovery\ (kg)}{recycling\ input\ (kg)} \tag{2}$$

2.7.2 Australian Vehicle Recycling System

The Australian vehicle recycling system is driven by financial gains through the recovery of valuable materials (Soo et al., 2016, 2015). Figure 2-9 represents the generic vehicle recycling flow in Australia. ELV are collected by auto recyclers through used car dealers, insurance companies, car repair centres or directly from the last vehicle owner. The collected ELV are then depolluted by removing the batteries, and draining of all fluids and gases. High demand auto parts are also removed for financial profit. Metal shredding yards then collect the remaining ELV due to the high steel content. These shredder facilities focus on the recovery of ferrous material to provide enough feedstock for large steel mills that run in high-volume production. In comparison to other developed countries, Australian metal shredding facilities are largely primitive for cost efficiency, and plastic materials contribute significantly to the amount of ASR that are landfilled. This is mainly caused by the low landfill costs in Australia (Kanari et al., 2003) compared to plastic recycling and waste reprocessing systems.

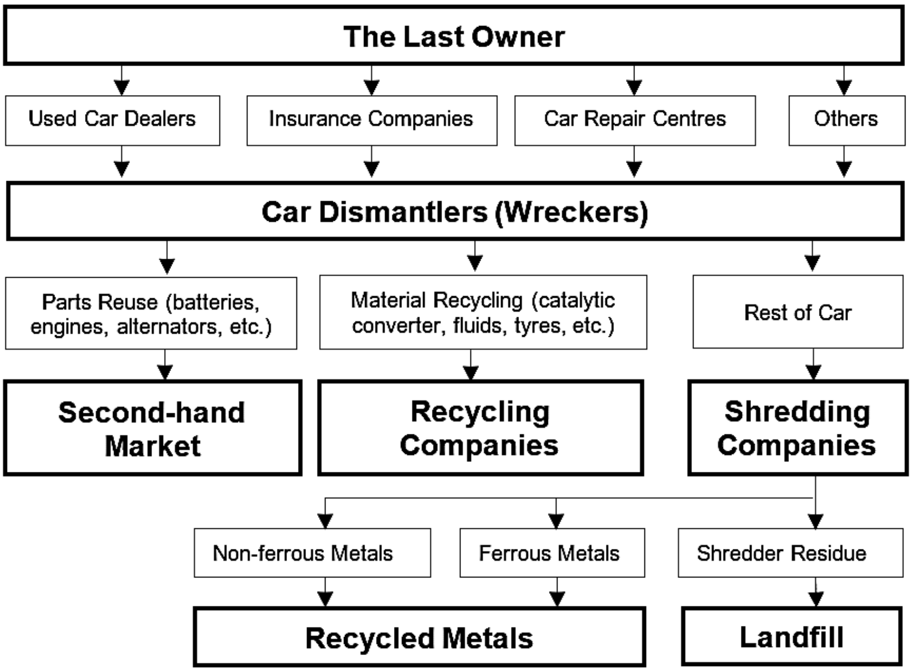


Figure 2-9: ELV recycling system in Australia (Adapted from (McNamara, 2009)).

There is a lack of initiative among Australian legitimate recycling facilities to invest in better recycling technologies since they do not receive large volumes of ELV. Moreover, the voluntary based ELV regulatory framework has led to a profit-driven automotive recycling industry. The types of recovered materials are limited to high volume metals with low recovery cost such as ferrous scraps (Soo et al., 2016). As shown in Figure 2-10, the ELV material flows in Australia undergo primitive recycling processes targeting high valuable metals.

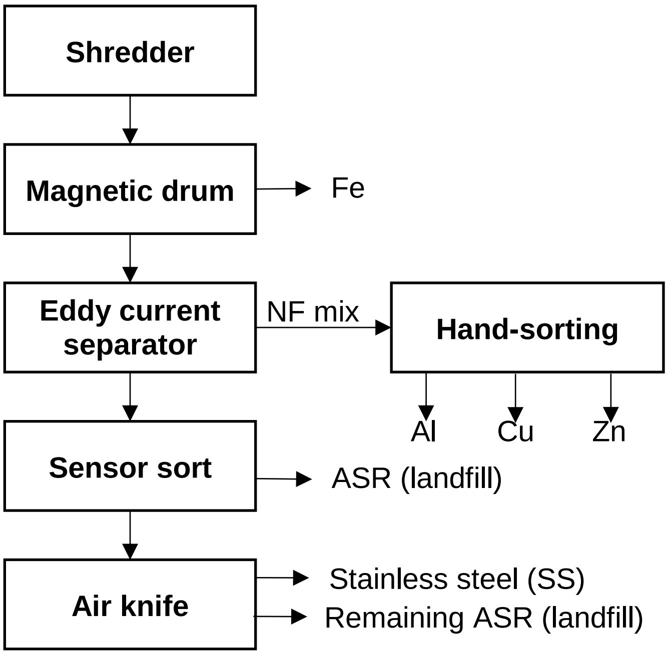


Figure 2-10: ELV material flows in Australia (Soo et al., 2017).

2.7.3 European Vehicle Recycling System

A generic ELV recycling system from the vehicle's last owner to the recycling phase is shown in Figure 2-11. The collected ELV undergo depollution procedures to remove batteries, fluids, and other materials that contain hazardous waste. Valuable parts are further disassembled to cater for the sale of reuse parts. The depolluted car hulks are then processed in material recycling facilities to recover valuable materials such as ferrous (Fe) and non-ferrous (NF) metals, and plastics. The remaining ASR are further treated through post-shredder technologies, as highlighted in Figure 2-11, to achieve the set recycling targets due to the strict compliance to ELV legislations.

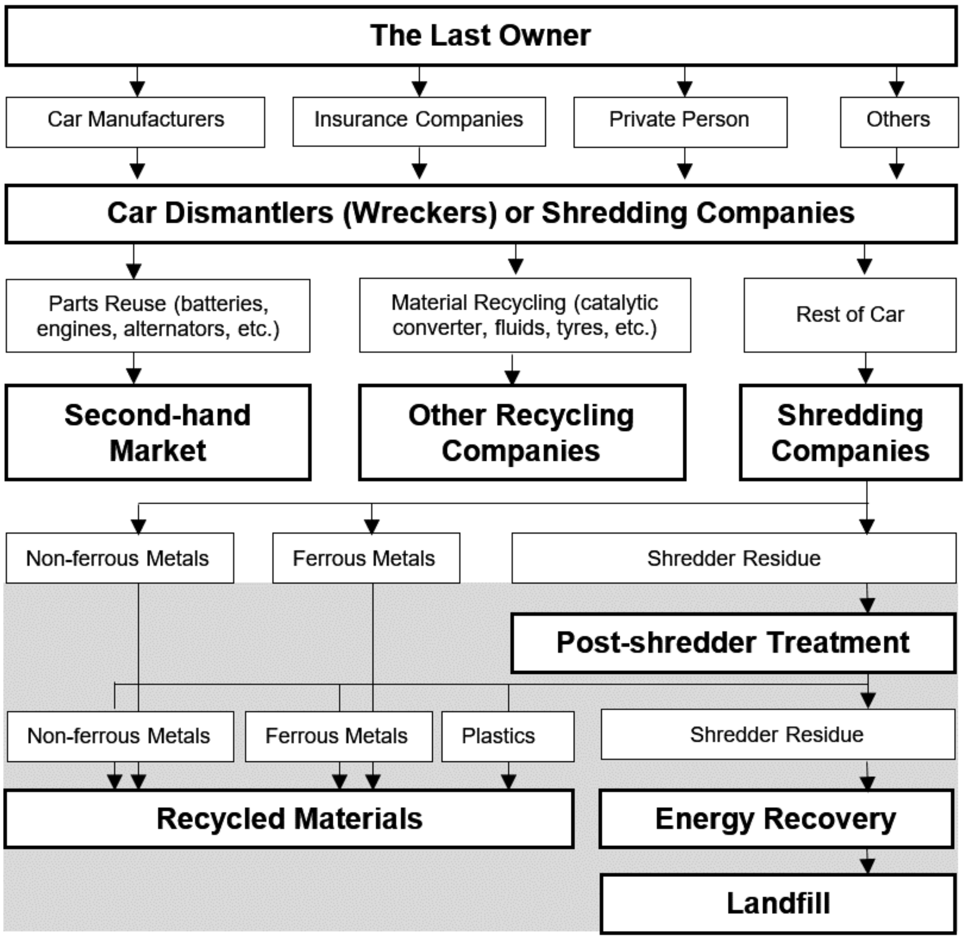


Figure 2-11: ELV recycling system in Europe (Belboom et al., 2016; Sakai et al., 2014).

One of the major differences during the collection stage in Europe is the issue of certificate of destruction for ELV. This requirement is carried out to ensure ELV are collected and disposed lawfully through an authorised recycling facility (Inghels et al., 2016). The number of ELV collected into proper recycling facilities has an impact on the cost effectiveness of material recycling processes and further post-shredder treatments. As seen in the Australian scenario, the lack of a proper collection system gives opportunities for unauthorised recycling facilities to compete with legitimate recycling sectors in acquiring ELV (McNamara, 2009). The continuous development of high performance recycling processes, such as density media separation and energy recovery facilities, enables further retrieval of valuable materials and thus, reduces the amount of waste to be landfilled in Europe. The generic ELV material flows in Europe is shown in Figure 2-12.

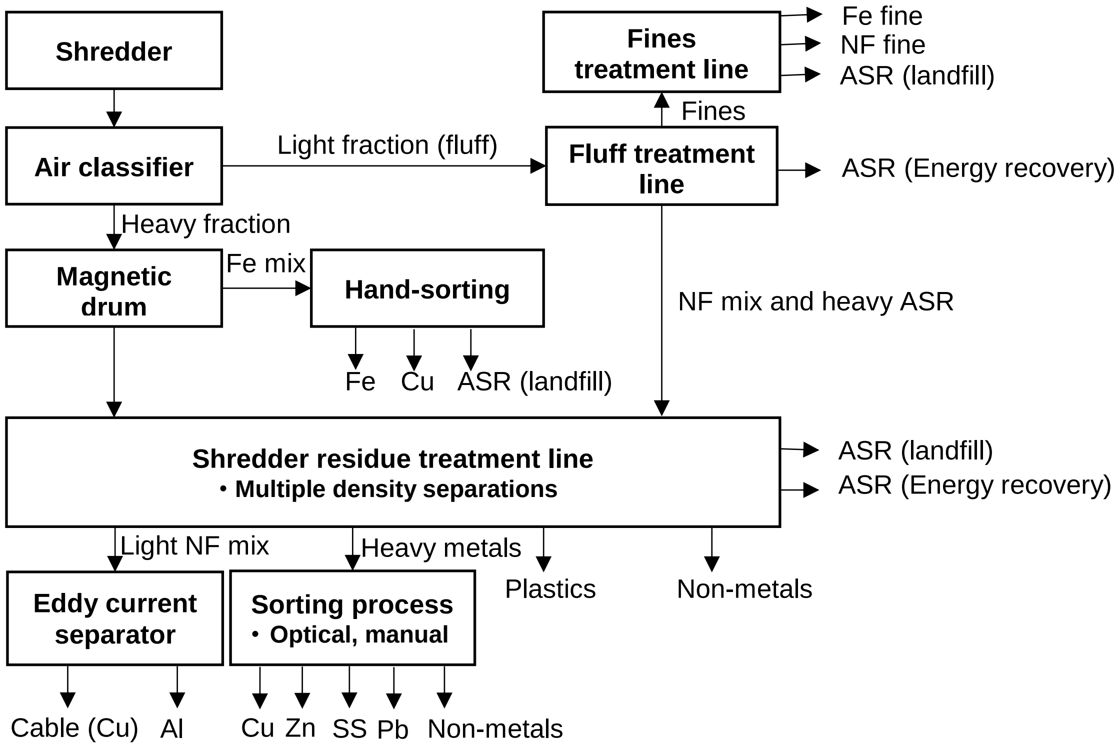


Figure 2-12: ELV material flows in Europe (Soo et al., 2017).

The strict recycling targets and scarcity of available landfill space in Europe have further encouraged minimal ELV waste disposal due to high landfill costs. This is in line with the ambition of preventing waste to landfill while stressing reuse, recycling, and waste incineration in accordance with Lansink's ladder (Lansink, 1980; Wolsink, 2010). Therefore, the implementation of advanced post-shredder technologies is continuously progressing since the associated recycling costs are still below the disposal cost. The economic incentives play a major role in the current ELV recycling; however, the implementation of strict legislation in Europe is crucial to adjust the current ELV recycling procedures through the influence on recycling costs, including fines. As a consequence, the European recyclers also looked into the potential of recycling non-metallic materials, such as plastics, to achieve a higher recycled mass fraction. Although plastic recycling is not as lucrative as metal recycling, there is still great potential value for secondary plastic production. Moreover, it provides environmental benefits and allows further reduction of waste disposal (Inghels et al., 2016).

2.8 Challenges in ELV Recycling

The material recycling and recovery rates from ELV are greatly influenced by the vehicle design trends (Andersson et al., 2017a). Through standard ELV recycling, 100%

separation of different materials is impossible, as seen in Figure 2-13. Some analysts have optimistically estimated the percentage fraction of materials recycled to be around 90-95% especially for metals (Das, 2000; Hakamada et al., 2007; Mayyas et al., 2012). However, the increasing complexity in vehicle designs has influenced the efficiency of recycling processes, and led to lower recycling efficiencies (Andersson et al., 2017b; Dalmijn and Jong, 2007; Gerrard and Kandlikar, 2007). Although design for disassembly or recycling has been considered at an earlier stage, the economic and technological practicability still lack in consideration (Sutherland et al., 2004). Close cooperation between vehicle manufacturers and recyclers is needed in order to optimise the retrieval of ELV materials during the recycling process.

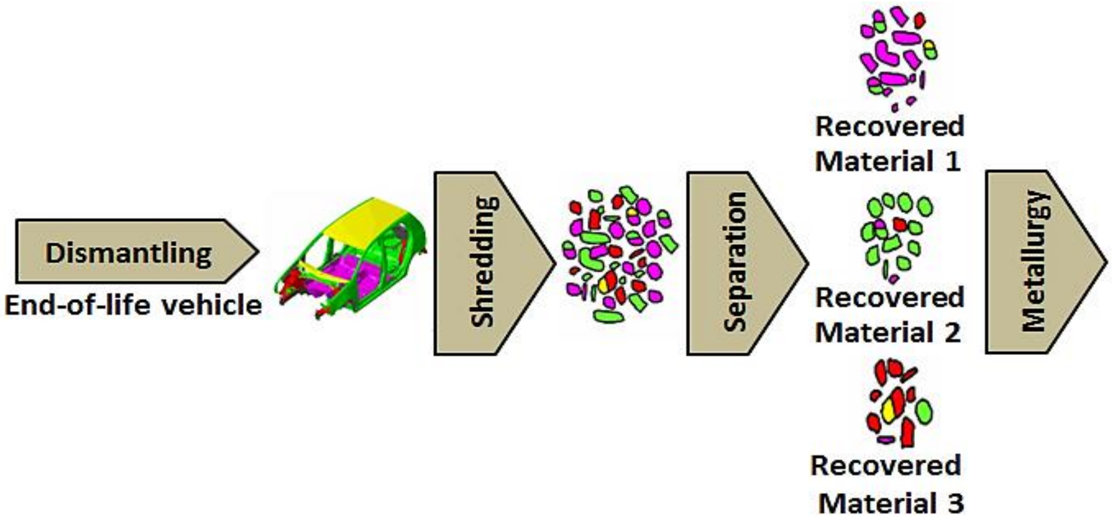
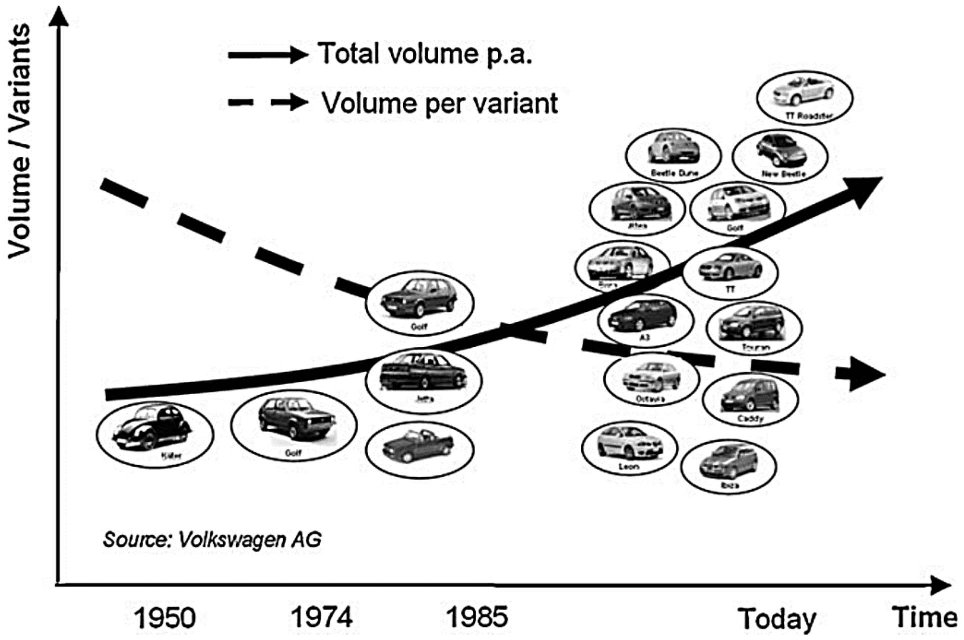


Figure 2-13: Standard ELV recycling with traces of impurities in different recovered output streams (Adapted from (Volkswagen Group, 2009)).

Although ELV are highly recyclable, waste is produced in the form of ASR, and is largely landfilled. ASR consist of non-valuable waste that includes plastic, foam, rubber, glass, hazardous substances such as heavy metals and flame retardants, and fine particles (Kim et al., 2004; Passarini et al., 2012; Sakai et al., 2014). There are also traces of valuable metals (Fe, Cu) that end up in the ASR stream depending on the efficiency of recycling processes used (Granata et al., 2011; Jordão et al., 2016; Khodier et al., 2017). The growing amount of ASR and valuable material losses have highlighted the importance of implementing better strategies at earlier vehicle design stage to cater for optimised material recycling rates through current separation technologies (Khodier et al., 2017; Satini et al., 2011; Vermeulen et al., 2011).

2.8.1 Effect of Multi-Material Designs on ELV Recycling

The commonly used recycling processes face increasing challenges for full material recovery due to the complexity of multi-material designs with their associated joining techniques. Moreover, there is an increasing variety of new vehicle designs, as shown in Figure 2-14, that led to the difficulty in fully optimising material recycling through the standard recycling processes. The evolution of lightweight multi-materials limits the choice of joining dissimilar materials, particularly for metal-to-polymer hybrid structures. The more frequently used joining techniques, such as mechanical fastening, adhesive bonding or a combination of both methods, are cost-effective for large production, and provide the ability to join dissimilar and similar materials (Meschut et al., 2014). Furthermore, the increasing use of mechanical fasteners to join plastic materials is observed in newer vehicle design (Amancio-Filho and dos Santos, 2009; Kah et al., 2014). As a consequence, perfect liberation of materials is becoming more challenging (Castro et al., 2005; Van Schaik and Reuter, 2007) due to the choice of joining techniques, and often the joint designs used also contribute to the contamination or material losses in different recovered streams. For example, steel screws used to join aluminium materials can end up in the aluminium recovered stream (Soo et al., 2015).



Source: Volkswagen AG

Figure 2-14: Increasing variety of new vehicle designs in the automotive industry (Reproduced with permission from (Juehling et al., 2010)).

The use of multi-materials and their associated joining techniques has caused the growth of material impurities in different valuable recovered streams, and thus degrade the quality of secondary materials. This has consequently creates a cascading effect of material degradation in each recycling loop (Paraskevas et al., 2015). Natural resources are continuously extracted due to the demand for producing material with high grade quality, or to be added in the dilution of metal impurities present in the recovered output streams (Castro et al., 2007; Soo et al., 2016). For instance, shredded particles containing both aluminium and small steel fractions (i.e. steel screw still attached to aluminium material) are not further liberated due to cost. In most cases, steel is used as an alloying element for secondary aluminium alloy production. However, the amount of iron present in the alloy is crucial in determining the mechanical properties of the secondary material produced since they cannot be easily eliminated during the recycling stage (Nakajima et al., 2010). As a result, the original functional quality of the material is lost and the new material cannot be used to replace the previous product.

In countries with no specific ELV regulations, there is a growing amount of ASR that are currently landfilled due the increasing use of polymers and polymer composites in lightweight vehicles (Soo et al., 2015). Post-shredder technologies that are implemented in developed countries with strict vehicle recycling regulations are not common due to the higher cost of post-shredder treatments in comparison to the landfill cost. When polymers and composite materials are joined using mechanical fasteners made of metallic material such as steel, a small Fe content will most likely end up in the ASR stream, causing the loss of valuable materials. This is also the case for the increasing use of adhesive bonding for metal-to-polymer structure. The complexity of recovering different polymer types from ELV would require proper post-shredder technologies to be set up that can be costly for the current ELV recyclers (Cossu and Lai, 2015). Therefore, landfilling is favourable from the economic perspective for countries with the lack of strict vehicle legislations (Puri et al., 2009; Ruffino et al., 2014).

2.8.2 Quality of Recovered Material

Material degradation is inevitable due to the presence of impurities in each valuable recovered material stream through the current recycling practices. This is caused by the combination of different material types or part designs, such as steel encapsulated with rubber, or the use of steel fasteners to combine steel and plastic materials (Castro et al., 2005). The impurities' material types have a large effect on the material quality when they are recycled to be reused as secondary material (Reuter et al., 2004). There is a range of tolerable amount of impurities that could be present in the recovered scrap to ensure the secondary material grades are fulfilled. For instance, bar steel made of steel scrap could have a maximum of 0.4wt.% copper content, whereas cold rolled sheet only accept a maximum of 0.04wt.% copper content (Savov et al., 2003). If the contaminated vehicle steel scrap is used to reproduce the original steel grade such as the cold rolled sheet, impurities such as copper will need to be diluted using more high purity steel (Castro et al., 2007).

The recovery of different NF metals poses a more difficult challenge. The separation of different NF metals, such as aluminium, magnesium, and copper, can be costly to recyclers depending on the recycling processes utilised, and the amount of different NF metals present in the input stream. Therefore, smaller fractions of NF metal often end up in other light metal fractions, or used as alloying additives (Ehrenberger and Friedrich, 2013). Nevertheless, there is a limit on the amount of foreign elements that can be present in the base metal to obtain the desired material quality. The linkage of various base metals and their co-elements from the perspective of metallurgical recycling processes for different alloys is shown in the element radar chart by Hiraki et al. (2011). Some of the foreign elements distributed in the metal phase for different base metals are elements that cannot be easily removed, and can end up as tramp elements—contaminants that are not added on purpose, and can have an effect on the quality of metals desired (Hiraki et al., 2011).

2.9 Design for Sustainability Framework

Ecodesign is a sustainable product development framework often used to devise strategies to address the environmental concerns associated with the entire life cycle of a vehicle during the design process. Through this approach, the environmental aspects are incooperated to the initial product development stage as part of the design requirements. (Jawahir et al., 2006) have presented a comprehensive list of design for sustainability framework, as shown in Figure 2-15, that explores the elements of sustainable product from a holistic view. Nevertheless, these elements often conflict and are prioritised by the sustainability requirements (De Silva et al., 2009).

The sustainability framework is based on the three pillars of sustainability: environment, social and economic. For many years, vehicle manufacturers have incorporated sustainable product development as part of their corporate social responsibility (Koplin et al., 2007; Zhu et al., 2007). The life cycle cost analysis of vehicle has been studied in the past to evaluate the potential benefits of using more lightweight materials in vehicle body structures (Witik et al., 2011), incorporating alternative vehicle powertrain technologies (Hellgren, 2007; Ogden et al., 2004) and other economic aspects during the vehicle life cycle. One of the major social challenges facing the automotive industry is the affordability of sustainable vehicles (He et al., 2014; Litman and Burwell, 2006; Zhu et al., 2007). The interconnection between the different areas of sustainability is highly complex (Koplin et al., 2007). There is a need for the development of comprehensive vehicle sustainability assessment framework that relates well to the overall sustainability concerns (Jasiński et al., 2016). For instance, minimising the use of resources such as energy, water, materials, etc. has a significant economic benefit during the vehicle manufacturing phase. On the other hand, reducing emissions and toxicities during the vehicle use phase contributes to the human health and societal wellbeing. Environment is one of the most crucial aspects of sustainability to ensure a safe operating space within the earth's capacity (Rockström et al., 2009).

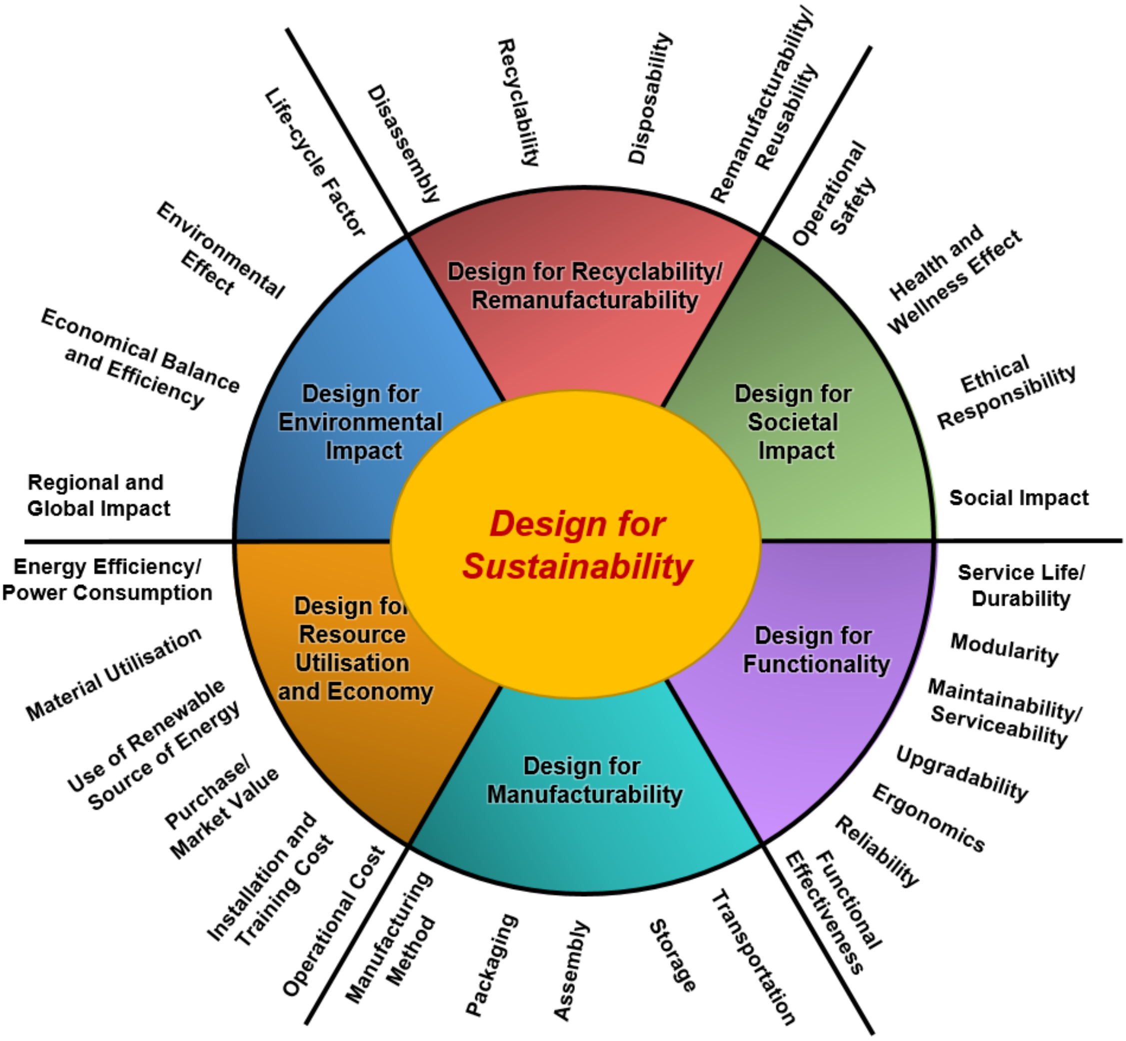


Figure 2-15: The elements of design for sustainability (Reproduced with permission from (Jawahir et al., 2006; Lu et al., 2011)).

Design for Recyclability or Remanufacturability (DfR) is the most pertinent framework relating to EoL treatment strategies. The sub-elements include Design for Disassembly, Design for Recyclability, Design for Disposability, and Design for Remanufacturability or Reusability. Green engineering design approach is undertaken by car manufacturers to support more lightweight vehicles (McAuley, 2003). During the DfR process, the choice of materials and their associated joining techniques is critical because it influences the ease of disassembly and material recovery at the EoL phase (Bogue, 2007). Therefore, both material and joint selection must be studied concurrently to optimise the environmental performance of ELV. Interaction between vehicle designers and recyclers is also gaining importance to understand the real impact of vehicle designs on practical EoL scenarios (Bras, 1997). Often, there is a knowledge gap between the product design, and the feasibility of current recycling technologies due to the varying design complexities, cost, and technical constraints (Froelich et al., 2007b; Miller et al., 2014; Van Schaik and Reuter, 2004). Some of the example methods and tools used by vehicle manufacturers to assist in product design include guidelines and indicator systems, eco-labels, and LCA studies.

2.10 Design for Recycling Guidelines

In most recycling guidelines, the three major aspects that have the largest impact on recyclability are often emphasised: structural design, material choice, and fastener selection. The interconnection between these characteristics determines the material liberation level in the recycling stream (Castro et al., 2005; Van Schaik and Reuter, 2007).

Material selection has become an essential part of the automotive production and assembly due to the increasing lightweight vehicle structures. Toward producing more lightweight vehicles, material substitution and structural design changes are common practice to optimise the vehicle mass reduction potential (Fuchs et al., 2008). The choice of material is determined by a number of factors including materials' criticality (Knoeri et al., 2013); optimisation potential based on functional equivalence; and eco-efficiency (Ashby, 2012). Therefore, there are a variety of multi-criterion decision-making methods used by manufacturers to select the most appropriate materials, and to solve conflicting requirements (Girubha and Vinodh, 2012). The most basic material selection guidelines for manufacturers are the white, grey, and black material lists to encourage the use of certain materials (white list) and to deter others (black list). This is an example method used by Volvo to assist in their vehicles' material selection (Luttropp and Lagerstedt, 2006).

There are limits to the current ecodesign strategies to improve the material recyclability (Worrell and Reuter, 2014). This is largely due to the difficulties in bridging the gap between design phase, such as selection of material combinations, and the industrial material recycling processes. The increasing complexity of multi-material designs further reduces the effectiveness of current sorting and recycling processes, hindering the reuse of high valuable materials to replace virgin materials. (Castro et al., 2004) have proposed the use of thermodynamic evaluation of material combinations (THEMA) model to support decision-making in product design looking from the metallurgical recycling perspective. The THEMA model is a decision-making tool that takes into consideration the constraints in recycling processes; the compatibility of different material mixtures; and the limitations during metallurgical processing. The basic steps of the model are illustrated in Figure 2-16 through an example using Al-Fe combinations. This method can be used to evaluate the material compatibility of highly complex products, such as vehicles, as can be seen in Figure 2-17.

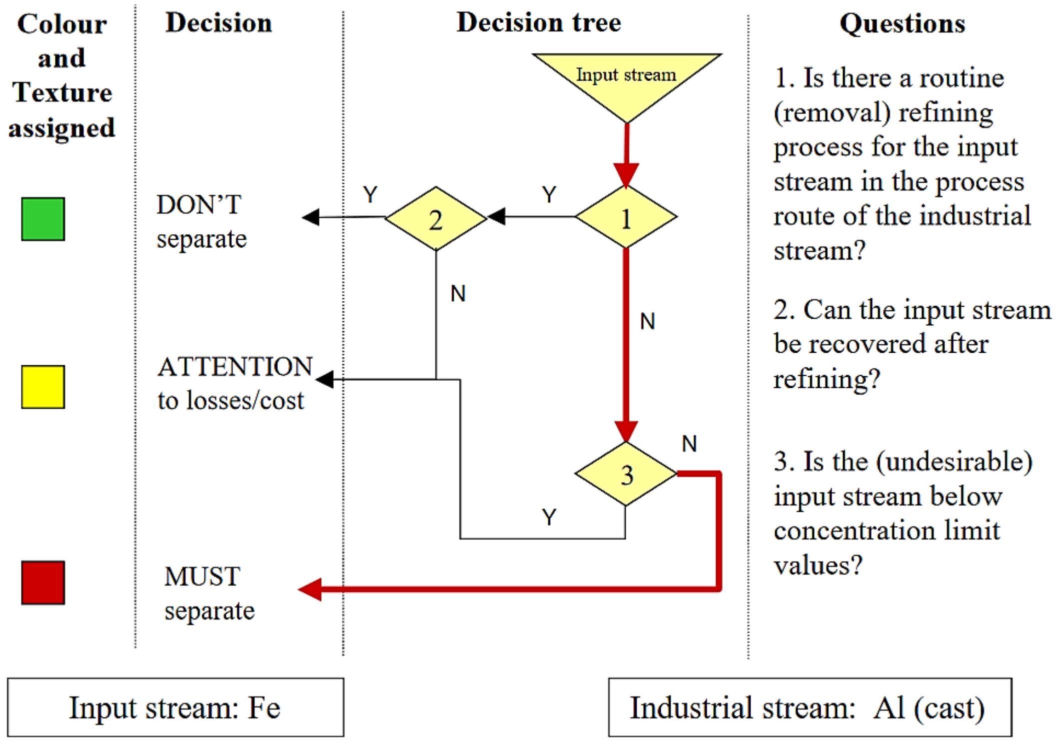
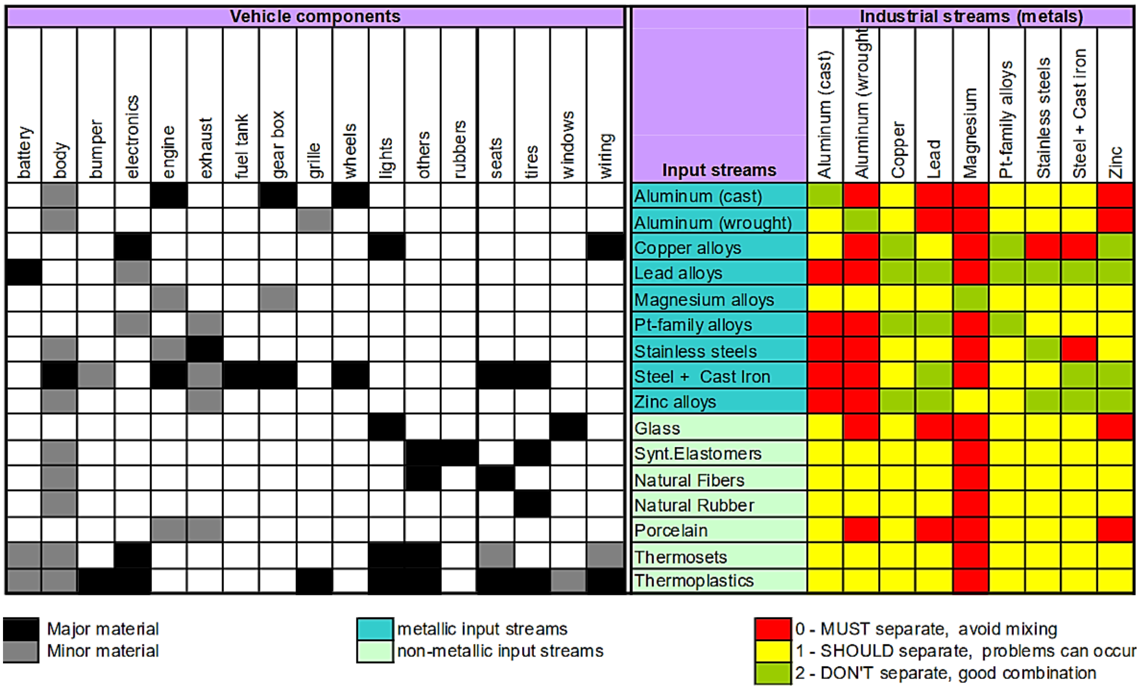


Figure 2-16: The decision-making steps through THEMA model. The compatibility of Al-Fe combinations entering the Al stream (Reproduced with permission from (Castro et al., 2004)).



Vehicle components																		Industrial streams (metals)								
battery	body	bumper	electronics	engine	exhaust	fuel tank	gear box	grille	wheels	lights	others	rubbers	seats	tires	windows	wiring	**Input streams**	Aluminum (cast)	Aluminum (wrought	Copper	Lead	Magnesium	Pt-family alloys	Stainless steels	Steel + Cast iron	Zinc
	▨			■			■		■								Aluminum (cast)	🟩	🟥	🟨	🟥	🟥	🟨	🟨	🟨	🟥
	▨							▨									Aluminum (wrought)	🟨	🟩	🟨	🟥	🟥	🟨	🟨	🟨	🟥
			■							■						■	Copper alloys	🟨	🟥	🟩	🟨	🟥	🟩	🟥	🟥	🟩
■			▨														Lead alloys	🟥	🟥	🟩	🟩	🟥	🟩	🟩	🟩	🟩
				▨			▨										Magnesium alloys	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟨
			▨		▨												Pt-family alloys	🟥	🟥	🟩	🟩	🟥	🟩	🟨	🟨	🟨
	▨			▨	■												Stainless steels	🟥	🟥	🟨	🟨	🟥	🟨	🟩	🟥	🟨
	■	▨		■	▨	■	■		■				■	■			Steel + Cast Iron	🟥	🟥	🟨	🟩	🟥	🟨	🟨	🟩	🟩
	▨				▨												Zinc alloys	🟥	🟥	🟩	🟩	🟨	🟨	🟩	🟩	🟩
										■					■		Glass	🟨	🟥	🟨	🟥	🟥	🟨	🟨	🟨	🟥
	▨										■	■		■			Synt.Elastomers	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨
	▨										■		■				Natural Fibers	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨
	▨													■			Natural Rubber	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨
				▨	▨												Porcelain	🟨	🟥	🟨	🟥	🟥	🟨	🟨	🟨	🟥
▨	▨		■							■	■		▨			▨	Thermosets	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨
▨	▨	■	■					■		■	■		■	■	▨	■	Thermoplastics	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨

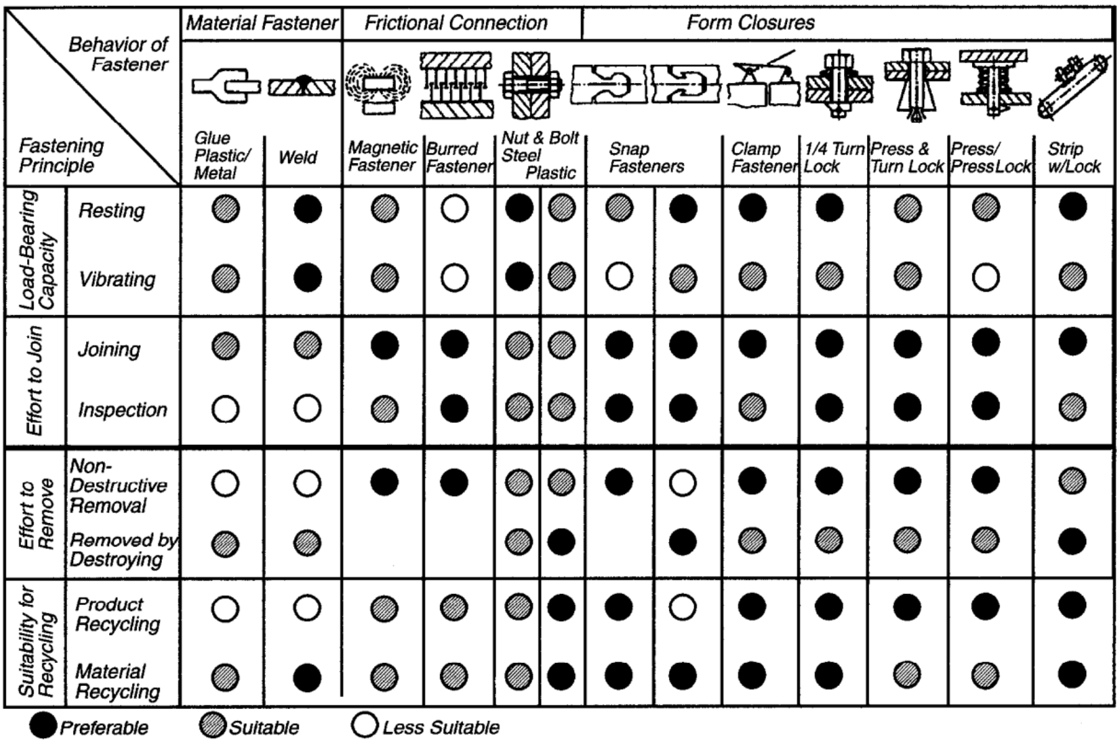
■ Major material
▨ Minor material

metallic input streams
non-metallic input streams

🟥 0 - MUST separate, avoid mixing
🟨 1 - SHOULD separate, problems can occur
🟩 2 - DON'T separate, good combination

Figure 2-17: Application of THEMA model to assist in decision-making for different material combinations used in vehicles (Reproduced with permission from (Castro et al., 2004)).

The types of materials will have an impact on the choice of joining techniques. There are various fastener selection guidelines to assist designers in choosing the most preferred joining techniques based on the intended function; however, most of them emphasise on the selection of fasteners to assist in Design for Disassembly that is non-destructive to the product (Argument et al., 1998; Edwards et al., 2006; Ghazilla et al., 2014; Shu and Flowers, 1999, 1996). These guidelines may not be applicable to the destructive nature of commonly used shredding process (Newell, 1965) during EoL recycling. The most detailed overview of the German recycling rating from the joint selection perspective is outlined in the VDI 2243 guidelines (VDI 2243, 1993), as seen in Figure 2-18. Material recycling rating for different types of joining methods are taken into consideration in selecting the most preferred types of joint based on the required functionality.



Behavior of Fastener / Fastening Principle		Material Fastener		Frictional Connection				Form Closures						
		Glue Plastic/ Metal	Weld	Magnetic Fastener	Burred Fastener	Nut & Bolt Steel	Nut & Bolt Plastic	Snap Fasteners	Snap Fasteners	Clamp Fastener	1/4 Turn Lock	Press & Turn Lock	Press/ PressLock	Strip w/Lock
Load-Bearing Capacity	Resting	◍	●	◍	○	●	◍	◍	●	●	●	◍	◍	●
	Vibrating	◍	●	◍	○	●	◍	○	◍	◍	◍	◍	○	◍
Effort to Join	Joining	◍	◍	●	●	◍	◍	●	●	●	●	●	●	●
	Inspection	○	○	◍	●	◍	◍	●	●	◍	●	●	●	◍
Effort to Remove	Non-Destructive Removal	○	○	●	●	◍	◍	●	○	●	●	●	●	◍
	Removed by Destroying	◍	◍			◍	●		●	◍	◍	◍	◍	●
Suitability for Recycling	Product Recycling	○	○	◍	◍	◍	●	●	○	●	●	●	●	●
	Material Recycling	◍	●	◍	◍	◍	●	●	●	●	●	◍	◍	●

● Preferable ◍ Suitable ○ Less Suitable

Figure 2-18: Joint selection table translated from VDI 2243 in 1993 (Reproduced with permission from (Rosen et al., 1996)).

The design recommendations relating to joint selection in VDI 2243 was updated in 2002, and has become less specific to ensure their applicability for a variety of complex product designs. The updated guidelines provide a more comprehensive coverage of technical and economic aspects to optimise decision-making during the design phase (Abele et al., 2007; VDI 2243, 2002), as seen in Table 2-14. Some of the generic suggestions relating to dismantling, and the choice of joining techniques listed in the guidelines are as follows (VDI 2243, 2002). These guidelines are consistent with the design for disassembly and recycling guidelines by Dowie and Simon (Dowie and Simon, 1995).

- Minimise the number and variation of connecting elements.
- Standardise connecting elements.
- Provide standard dismantling directions to ease dismantling access.
- Design non-destructive detachable connections to ease disassembly and accessibility after use phase.
- Snap connections are preferred over screw connections where possible.
- Minimise non-detachable connections such as welding, riveting, and adhesive bonding. Otherwise, only use with recycling-compatible materials.

- Cater for standardise dismantling tools and ensure accessibility.
- For flat subassemblies, use external snap connections and avoid screw connections.
- Design fixing elements for electromechanical components to be accessible even without power supply.

Table 2-14: High-level checklist relating to recycling-optimised product development specific to connections (Adapted from (VDI 2243, 2002)).

Recycling Criteria	Assessment	Potential Optimisation
Types of connection	• Detachable non-destructively	• Not necessary
	• Partial destruction for connection	• Use non-destructive connection
	• Destruction include component damage	• Use detachable connections
Variety of connections	• Single or few (uniform type)	• Not necessary
	• Functionally-specific variety (standardised)	• Test possible reduction
	• Unmanageable variation (too many)	• Reduce number of connections

Vehicle manufacturers often face conflicting ecodesign guidelines (Luttropp and Karlsson, 2001). For instance, multi-material designs with a variety of joining approaches are used to minimise the energy and resource consumption during vehicle use phase that conflict with the guideline to use fewer joining elements in accordance to the ‘Ten Golden Rules’—a set of ecodesign guidelines used by companies and researchers (Luttropp and Lagerstedt, 2006). The use of fewer joining elements is also supported by the Boothroyd and Dewhurst method to improve the efficiency of product manufacturing from the design for assembly perspective (Boothroyd et al., 2010; Boothroyd and Alting, 1992; Warnecke and Bäßler, 1988). In most cases, the contradictions are overcome based on priorities and goals, i.e vehicle fuel efficiency improvement through multi-material designs is often the priority for manufacturers. Cerdan et al. (2009) have observed the lack of design for recycling strategies, and proposed a better implementation of ecodesign indicators through quantitative measures. The relationship between the proposed ecodesign indicators and the commonly used life cycle impact assessment are integrated to allow for a more realistic scenario analysis.

2.11 Life Cycle Thinking Approach

Life cycle thinking is a method to evaluate the impacts of activities that have an effect on the environment from a holistic view. The aim is not just to improve the ecological footprint, but also to have a better indication of the socio-economic performance throughout the life cycle of the product or processes. Environmental Life Cycle Assessment (LCA) method is the most established and widely used life cycle thinking approach since 1970s (Guinée et al., 2011). Over the past four decades, there have been a range of life cycle thinking methods developed from the standard LCA including Life Cycle Costing (LCC), Social Life Cycle Assessment (SLCA), and Life Cycle Sustainability Assessment (LCSA) (Guinée et al., 2011; Klöpffer, 2003).

The Society of Environmental Toxicology and Chemistry (SETAC) has played a major role in the development of LCA (Andersson et al., 1998; Bretz, n.d.; Klöpffer, 2006; Todd et al., 1999). The LCA method is carried out in accordance with the ISO 1404X standards (ISO, 2006). According to the method outlined, LCA involves four main iterative processes: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006). Different products can be compared based on the same functional unit. LCA identifies the input and output of vehicle inventories in each life cycle stages and then, evaluates the potential environmental impact accordingly. The analysis allows manufacturers to make better informed decisions and assists government in automotive-related legislations or policies (Finnveden, 2000; Klöpffer, 2003). Furthermore, trade-offs between the various life cycle stages can be assessed to understand the environmental impact with respect to each phase. It is important to note that the scope, assumptions, limitations, and steps taken at each life cycle stage must be outlined clearly in the methodology to ensure adequate description of the product systems to address the objective of the study.

The growing importance of the three pillars of sustainability: environment, social, and economy has led to the broadening of standard LCA scope (Heijungs et al., 2010; Jeswani et al., 2010). LCC method is used to estimate the economic cost of a product during the entire life cycle in order to assist in decision-making relating to cost-effectiveness (Kloepffer, 2008; Swarr et al., 2011). To assess the social impacts of a product that are not currently addressed in LCA, such as work conditions, labour practices, and product responsibility, SLCA method is established (Benoît et al., 2010; Jørgensen et al., 2008). LCSA method is introduced to cater for a more holistic sustainability assessment framework. It is a combination of the LCA, LCC, and SLCA methods to account for the environmental, social, and economic performances of a product (Finkbeiner et al., 2010; Kloepffer, 2008; Zamagni, 2012). The expansion of LCA through LCC, SLCA, and LCSA is in accordance with the general methodological framework for LCA although they are not standardised (Guinée et al., 2011; Swarr et al., 2011). One of the main barriers in performing the assessment through these life cycle thinking methods is the lack of data availability (Jeswani et al., 2010; Jørgensen et al., 2008). Therefore, the LCA method is still the most widely used tool in industry since its database and practice are well established.

Automotive manufacturers often use LCA method to assist in decision-making with respect to the entire life cycle: material extraction, production, use, and EoL phases. It is used to assess the environmental footprint of vehicles, and allow modifications for new vehicle designs at earlier phases to improve the environmental impact for different life cycle stages. The research themes for some of the previous automotive LCA studies focusing on the respective phase are summarised in Table 2-15.

Table 2-15: Categorisation of past automotive LCA studies based on the research themes for the respective LCA phases.

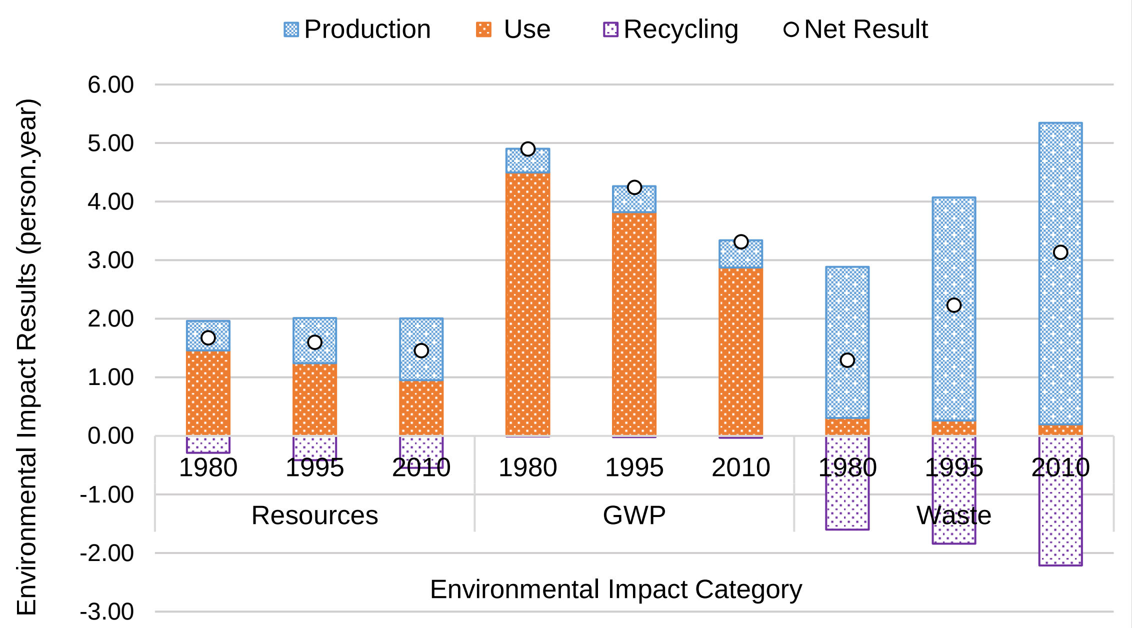
LCA Phase	**Research Theme**	**References**
Production	Material selection for lightweight vehicle/vehicle part/vehicle structure	(Pryshlakivsky and Searcy, 2017; Tharumarajah and Koltun, 2007)
Use	Alternative fuels/powertrain technologies for vehicle	(MacLean and Lave, 2003; Moro and Helmers, 2017; Nicolay et al., 2000; Spielmann and Althaus, 2007)
EoL	Adoption of different recycling processes and waste treatment scenarios	(Belboom et al., 2016; Ciacci et al., 2010; Passarini et al., 2012)
EoL	Material selection for vehicle/vehicle parts/vehicle structure	(Badino et al., 1997; Dos Santos Pegoretti et al., 2014; Ehrenberger and Friedrich, 2013; Passarini et al., 2012)
Entire life cycle	Resource depletion	(Hernandez et al., 2017)

Table 2-15 (Continued)

LCA Phase	**Research Theme**	**References**
Entire life cycle	Material selection for lightweight vehicle/vehicle part/vehicle structure (BIW)	(Alonso et al., 2007; Bonollo et al., 2013; Das, 2011, 2000; Dhingra and Das, 2014; Fuchs et al., 2008; Mayyas et al., 2012; Nanaki and Koroneos, 2012; Puri et al., 2009; Ribeiro et al., 2007; Schmidt et al., 2004; Sun et al., 2017; Witik et al., 2011)
Entire life cycle	Assessment of an average passenger vehicle/vehicle part/vehicle structure for specific period or country	(Castro et al., 2003; Dos Santos Pegoretti et al., 2014; Koffler, 2014; Messagie et al., 2010; Schmidt, 2006; Schmidt et al., 2004; Subic et al., 2010; Subic and Francesco, 2006; Sullivan et al., 1998)
Entire life cycle	Alternative fuel/powertrain technologies for vehicle	(Hawkins et al., 2013; Helmers et al., 2017; MacLean et al., 2000; Messagie et al., 2010; Nemry et al., 2008)
Entire life cycle	Climate change impact of material selection for vehicle	(Danilecki et al., 2017; Dhingra and Das, 2014; Geyer, 2008; Hakamada et al., 2007; Kim et al., 2010; Saur et al., 2000; Song et al., 2009; Sullivan et al., 1998; Ungureanu et al., 2007)

In previous studies, the vehicle use phase has been identified as the major contributor to the total environmental impact due to the CO_2 emissions and fuel consumption (Das, 2000; Mayyas et al., 2012; Puri et al., 2009; Schmidt et al., 2004; Sullivan et al., 1998). Consequently, vehicle manufacturing design has focused towards lightweight materials with the aim to improve fuel efficiency during use phase besides increasing the recyclability of materials during ELV to optimise the overall environmental performance. Most of the studies, therefore, are centred around material selection or substitution to improve the vehicle's carbon footprint. This highlights the importance of understanding the side effects of this focus on other environmental impact categories. Nemry et al. (2008) have carried out life cycle analysis for mass-reduced vehicles based on a reference passenger car. They have shown that there is an increasing trend of waste produced despite the decreasing environmental impacts in GWP and primary energy consumption (Nemry et al., 2008).

A simplified vehicle LCA study based on historical material composition trend over time was carried out by (Soo et al., 2015), and the results are shown in Figure 2-19. There is a decreasing trend of GWP and resources consumption from 1980 to 2010 due to the fuel efficiency improvement in newer vehicle designs. In contrast, the waste category indicated an increasing trend. The outcomes are consistent with the findings from Nemry et al. (2008).



Resources category is normalised based on the extraction of different raw materials.
Waste category is normalised based on the different types of waste (bulk waste, hazardous waste, nuclear waste, etc.)

Figure 2-19: Normalised result for resources, GWP, and waste categories for a vehicle made in respective years based on EDIP 1997 and EDIP 2003 v1.04 (Soo et al., 2015).

2.12 Integrating Exergy Losses into LCA

Exergy analysis can be used to broaden the LCA method. Exergy is defined as available work. It is based on the thermodynamics principles: conservation of energy, and the loss of energy due to entropy generation (Amini et al., 2007). Through thermodynamic life cycle approach, resource depletion for irreversible use of non-renewable materials can be better interpreted through exergy losses. This extension was first introduced by (Cornelissen, 1997) and since then, is better known as Exergetic Life Cycle Assessment

(ELCA). Although there are few studies that have applied this concept (Amini et al., 2007; Castro et al., 2007; Nakamura et al., 2012; Paraskevas et al., 2015), it is not widely used among manufacturers due to their lack of knowledge in the area (Castro et al., 2007).

ELCA is an important concept to assess the holistic environmental impact of complex multi-material vehicle designs, particularly the use of natural resources. The difficulty of full material separation from the different material combinations and their associated joining techniques needs to be addressed more effectively to assist in better design choices. Metal quality loss is unavoidable and thus, dilution process is a common practice through the addition of high purity materials. Therefore, closed-loop recycling needs to account for the environmental impact associated with the extraction of additional non-renewable resources used for dilution during the secondary material production, to be reused for the same product. The elements that need to be diluted are tightly-linked to the types of impurities that end up in the recyclates. The element radar chart by Hiraki et al. (2011) serves as a guideline to identify problematic elements that need to be accounted for in an ELCA analysis. This is then projected in the exergy calculation to identify the mass of high quality metal required during the dilution process of contaminated scraps. An example calculation for the exergy losses through material quality for Al scrap can be seen in Table 2-16. In this example, contaminated Al scrap consisting of mainly Al 2036 was diluted to Al 380 with a limited iron content of 0.8%. An additional 17kg high quality Al 2036 was required to dilute the Fe content to the maximum allowable content. The alloy compositions for Al 2036 and Al 380 alloys are as follows.

- Al 2036 alloy: Al 96.6%, Cu 2.6%, Si 0.5%
- Al 380 alloy: Al 89.4%, Fe 0.8%, Mg 0.2%, Mn 0.4%, Si 8%

Table 2-16: Exergy losses calculation for contaminated Al 2036 scrap used to produce secondary Al 380 alloy (Reproduced with permission from (Castro et al., 2007)).

Description	**Alloy/Mix**	**Mass (kg)**	**Elements (%)**			
			Al	**Cu**	**Fe**	**Si**
Contaminated Al scrap (2036)	Al 2036	108	96.9	2.6	0	0.5
	Fe	1	0	0	100	0
Melted contaminated Al scrap	Al 2036 + Fe	109	95.9	2.6	0.9	0.5
Dilution alloy	Al 2036	17	96.9	2.6	0	0.5
Desired Al quality	Al 380	126	96.1	2.6	0.8	0.5

2.13 System Dynamics Approach in LCA

The LCA method often reflects the ‘snap-shot’ condition that can be accurate for a certain period of time, but does not account for the dynamical changes over time (Finnveden, 2000; Stasinopoulos et al., 2012b). A dynamical model that contemplates the system behaviours over time by considering the environment, economy, and social aspects would give a better interpretation of the vehicle life cycle analysis (Kloepffer, 2008). In most LCA studies, assumptions are common practice for simplification but the range of limitations restricts the opportunities to assess the real scenarios for the whole life cycle. The limitations of dynamic characteristics can be accounted for using the System Dynamics (SD) approach (Changsirivathanathamrong et al., 2007; Stasinopoulos, 2013; Udo et al., 2004).

SD is a widely used method to unravel the dynamic complexity of a system through mental models, and to aid effective decision-making (Sterman, 2010). These mental models are used to understand how the structure of the complex system affects their behaviours. Therefore, SD modelling has been used by managers and policy-makers to analyse policies and strategies, taking into account the dynamic changes affecting the economic, technological, social, and environmental factors, to address critical issues in the automotive sector. The uncertainties in fuel consumption, driving intensity, fleet-based product, and vehicle management systems are some of the issues that have been addressed in past research (Armah et al., 2010; Halabi and Doolan, 2013; Kumar and Yamaoka, 2007; Rodrigues et al., 2012; Stasinopoulos et al., 2012a).

SD is one of the suggested strategies to complement LCA to account for the temporal dimension, wider scope, and larger data range of life cycle impacts (Finnveden et al., 2009; Sandén and Karlström, 2007; Udo et al., 2004). To extend the standard LCA to account for the dynamics of a large system, such as the vehicle system, (Udo et al., 2004) have suggested to only include a few core dynamics in the modelling task for simplification purpose. The extension of LCA through the core dynamics is applicable when there is a connection with the LCA modelling phases. This strategy integrates LCA and SD to generate a single set of results. An SD approach in LCA allows for changes in the wider system over the product life cycle which results in a more realistic estimation of the environmental impact. Therefore, the limitations of static or standard LCA approach can be overcome using dynamical modelling ((Ekvall et al., 2007). Based on the previous studies (Stasinopoulos, 2013; Stasinopoulos and Compston, 2014), SD approach has proven to be a viable tool for the assessment of dynamical vehicle life cycle analysis. The dynamical life cycle approach has the potential to integrate the strengths of two different tools (Clift et al., 1998; Udo et al., 1994).

2.14 This Work

Vehicle manufacturers have focused on the use of lightweight materials and multi-material concepts to produce more sustainable vehicles. This has resulted in significant reduction of CO_2 emissions during use phase to achieve the strict vehicle emission standards. Nevertheless, the varied range of joining techniques used to join multi-material vehicle designs presents challenges at the end-of-life, especially the feasibility of current recycling processes to recover materials in a closed-loop recycling (see Section 2.6). LCA has been widely used to assess the environmental impacts throughout the vehicle life cycle stages. However, the correlation between the increasing development in new multi-material vehicle designs, and the commonly used shredding process for material recovery is not captured well in the current analysis (see Section 2.8).

The interaction between multi-material vehicle designs and their associated joining choices is critical to facilitate the reuse, remanufacturing, and closed-loop recycling of lightweight vehicles. One of the crucial factors that needs to be addressed is the gap between vehicle designs and the EoL phase. In recent years, the combination of lightweight materials, such as aluminium, AHSS, magnesium, composites, and fibre reinforced polymers, is widely used in the mass-optimised vehicle designs. This has consequently led to the increasing complexity in vehicle designs that limits the choice of joining techniques. The commonly used multi-material joining processes have further hindered perfect material liberation through the current shredder-based recycling processes. Therefore, the influence of joining techniques used for multi-material vehicle manufacturing needs to be considered in the life cycle analysis to optimise closed-loop material recycling, and to minimise valuable materials entering landfills.

This research emphasises on the challenges that hinder the closed-loop material recycling for lightweight vehicles, particularly on the decisions made during the early design phases. The main research question is:

> How does the choice of joining techniques used for lightweight materials affect the recyclability of vehicles' components and materials at the EoL phase through current recycling practices?

Aligned with the main research question, some other associated research questions are:

- What method can be used to assess the joining impacts during the recycling phase towards a closed-loop ELV recycling system?
- How does the shift towards the use of more lightweight materials affect the vehicle life cycle environmental impacts considering the continuous recycling loop and long-term delay in material degradation and valuable material losses?

LCA is an effective tool to quantitatively assess the environmental impact of vehicles. The standard LCA method is extended to account for the exergy losses, and to include core dynamics that allow the system behaviours to change over time based on the material and joining trends in vehicle industry. To address the influence of complex multi-material vehicle designs on current ELV recycling practices, exergy analysis is integrated into the recycling phase of vehicle LCA. An SD approach in LCA is chosen for this study to account for the dynamic behavioural patterns of the environmental impacts due to the changing vehicle designs, and their effects on the quality of recyclates. The interaction between vehicle design and recycling phases can be observed through the dynamical life cycle analysis by integrating the strengths of LCA and SD approaches.

Chapter 3

Research Methodology

3.1 Introduction

This chapter details the research methods used in this study. In the first section, the research strategy is described to provide an overview of the sequential phases from problem definition up to the dynamic model formulation. The next section explains the case study research methods and the industrial data collection processes used to gather in-depth information on material recycling efficiencies from a joining techniques perspective. The choices of assessment methods with their associated analytical tools are then discussed in line with the approach taken to address the research questions outlined in Chapter 2.

3.2 Research Strategy

To investigate a defined research problem, the aim and objective of the research need to be stated explicitly. This will then allow the implementation of a clear research strategy through an action plan that addresses the research questions (Singh and Bajpai, 2007).

An overview of the research processes and steps taken in this study is shown in Figure 3-1. During the exploratory phase, data on the vehicle's material composition, joining technique trends, and the commonly used recycling processes in industry was collected. The information provided a better understanding of the current trends and the extent of work already accomplished both in theory and in practice through academic research and industry. The knowledge gap between the choice of joining techniques and the ELV recyclability in current recycling practices was identified. This was then used as the foundation to formulate the research questions during the theory development stage.

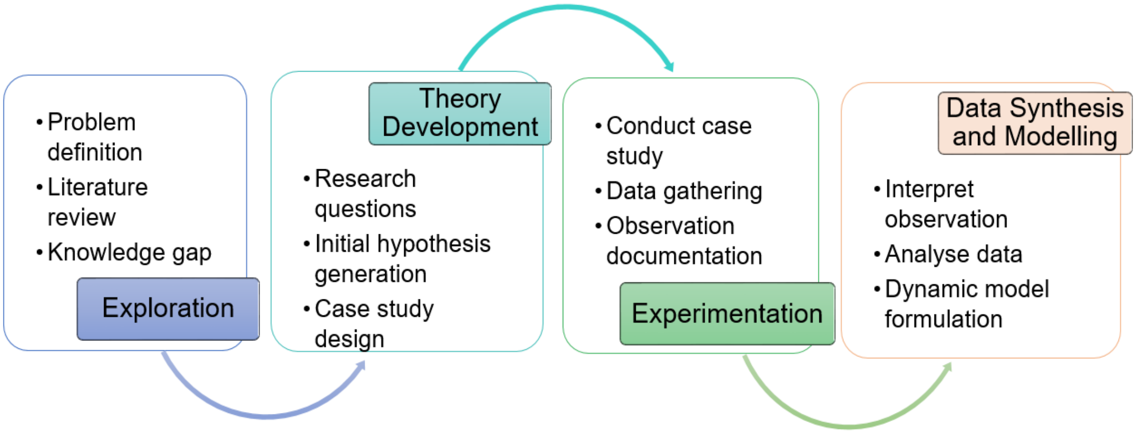


Figure 3-1: Steps and phases of the research process used in this study (Eisenhardt, 1989; Tellis, 1997; Yin, 2007).

Based on the research questions, the types of data to be collected were identified, and the associated research methods were used to assist the experimental design phase, as can be seen in Table 3-1. The three research questions highlighted in Chapter 2 are as follows.

RQ1: How does the choice of joining techniques used for lightweight materials affect the recyclability of vehicles' components and materials at the EoL phase through current recycling practices?

RQ2: What method can be used to assess the joining impacts during the recycling phase towards a closed-loop ELV recycling system?

RQ3: How does the shift towards the use of more lightweight materials affect the vehicle life cycle environmental impacts considering the continuous recycling loop and long-term delay in material degradation and valuable material losses?

The main research method used in this study was exploratory case studies. This type of case study research aims to explore a phenomenon that has not been well investigated in the past, and to use the observations to initiate further examination for future study (Yin, 2007). This method was chosen to investigate the influence of joining techniques on ELV recycling based on the feasibility of current recycling practices. The case studies were designed with an exploratory motive based on the developed research questions due to the lack of literature data or past research on the influence of joints on vehicle recycling. Industry experiment data was collected and they served as an initial step to assess the characteristics of joints that hinder ELV recycling. The case study research method is described in Section 3.3.

Table 3-1: The types of data and research relevant to the research questions of this study (Johnson and Onwuegbuzie, 2004; Kothari, 2004).

Research Question	**Subject**	**Description**
RQ1 and RQ2	Research Type	Exploratory, empirical observation, quantitative
	Data Type	*Qualitative data:* Observations on the types of joining techniques and the characteristics of joints causing impurities in the recycling facility *Quantitative data:* The number of joint input and the fraction of unliberated joints in different output streams
	Main Outcome	a) Develop initial understanding of the characteristics of different joining techniques and their implication on recycling efficiency and waste produced in current recycling practices b) Quantify the fraction of unliberated joints
RQ3	Research Type	Exploratory, empirical observation, quantitative
	Data Type	*Qualitative data*: The use of unstructured data, such as raw text and observed trends, to conceptualise the behavioural patterns of the vehicle recycling systems *Quantitative data:* Impurities due to joints for different output streams and the types of impurities
	Main Outcome	a) Assess the vehicle life cycle environmental impacts including exergy losses quantitatively b) Develop the dynamical recycling model based on the environmental performance

The final steps were the data synthesis and modelling phases. In these steps, two main analytical tools were used: LCA and SD approach. LCA method was used to assess the environmental impacts of vehicle life cycle quantitatively since it is commonly used among vehicle manufacturers to determine the environmental improvement potentials. Based on the data collected, vehicle life cycle analysis emphasising on the design and recycling phases was carried out to investigate the consequences of vehicle design trends, material quality loss, and legislative boundaries. However, the lack of temporal information has limited the accuracy of LCA results to assist in decision-making process (Udo et al., 2004). To overcome this limitation, LCA integrated with SD approach is proposed to account for the temporal effect and changing behaviours in a complex system (Levasseur et al., 2010). Using this approach, the dynamic vehicle life cycle inventories were computed to investigate the changing environmental impact outcomes. The challenges associated with the varying material recycling efficiencies observed from the analysis were then used to formulate the dynamical hypothesis of the vehicle recycling model that accounts for temporal effect.

3.3 Research Methods

This section discusses the choice of research methods used to collect data in this study. The analytical techniques used to interpret the collected data to provide insightful results are then explained.

3.3.1 Industrial Experiments

Industrial case study approach was the main research method used for this study due to the lack of data in literature on the interaction between complex multi-material vehicle designs and their associated joining techniques, and the challenges at EoL phase. This approach was preferred in comparison to the lab-based experiments to account for the actual shredding scenario in large-scale recycling facilities that takes into consideration the diverse conditions lacking in a controlled environment. This is critical to provide new insights into the influence of joints on the material separation efficiencies through current recycling practices that is not widely available.

To generalise the empirical evidence on the types of joining techniques likely to create difficulty through different recycling approaches, multiple case studies were performed in different countries, as can be seen in Figure 3-2. In this approach, general conclusions can be drawn based on the findings from the multiple case studies carried out under different conditions or scopes (Mills et al., 2010; Wieringa, 2014). Two industrial experiments were conducted in different geographical regions (Australia and Belgium) to investigate the types of joining techniques likely to cause impurities in the valuable output streams, and material losses in the ASR stream through different recycling approaches. The outcomes from the case studies were used to generalise the types of joining techniques and joint characteristics causing imperfect material liberation during ELV recycling to address the first research question (RQ1). Additionally, the differences observed from the case studies allowed more specific recommendations on design guidelines (materials and connections) and recycling approaches to improve the material recycling efficiencies across a broad range of cases. The information was then used to describe the distinct system behavioural patterns for the ELV recycling scenarios based on the legislative boundaries and environmental performance.

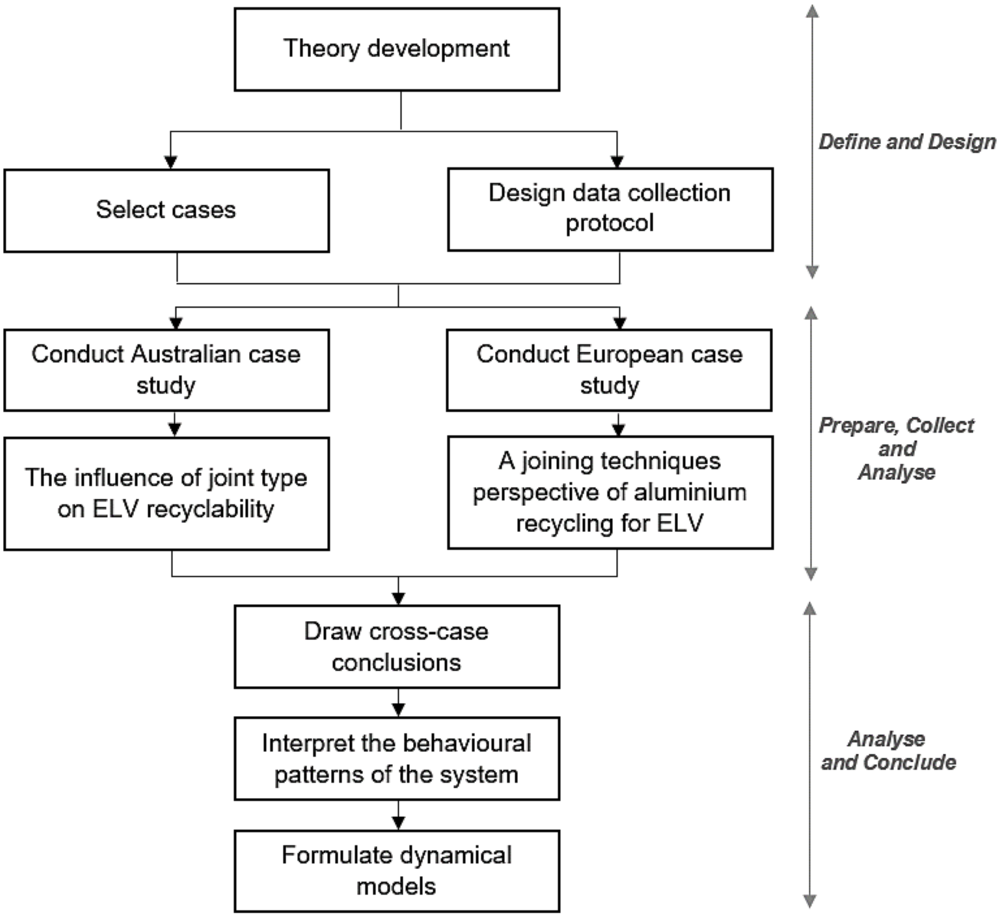


Figure 3-2: Multiple case studies approach used for this study (Adapted from (Yin, 2007)).

3.3.2 Case Study Data Analysis Techniques

Case study data can be analysed in different ways. A clear analytical strategy is essential to assist interpreting the results more effectively to answer the “how”, “what”, and “why” research questions that have led to the case study experiments. The analytical techniques used to examine the case study results were pattern matching, cross-case synthesis, and time-series analysis (Anfara Jr et al., 2002; Yin, 2007). These techniques were chosen to form a robust case study analysis that ultimately provide compelling outcomes based on the industrial experiments.

Pattern matching technique was used to match the empirical experiments to the patterns of the initial generated hypothesis (Eisenhardt, 1989; Trochim, 1989). This method allowed the pattern behaviours of vehicle material and joining trends observed from past research to be matched with the observed patterns from each case study analysis. The matching process between the conceptual patterns based on past vehicle trends, and the observed patterns from the individual case study can be seen in Table 3-2. For this study, when the observed patterns matched with the predicted conceptual patterns from past research, a solid conclusion was reached to support the initial hypothesis: joining techniques used have an effect on the ELV recyclability.

Table 3-2: Pattern matching technique used to compare the impact of vehicle design trends on vehicle recycling based on conceptual patterns (from literature) and observed patterns (from case studies).

Conceptual Patterns (Based on Literature)	**Source of Observed Patterns (Case Studies)**
• The complexity of multi-material vehicle designs has limited the choice of joining techniques that cater for the combination of different material types (e.g. mechanical fasteners, adhesive bonding, etc.) • Multi-material combinations have led to the increasing use of joint with dissimilar material types	Material and joining audits from the Australian case study
• The choice of joining techniques used for multi-material designs will influence the material liberation level	Shredded output analysis from the Australian case study
• The current shredder-based recycling processes will no longer cater well for optimised material recycling efficiency for newer vehicle designs and their associated joining techniques • The increasing complexity in multi-material designs will increase the use of non-renewable resources due to unliberated joints	Recovered Al analysis from the Belgian case study

To reflect on the observations obtained from the case study analysis for multiple cases, cross-case synthesis technique was adopted. This technique was used to analyse the multiple case studies that were treated as individual case study. The observed patterns based on the “two-case” case study were then used to draw meaningful conclusions (Mills et al., 2010). The analysis process for cross-case synthesis is very similar to pattern-matching approach except that the final conclusion is based on the overall pattern observed from multiple case studies rather than the individual case study outcomes (Yin, 2011, 2007). For cases where two different case studies are conducted with the same objective under different conditions or procedures, the cross-case synthesis provides a strong, plausible, and robust argument that are supported by the case studies' data. In this study, the results obtained from the Australian and Belgian case studies were aggregated to further validate the joint types more likely to cause impurities and valuable material losses for different output streams.

The final technique used to analyse the case study outcomes was time-series analysis (Yin, 2011, 2007). This technique is critical for this study due to the significant influence of temporal effect on the generated pattern behaviours for different ELV recycling systems. Time-series analysis was carried out to observe the vehicle trends from the case study data against the predicted time-series pattern behaviour from a broader system boundary perspective. Based on previous studies, the focus on GWP contributed by the vehicle use phase has shown significant improvement in vehicle CO_2 emissions through lightweight vehicles. The changes in vehicle designs have consequently led to increasing waste produced and natural resources consumption during the recycling phase that are not well considered in current life cycle analysis. This limitation needs to be addressed through more effective approaches. Through time-series analysis, the rebound effects of the current vehicle trends on the vehicle life cycle analysis are highlighted. The dynamic pattern behaviours of changing vehicle trends, and the use of different recycling processes are presented based on the observations from the case studies.

3.4 Analytical Tools

To perform the analysis for this study, several tools were utilised to achieve the research objectives, as can be seen in Table 3-3. The three main analytical tools used were LCA (ISO, 2006), exergy analysis (Cornelissen, 1997), and the SD approach (Sterman, 2010). Exergy analysis and SD approach were integrated into the standard LCA to produce a dynamical life cycle assessment that takes into consideration the temporal effects of material and joining trends on ELV recyclability. As reviewed in Chapter 2, the increasing challenges for optimised material recycling, and the lack of temporal dimension in current vehicle LCA hindered a holistic life cycle analysis. Therefore, exergy analysis was integrated into LCA to account for the material and quality losses during the vehicle recycling phase. An SD approach was then used to describe the dynamic behaviour patterns of the vehicle recycling systems from the environmental and legislative perspectives using widely known system archetypes.

Table 3-3: The analytical techniques and their respective tools used to address the research questions of this study.

Analytical Techniques	Analytical Tools	Addressed Research Questions
Pattern matching	LCA, ELCA	RQ1, RQ2
Cross-case synthesis	LCA, ELCA, SD approach (System Archetype)	RQ1, RQ2
Time-series analysis	LCA, ELCA, SD approach (System Archetype)	RQ1, RQ2, RQ3

An overview of the incorporated analytical tools to produce a dynamical life cycle analysis is shown in Figure 3-3.

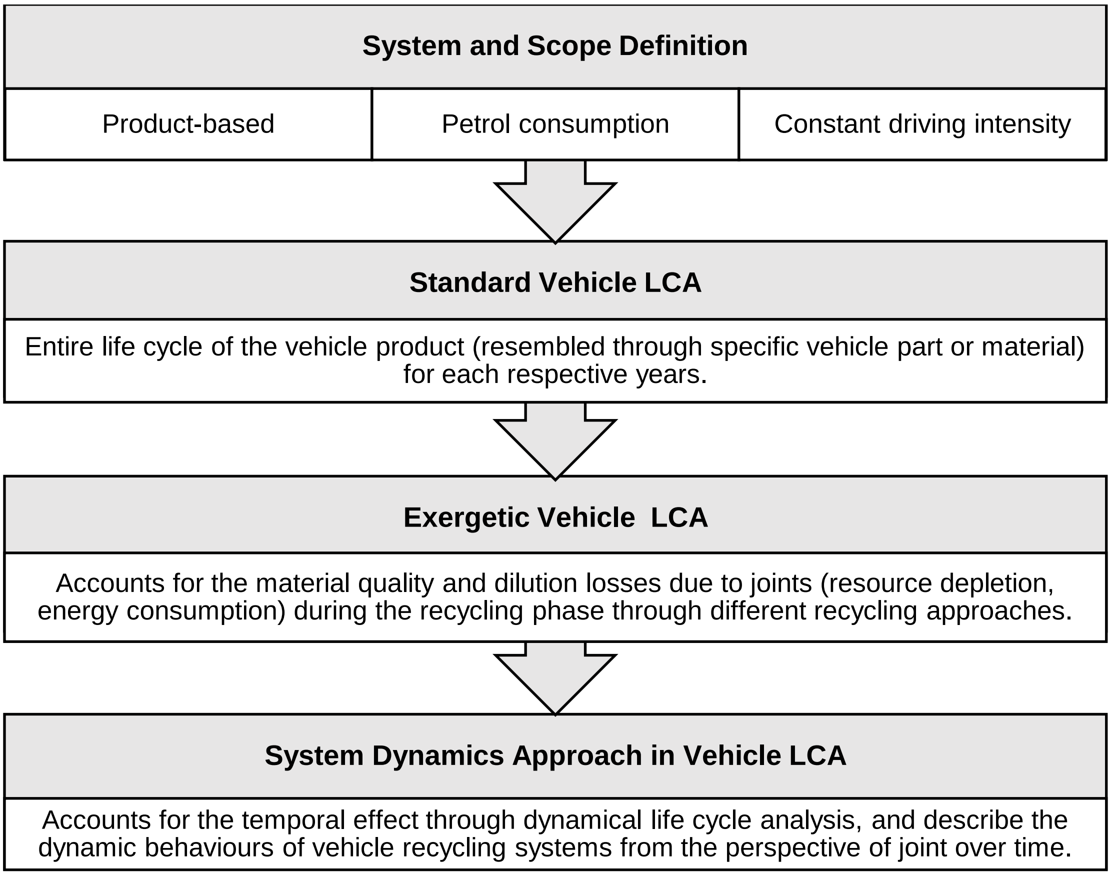


Figure 3-3: General description of the integrated analytical tools of this study.

3.4.1 Exergetic Life Cycle Assessment

To quantify to what extent the unliberated joints are affecting the different output fractions, ELCA method was used to integrate dilution and quality losses, and to replace valuable materials lost in ASR through the current vehicle life cycle analysis. This method accounts for the limits of metallurgical recycling in a closed-loop system that are lacking in standard vehicle LCA used to assist vehicle manufacturers in decision-making. The integration of exergy analysis into standard LCA provides quantitative measures to optimise closed-loop recycling from a joining techniques perspective that can address the second research question (RQ2).

Exergy analysis was used to demonstrate the material and quality losses that lead to the depletion of natural resources and energy consumption to account for a more realistic recycling scenario. This method was incorporated into standard LCA to represent the closed-loop recycling of complex vehicle designs. The framework is similar to the standard LCA (ISO, 2006) except for the more extensive inventory analysis during the vehicle recycling phase (Cornelissen, 1997; Jeswani et al., 2010). The additional environmental burden associated with EoL phase is highlighted in Figure 3-4.

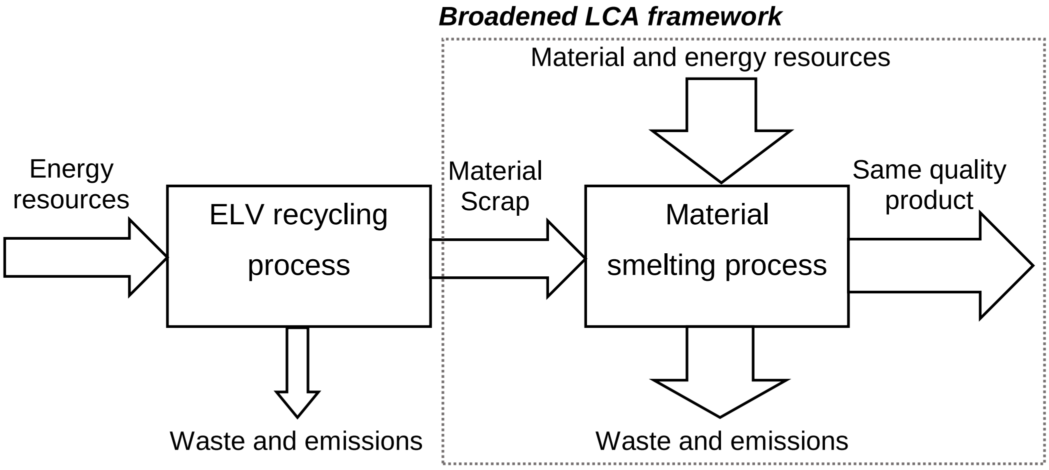


Figure 3-4: Integration of exergy losses into standard LCA for a closed-loop recycling system.

GaBi software was used to model the vehicle's life cycle. A complete vehicle LCA was modelled using the energy system, materials, and transport data available in the GaBi Professional database to reflect the inventory information obtained from case studies. The entire life cycle was included in the life cycle analysis that consisted of production (material extraction and manufacturing), use, and EoL (metallurgical recycling) phases. This software tool is widely used by vehicle manufacturers to assess the environmental performance of their products, and to assist in decision-making for product sustainability through process modelling.

3.4.2 System Dynamics Approach in LCA

There is a lack of consideration for the changing multi-material vehicle design trends and their associated joining techniques on the decreasing quality of recycled materials. The impacts of changing vehicle designs on ELV recyclability have become increasingly important due to the rapid development in lightweight multi-material vehicles. Therefore, these parameters need to be critically assessed using mental models to address the dynamical changes over time. In this study, SD modelling is suitable to explore the complex problem in the automotive industry due to the following reasons:

- It helps to understand the main causes and consequences that in turn allow the anticipation of obstacles and challenges for a closed-loop recycling system.
- It is a suitable approach to develop an understanding of the main causes that lead to the gap between vehicle design and recycling phases.
- It outlines the boundary of the complex vehicle recycling systems to allow better understanding of the underlying problem.
- It offers an effective outcome by discovering the relationships and connections between the trends of material combinations with their choice of joining techniques, and the vehicle recyclability from a holistic perspective.

To account for the lack of temporal effect in vehicle LCA, SD approach was incorporated as it addresses the dynamical vehicle life cycle over time. SD models were used to explore the complexity of vehicle recycling systems, and their interactions between different life cycle phases. This approach examines the problem from a broader view of the interconnected systems to allow a better understanding of the gap between changing vehicle designs and their effects on the ELV recycling. An SD approach was used to interpret the dynamics in vehicle designs, and how they can affect the critical parameters that determine the vehicle life cycle environmental impacts over time to address the third research question (RQ3). One of the key challenges that was closely examined is the long-term delay of increasing dilution, quality, and material losses that are not well captured in most vehicle life cycle analysis, as shown in the Figure 3-5.

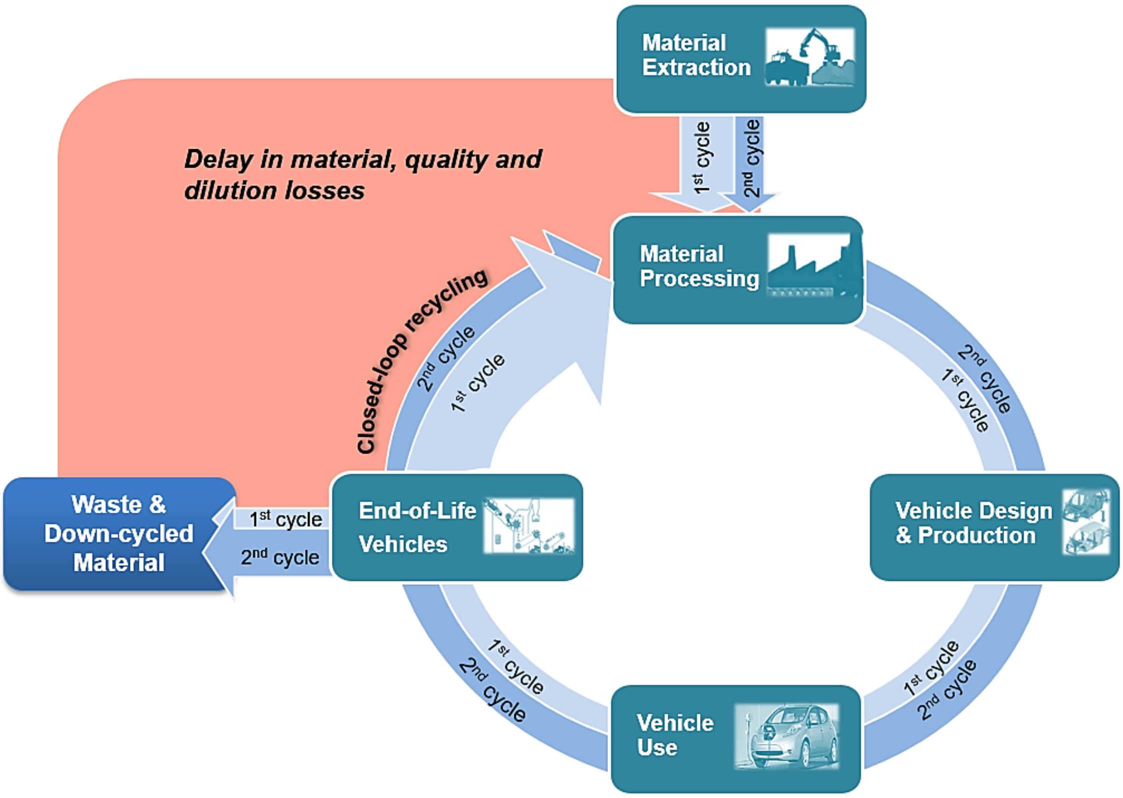


Figure 3-5: The challenges of closed-loop material recycling in the recursive vehicle life cycle.

The influence of joints on the material recyclability was measured through the exergy losses to be included in the dynamic vehicle recycling models. The variation in life cycle inventory data affected by the material, quality, and dilution losses was included based on the influence of joint types on the presence of impurities or the valuable material losses. With such comprehension of the dynamics in the vehicle recycling systems, high-leverage policy framework can be implemented by anticipating the system behaviour outcomes. This level of understanding for a complex system is limited through the standard LCA method largely used by the vehicle manufacturers. The framework for a dynamic LCA method can be seen from Figure 3-6.

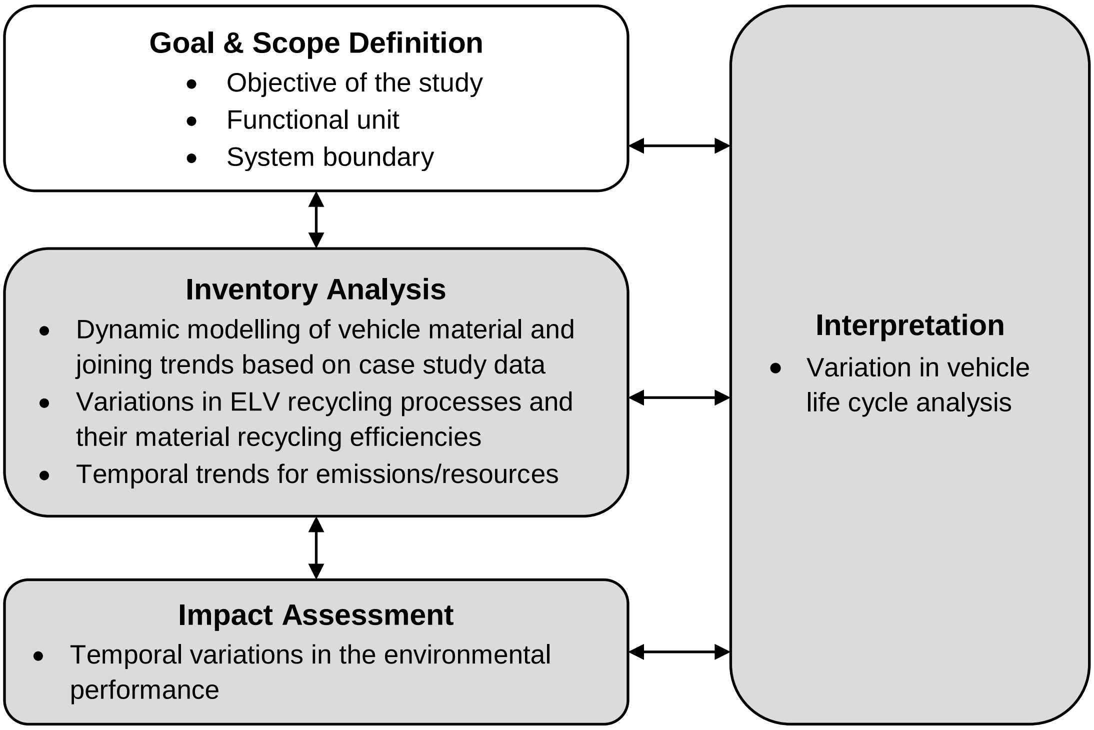


Figure 3-6: Methodological framework and phases of dynamic LCA approach. The phases differed from the standard LCA framework are highlighted (Adapted from (Collinge et al., 2013; Levasseur et al., 2010; Pehnt, 2006)).

SD mental models were conceptualised based on the behavioural patterns of the vehicle recycling systems observed from both case studies in Australia and Europe (Sterman, 2010). The characteristics of the dynamical vehicle recycling models can then be further classified into the respective systems archetypes—expression of the system's pattern behaviour—to examine the problem, and the underlying situation that leads to the problem (Wolstenholme, 2003). System archetypes are system thinking tools that assist in the categorisation of pattern behaviour to familiar dynamic systems through basic structures (Kim and Anderson, 1998; William, 2002). This tool allows the depiction of the problem through key variables, developed structure-behaviour pairs, and the understanding of the historical behaviour and observations from industry data in time series to be matched to well-known pattern behaviours. To formulate the dynamical hypothesis for the influence of joints on vehicle recyclability, system archetypes were used in four different approaches (Kim and Lannon, 1997):

- To identify unique insights for different archetypes and how they can potentially be used to describe the problem under study (using archetypes as "lenses").
- To resemble the main feedback loops for vehicle recycling by comparing them to the basic structural patterns or loop structures (i.e. causes and effects).

- To theorise the dynamic behaviours of the vehicle recycling systems based on the observations from case study data complemented by historical trend.
- To predict the likely behaviour in time series based on the current behavioural patterns, and identify early actions that can be taken to achieve a desired outcome. This serve as the first step to produce qualitative models that can then be used as the foundation for generating quantitative SD models.

The cause and effect relationships between different life cycle phases observed from the case studies were determined using the general behavioural patterns that can be interpreted through fundamental structures representing the basic system archetypes. Based on the identified system behaviour, effective measures can be taken to resolve fundamental issues, or anticipate the consequences of planned actions. The integration of system archetypes into the SD modelling process is summarised in Figure 3-7. STELLA software (version 10.0.3) was used to illustrate the vehicle recycling models for this study.

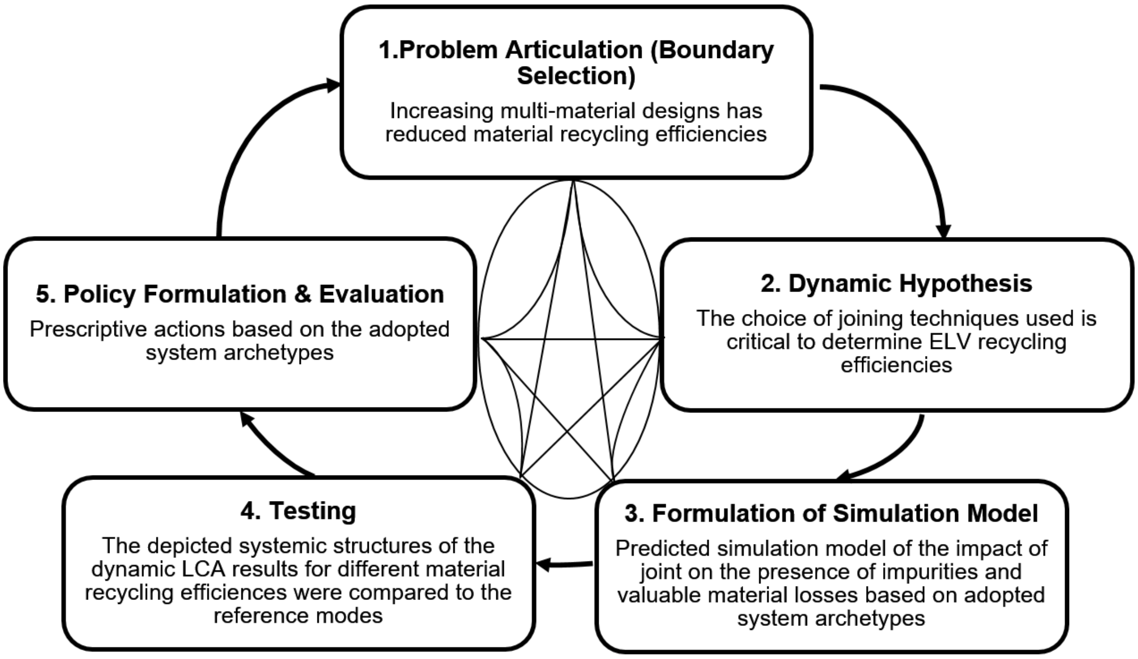


Figure 3-7: Overview of the iterative SD modelling process applied in this study (Adapted from (Sterman, 2010)).

3.5 Concluding Remarks

This chapter presented the case study methods, data analysis techniques, and the respective analytical tools integrated for this study. To address the main research questions of this research, data collection through industrial experiments was one of the most crucial steps due to the lack of literature data on the implication of joining techniques on current ELV recycling practices. The data gathered on vehicle material and joining trends based on two industrial case studies was used to provide a quantitative assessment of the dynamical vehicle life cycle analysis, as will be detailed in Chapter 4 and Chapter 5. The interaction between new vehicle designs and ELV recycling was then interpreted based on the case study observations from the broader environmental and legislative perspectives. Based on the multiple-case study analysis techniques, the appropriate analytical tools were chosen: LCA, ELCA, and SD approach.

The integration of multiple analytical tools into the standard LCA was essential to broaden the LCA framework, and to account for the lack of temporal dimension. The effect of changing dynamics in vehicle multi-material designs on ELV recyclability is not well represented in the standard LCA. The recycling challenges associated with the complex multi-material designs, for instance, need to consider the exergy losses associated with the material quality in a closed-loop system. Therefore, exergy analysis was integrated into LCA to account for the material, quality, and dilution losses during ELV recycling. Additionally, the fixed function of time in LCA does not allow the environmental impacts associated with different life cycle stages to be interpreted through time. An SD approach was used to account for the relative temporal differences on the inventory data of LCA.

An SD approach in LCA was adopted to provide the ability to account for the dynamical changes in the vehicle life cycle environmental impacts. This approach was used to provide a better interpretation of the changing material designs and their impacts on various life cycle phases with time effect through mental models. The trends observed through the vehicle life cycle analysis were then used to interpret the current automotive industry based on widely known system archetypes. The application of system archetypes as the system thinking tools enabled the dynamic behaviours of vehicle recycling systems (illustrated through mental models) to be characterised to known structural patterns to assist the implementation of effective actions or policies, as will be discussed in Chapter 6.

Chapter 4

Relationship between Joint Types and Vehicle Recycling

Australian Case Study

Publications relevant to this chapter:

Soo VK, Compston P, Doolan M. Is the Australian Automotive Recycling Industry Heading towards a Global Circular Economy? – A Case Study on Vehicle Doors. *Procedia CIRP* 2016; 48:10-15.

Soo VK, Compston P, Doolan M. The Influence of Joint Technologies on ELV Recyclability. *Waste Management* 2017; 8:421-433.

4.1 Introduction

This chapter presents the case study on a specific vehicle part (car door) that represents the complexity of multi-material vehicle body structures in the Australian context. It can be divided into two main sections: environmental impact assessment for different vehicle designs; and the effective joining techniques to assist in ELV material separation in the current practices.

The first section provides comprehensive material data for a comparative LCA highlighting the presence of impurities during the recycling phase. A thorough material audit is carried out for the chosen vehicle part. The study also assesses the sensitivity of the life cycle impact under different EoL scenarios, to better understand the increasing challenges to achieve the sustainable circular economy.

The second section highlights the types of joining technologies used in the automotive manufacturing industry that hinder the sorting of ELV materials. The study is based on an industrial shredding trial of car doors in an Australian recycling facility. The characteristics of joints that lead to impurities and valuable material losses are investigated to understand how they can influence the material recyclability in the current sorting practices, and thus, minimise ELV waste. Correlation analysis is conducted to further support the influence of joining choices on material separation efficiencies.

4.2 Car Door Case Study

A vehicle door was chosen to understand the environmental impacts of different material designs, and how the different joining techniques can have an impact on material separation efficiencies during ELV recycling. The growing complexity of combining different material parts will influence the ecological footprint and the choice of joint types used. The vehicle door was used to represent the increasing complexity of new vehicle designs. It is one of the vehicle parts often targeted for multi-material concepts to further reduce the overall vehicle mass without compromising safety (Cui et al., 2008; Puri et al., 2009; Sakundarini et al., 2013). The vehicle door structure consists of many connected parts with a variety of materials such as metals for reinforcement (side impact beam), non-metals for interior door panels, and electronic components for the lock system and window regulators. Therefore, the material and joining techniques observed from car doors are representative of the trends in vehicle designs. It is important to note that the audit data obtained from the car door case study is not reflective of a vehicle's material composition.

Four vehicle door models were chosen for this case study to demonstrate the changing material composition and their associated joining techniques based on the Australian scenario. Vehicle door material audits were carried out for a full-size sedan Australian vehicle made in 1982 (Ford Falcon XE) and 1999 (Holden Commodore VT), a subcompact hatchback European vehicle made in 2009 (Ford Fiesta), and a subcompact hatchback Japanese vehicle made in 2013 (Mazda 2).

4.3 Environmental Impact Assessment

4.3.1 Goal and Scope Definition

This study assesses the environmental impacts of the material trend for different vehicle door designs using LCA in accordance with the ISO 14040 series. The environmental impacts associated with production, use, transportation, and recycling phase of vehicle doors were included. As door parts, such as outside rear view mirror, vehicle door hinge, and cylinder door lock were missing for some vehicle door models, the analysis excluded them for comparability. The analysis only considered gasoline consumption during use phase to represent the predominant fuel type in Australia. The sensitivity of the results for varying EoL scenarios was explored. To account for a more realistic cradle-to-cradle analysis, the effect of material quality loss, and the use of primary materials to produce acceptable secondary material grades were included using exergy analysis.

The functional unit was with respect to the production, use, and recycling of 0.1m^3 vehicle door with an average use life of 150,000km. This was chosen to allow comparability for the different vehicle door sizes. Transportation was included for the respective phases based on the location of the manufacturing site for the respective model and year. The Ford Falcon XE and Holden Commodore VT car doors only considered road transportation since they were locally made, whereas the Ford Fiesta and Mazda 2 car doors included the sea transportation because they were imported from Thailand.

4.3.2 Life Cycle Inventory

A thorough material audit was carried out for a vehicle door of each respective model via manual dismantling, as can be seen in Figure 4-1. The material types for each vehicle door part were observed, and their respective masses were recorded as shown in Table 4-1. The changing vehicle door material composition can be used to represent the material composition in vehicle body structures; conventional steels are increasingly replaced by lightweight materials such as plastics and composites.

Table 4-1: Mass percentage of material composition for different vehicle doors.

Material	**Falcon**	**Commodore**	**Fiesta**	**Mazda 2**
Steel, stainless steel (wt.%)	71.60	68.02	58.45	64.80
Aluminium (wt.%)	2.73	2.09	0.94	0.33
Plastics/composites (wt.%)	1.45	7.31	19.29	17.27
Copper, wire, brass (wt.%)	0	0.72	1.72	1.07
Glass (wt.%)	14.24	11.21	13.46	12.58
Other non-metals (wt.%)	9.98	10.65	6.14	3.95
Total mass (kg)	22.75	32.02	25.56	24.32

(a) Disassembled Ford Falcon XE made in 1982.

(b) Disassembled Holden Commodore VT made in 1999.

(c) Disassembled Ford Fiesta made in 2009.

(d) Disassembled Mazda 2 made in 2013.

Figure 4-1: Material audit for different vehicle models.

The vehicle doors were then normalised based on their respective volumes to be comparable. This was carried out to allow the different material designs fit into the standard vehicle door dimensions of an average passenger vehicle. Table 4-2 shows the normalised vehicle door mass for each model with fixed volume and size.

Table 4-2: Volume-based normalisation for different vehicle doors.

Description	**Falcon**	**Commodore**	**Fiesta**	**Mazda 2**
Estimated volume (m^3)	0.08	0.10	0.08	0.12
Mass per $0.1m^3$ (kg)	28.68	31.42	31.06	21.16

Table 4-3 shows the life cycle inventories for the different vehicle doors from cradle-to-grave that were modelled using the GaBi Professional v6.11 based on the material composition and assembly processes. The manufacturing processes for each material were considered based on the specific vehicle door parts. During the use phase, fuel efficiency improvements were included and estimated based on the kerb weight for each respective model during the entire use life, as shown in Table 4-4.

To account for the impact of material quality loss on LCA, additional high purity material in the next life cycle needs to be considered. In this study, only the presence of Cu impurities in the steel scrap was included in the analysis, and were estimated to be 0.26wt% (Brahmst, 2006; Worrell and Reuter, 2014). There was no contamination for the Ford Falcon XE vehicle door's steel scrap due to the absence of Cu in the material audit. The dilution process was based on the maximum Cu content of 0.04wt.% to be reused as cold rolled sheet (Castro et al., 2007; Savov et al., 2003). It was estimated that 1kg of steel scrap contaminated with Cu required 5.5kg of high purity pig iron to be added into the new mix/alloy to obtain the required steel grade. This was calculated based on the pig iron material composition obtained from (Kalpakjian and Schmid, 2013). The amount of pig iron used to dilute the Cu impurities present in different contaminated steel scraps representing the respective car door model is shown in Table 4-5.

Table 4-3: Vehicle door life cycle inventory (LCI).

Phase	Falcon	Commodore	Fiesta	Mazda 2
Production	**Steel –** steel cast part machining, steel cold rolled coil, steel sheet stamping and bending **Aluminium –** aluminium extrusion profile, die cast **Plastic/Composite –** Polypropylene and ABS injection moulding, Fibre reinforced SMC **Rubber –** Vulcanisation of synthetic rubber **Wire –** Copper wire with 0.06mm diameter **Glass** – Float flat glass **Leather** – PVC synthetic leather **Foam –** Polyurethane rigid and flexible foam			
Transportation	The distance was estimated to be 100 km via 27t payload capacity truck to assembly plant, shredder facility and landfill site			
Transportation (to distribution centre)	Estimated to be 200 km via 27t payload capacity truck (Coia, 2014)		Estimated to be 8,600 km via 200t bulk commodity carrier ship	
Use (150,000km)	16.7L/kg	12.6L/kg	9.5L/kg	9.8L/kg
Recycling	The recovery rates were estimated from literature, and resemble the current recycling practice in Australia. Value-corrected substitution method was used to resemble the down-cycling impact using the scrap credit LCI data from GaBi database **Steel/stainless steel** - 96% (Ferrão and Amaral, 2006a) **Aluminium** - 33.11% (averaged from (Gesing, 2004; U.S Department of Energy, 2013)) **Copper/wire** - 48% (Worrell and Reuter, 2014) **ASR** - Mixtures of plastic, rubber, glass, cardboard, foam, leather, and dust were landfilled			

Table 4-4: Estimated lifetime fuel consumption for each vehicle door model based on their respective kerb weights.

Vehicle door model	Kerb weight (kg)	Fuel consumption (L/100km)	Lifetime vehicle fuel consumption (L/150,000km)	Lifetime vehicle fuel consumption per mass (L/150,000km per kg)
Falcon	13201	14.7	22050	16.7
Commodore	1572	13.2	19800	12.6
Fiesta	1087	6.9	10350	9.5
Mazda 2	1038	6.8	10200	9.8

Table 4-5: Dilution of Cu impurities present in the steel scrap for each vehicle door model.

Vehicle door model	Mass (kg)		
	Contaminated steel scrap	Copper impurities	Pig iron used for dilution
Falcon	15.63	-	-
Commodore	20.93	0.05	115.12
Fiesta	14.38	0.04	79.06
Mazda 2	15.17	0.04	83.45

4.3.3 Life Cycle Impact Assessment

The midpoint indicators such as climate change, ozone depletion, human and freshwater toxicity, respiratory inorganic, ionising radiation, photochemical ozone formation, acidification, eutrophication, water and resource depletion are presented in Figure 4-2, Figure 4-3 and Figure 4-4. These midpoint impacts are based on the relative contribution to the 3 main areas of protection: human health, ecosystem quality, and natural resources (Huijbregts et al., n.d.; Renouf et al., 2015). Use phase is the major contributor to the environmental impacts except for the mineral and fossil depletion impact that is dominated by the manufacturing phase. Overall, the vehicle door has the greatest impact on human toxicity-cancer effects due to the discharge of heavy metals, such as chromium, arsenic, nickel, cadmium, lead, and mercury, to the freshwater during use phase.

Despite the environmental improvements observed for newer vehicle door designs as a result of better fuel efficiency, the positive environmental offset through recycling is showing a diminishing trend. The reduced use of steel materials for vehicle door manufacturing has caused a decreasing amount of materials recovered to be reused. In addition, the increasing use of plastic and composite materials has contributed to the reduction of positive environmental offset since they are currently landfilled.

The mineral, fossil and resource depletion has increased for newer vehicle door designs when compared to the Falcon XE vehicle door, as shown in Figure 4-2. This is largely contributed by the amount of Cu wires used as part of the electronic components for power window system. There is no improvement through the recycling phase due to the decreasing amount of Fe materials being recycled, and the low recycling efficiency for Cu and Al materials. It is worth noting that the material recycling efficiency may vary for different vehicle door models although a constant recovery efficiency was used in this case study for comparability.

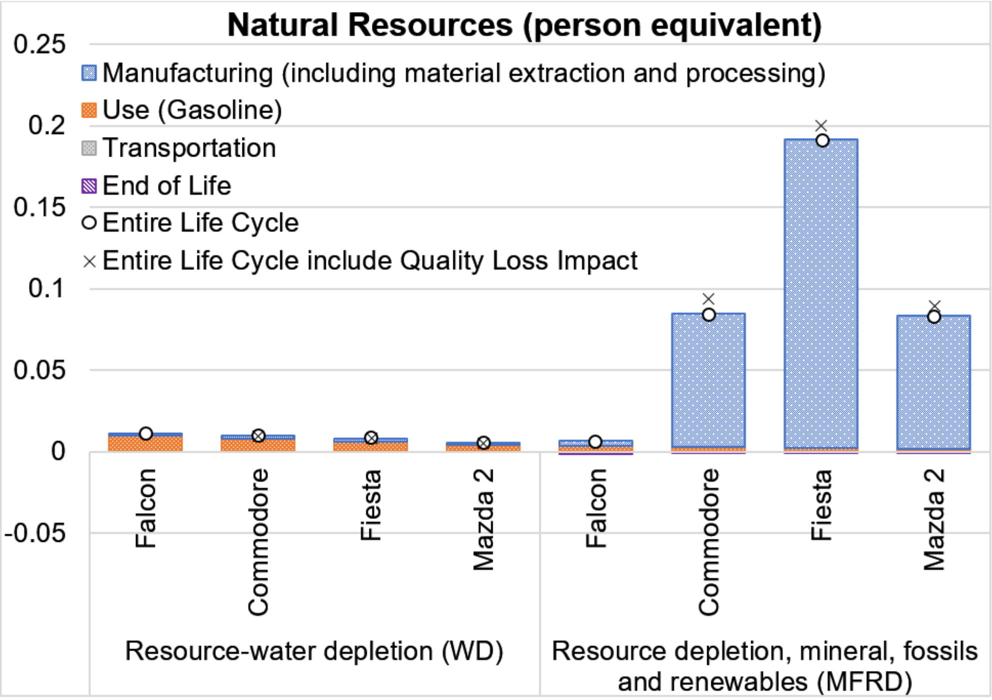


Figure 4-2: Midpoint indicators contributing to natural resources.

To account for a more complete life cycle analysis, steel quality loss due to the presence of Cu impurities was considered by including the dilution process using high purity steel. The steel degradation has a significant impact on the climate change, photochemical ozone formation, acidification, human toxicity, and terrestrial eutrophication as can be seen in Figure 4-3 and Figure 4-4. This is due to the air emissions, such as nitrogen oxides, carbon dioxide, and sulphur dioxide, during the extraction and processing of high purity steel used in the dilution process. Based on the climate change midpoint indicator, the environmental impact could potentially increase by more than 68%.

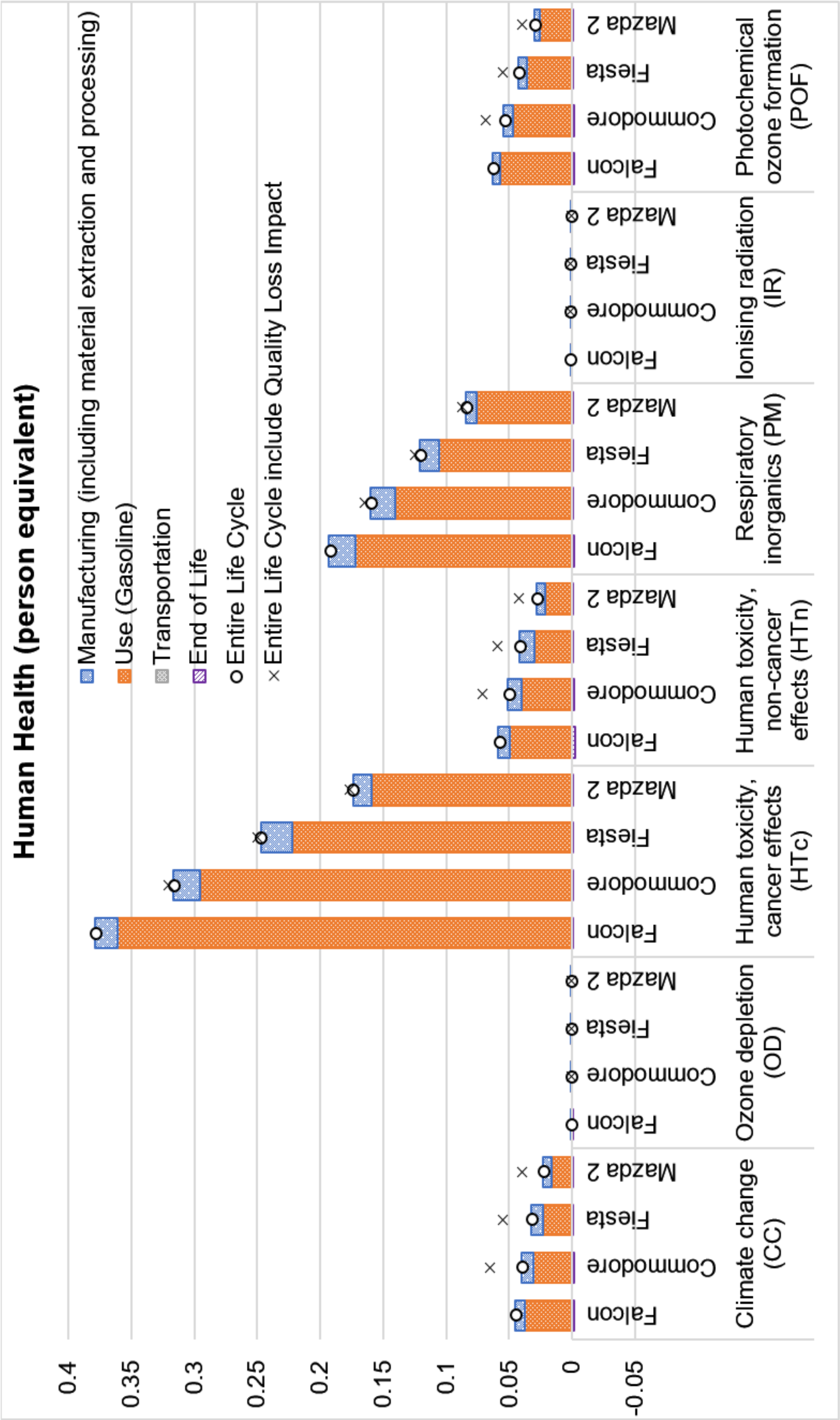


Figure 4-3: Midpoint indicators contributing to human health.

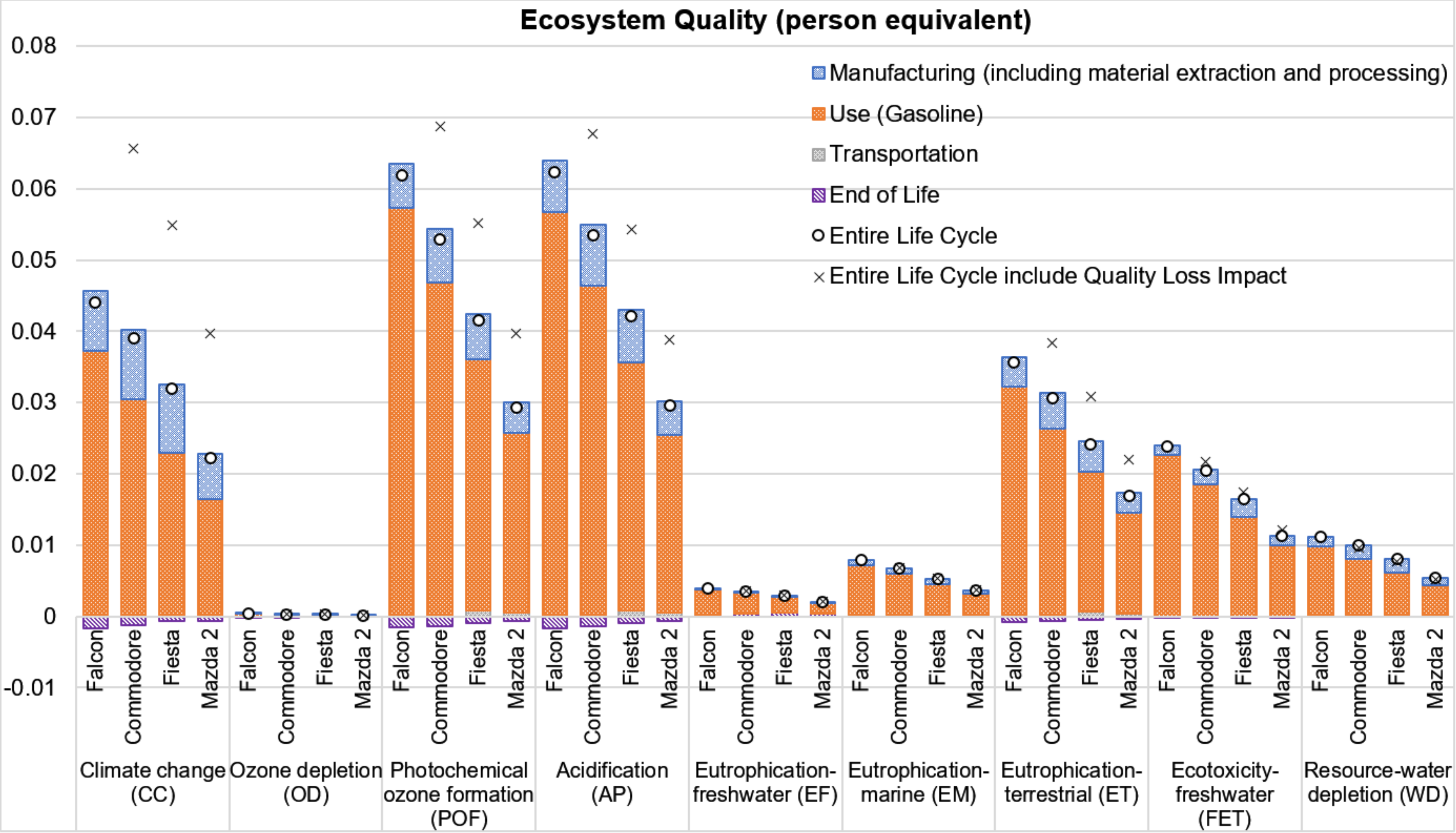


Figure 4-4: Midpoint indicators contributing to ecosystem quality.

4.3.4 Sensitivity Analysis

As shown in Table 4-6, a sensitivity analysis was carried out for different ASR recycling scenarios including landfill and material quality loss impact, plastic recycling, and ASR incineration. These recycling scenarios were compared to the base case of ASR landfill. Landfill and material quality loss scenario was excluded for Falcon due to the absence of Cu impurities. It is shown that the environment improvements are insignificant in comparison to the reference recycling scenario; nevertheless, plastic recycling offers an improvement of at most 25.87% as seen for the freshwater eutrophication in Ford Fiesta, whereas incineration increases the climate change impact by at least 1.26% for newer vehicle door design. Plastic recycling provides better environmental improvement in comparison to incineration. Therefore, ASR of mainly plastics should undergo further post-shredder treatment to improve the environmental performance in the recycling phase, particularly for newer vehicle door designs.

It is shown that the disposal of ASR in landfills caters well for the traditional vehicle door design rather than the newer vehicle door design. However, significant environmental improvement can be achieved for newer vehicle door design through plastic recycling and incineration. These new recycling approaches are not economically viable due to the low market demand for secondary plastic materials and the additional cost of incineration, although they provide better environmental performance. A sustainable circular economy would be increasingly challenging if the new recycling approaches are not market-driven and unprofitable.

Table 4-6: Sensitivity analysis for different ASR recycling scenarios with reference to the landfill as base case (%).

Vehicle Type	**Recycling Scenarios**	**CC**	**OD**	**POF**	**AP**	**EF**	**EM**	**ET**	**FET**	**WD**	**MFRD**
Falcon	Landfill (reference)	100	100	100	100	100	100	100	100	100	100
	Plastic recycling	99.79	99.35	99.92	99.92	98.63	99.60	99.92	100.01	100.10	99.99
	Incineration	99.93	99.21	99.69	99.64	93.41	99.57	99.72	99.12	100.11	99.01
Commodore	Landfill (reference)	100	100	100	100	100	100	100	100	100	100
	Landfill & material quality loss	168.57	122.44	129.91	126.48	101.40	102.60	124.99	105.55	96.34	111.53
	Plastic recycling	98.71	95.81	99.52	99.51	91.47	97.44	99.53	100.06	100.62	100
	Incineration	101.26	100.22	99.63	99.76	87.43	99.14	99.75	98.81	100.12	99.96
Fiesta	Landfill (reference)	100	100	100	100	100	100	100	100	100	100
	Landfill & material quality loss	172.20	125.49	132.85	129.06	101.45	102.84	127.30	105.95	96.12	104.37
	Plastic recycling	95.96	85.79	98.42	98.41	74.13	91.67	98.46	100.2	101.96	100
	Incineration	104.51	100.45	99.59	99.85	79.53	98.53	99.89	99.18	100.28	99.99
Mazda 2	Landfill (reference)	100	100	100	100	100	100	100	100	100	100
	Landfill & material quality loss	178.54	126.98	135.37	131.45	101.64	103.10	129.58	106.57	95.63	107.62
	Plastic recycling	96.36	87.53	98.59	98.57	75.85	92.45	98.62	100.19	101.83	100
	Incineration	104.11	100.40	99.69	99.91	82.15	98.76	99.95	99.41	100.27	99.98

CC: Climate Change; OD: Ozone Depletion; POF: Photochemical Ozone Formation; AP: Acidification; EF: Freshwater Eutrophication; EM: Marine Eutrophication; ET: Terestrial Eutrophication; FET: Freshwater Ecotoxicity; WD: Water Depletion; MFRD: Resource Depletion, Mineral, Fossils and Renewables.

4.3.5 Discussion

The commonly used LCA method to assist in sustainable manufacturing needs to address the down-cycling impact more effectively by considering the additional processes to recover targeted material quality. The analysis shows that the consideration for material quality loss produces a different environmental impact result in comparison to the standard practice that is crucial for a sustainable circular economy. The goal is not just to design for better EoL recovery but also to reduce the demand for natural resources, and sustaining the reusability of recovered materials at the same quality in a continuous closed-loop system. Additionally, the phase out of local manufacturing facility in the Australian automotive industry has led to the importation of vehicle. The environmental impact of transportation has increased due to shipping that is influenced by the distance travelled. Nevertheless, the contribution to the overall impact is still insignificant in comparison to use phase.

The increasing complexity in multi-material designs has further hindered material recycling with high purity. Consequently, the continuous extraction of natural resources is not prevented due to the demand for high purity material. The development in automotive manufacturing design has led to the improvement in use phase that is the major contributor to the overall environmental impact; however, it has also led to the exhaustive use of more natural resources, causing a rebound effect (Soo et al., 2015). Therefore, it is crucial to acknowledge the material degradation issue and ensure an optimised product design for recycling based on the current recycling practices.

There is a lack of understanding of the influence of joining choices for multi-material vehicle designs and their impacts on material separation efficiencies. In most LCA, material recycling efficiencies are often assumed to correspond to the input material composition that are not representative of the actual separation efficiency in common practices. Although previous works have focused on the impact of multi-material vehicle designs on vehicle recyclability (Gesing, 2004; Ribeiro et al., 2007; Sakundarini et al., 2013), it is unclear how the changing material trend affects the choice of joining techniques used. This in turn influences the efficiency of material recovered with high purity, and the amount of ELV waste entering landfills.

The next section highlights the types of joining technologies used in the automotive manufacturing industry that hinder the sorting of ELV materials. The characteristics of joints causing impurities and valuable material losses are observed through an industrial shredding process of car doors in Australia. This study is representative of the initial phases of current global ELV sorting practices. Although several past research have investigated the relationship between product design and the liberation behaviours during material separation (Castro et al., 2005; Van Schaik and Reuter, 2007), the outcomes have been limited to the observations from the output shredded streams. The relationship between known input joint data for multi-material parts, and the impurities or valuable material losses in output streams is investigated using correlation analysis to support the observations from this case study. This work provides new insights into the joint types to optimise the valuable material separation for increasing vehicle recycling efficiency.

4.4 Industrial Experiment

For this case study, the most popular Australian vehicles in the 1980s, 1990s, and 2000s were chosen to demonstrate the trend of changing material composition and their associated joining techniques. Each bale was created based on the car door models representing those period (Hagon, 2013): Ford Falcon representing Bale 1 (B1); Holden Commodore representing Bale 2 (B2); and Ford Fiesta and Mazda 2 representing Bale 3 (B3), as shown in Figure 4-5. The car doors were removed from the respective vehicle models available in the Australian auto recycler facility. The collection of car doors with similar design and material composition is important to allow the extrapolation of joint audit data for each respective vehicle door model for the entire bale.

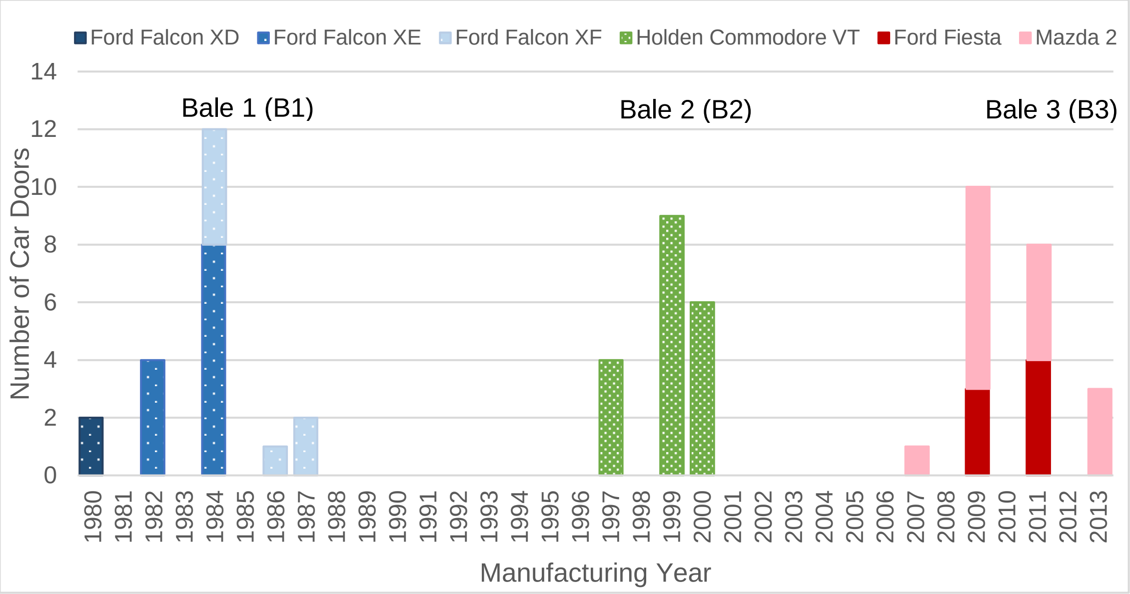


Figure 4-5: Vehicle door models representing different bales.

4.4.1 Material and Joining Techniques Audit

A thorough material audit and quantitative assessment of the joining techniques were carried out for a complete vehicle door model representing each bale, as seen in Figure 4-1. The types and number of joining techniques connecting each disassembled vehicle door parts were recorded during the material audit. The disassembled vehicle doors were not included for the respective bales. At the collection of vehicle doors from the auto recycler yard, each vehicle door (in assembled form) was inspected for missing parts to ensure the mass balance of input and output material flows. The different car door models were then sorted and baled accordingly to ease transportation to the shredder facility, as seen in Figure 4-6.

Figure 4-6: Baling process for the collected car doors representing each bale.

Upon arrival at the shredding facility, each bale was weighed. To ensure the conservation of mass throughout the recycling processes, the input and output material flows for baling and shredding processes were analysed, as seen in Table 4-7. During the baling process, material losses for the bales ranged from 6.6-10% due to the broken window glass. The window glasses shattered when they were transported to the compacter via a vehicle dismantling machine. The material losses for Bale 2 and 3 during the shredding process were consistent with the normal shredder operation in the facility, which is about 5%. Most of the material losses were fractions of light plastic, foam, fibrous material, leather or dirt due to the residual materials inside the shredder, shaker tables and conveyers; lost when moving the material through the conveyor systems; and gaps in the conveyor transition points.

Bale 1 showed significant material loss. The aged vehicle doors in Bale 1 consisted of steel rust, causing them to be weak. The material loss was assumed to be mostly fine steel rust trapped in the shredder during the shredding process. The cleaning process done prior to the trial allowed the fine fractions to fill in the large gaps and low points inside the shredder, thus allowing the materials in Bale 2 and 3 to flow better. This was further supported by the significantly low Fe recovery for Bale 1. Therefore, the additional 18% of material loss in Bale 1 was assumed to be fine steel rust that would be recovered through the magnetic separation process.

Table 4-7: Mass balance of output samples for different recycling processes.

Bale Category	**Baling Process**			**Shredding Process**		
	Total Input (kg)	**Total Output (kg)**	**Material Loss (%)**	**Total Input (kg)**	**Total Output (kg)**	**Material Loss (%)**
Bale 1 (B1)	500	450	10.0	450	346	23.1
Bale 2 (B2)	566	518	8.5	518	488	5.8
Bale 3 (B3)	473	442	6.6	442	420	5.0

The material composition of each bale was based on the material audit data for the respective vehicle door models, as can be seen in Figure 4-7. Material composition for missing parts was excluded. Most of the material trends observed from the vehicle door audit were representative of the current vehicle structure; thus, the joining choices used are reflective of the vehicle joining trends.

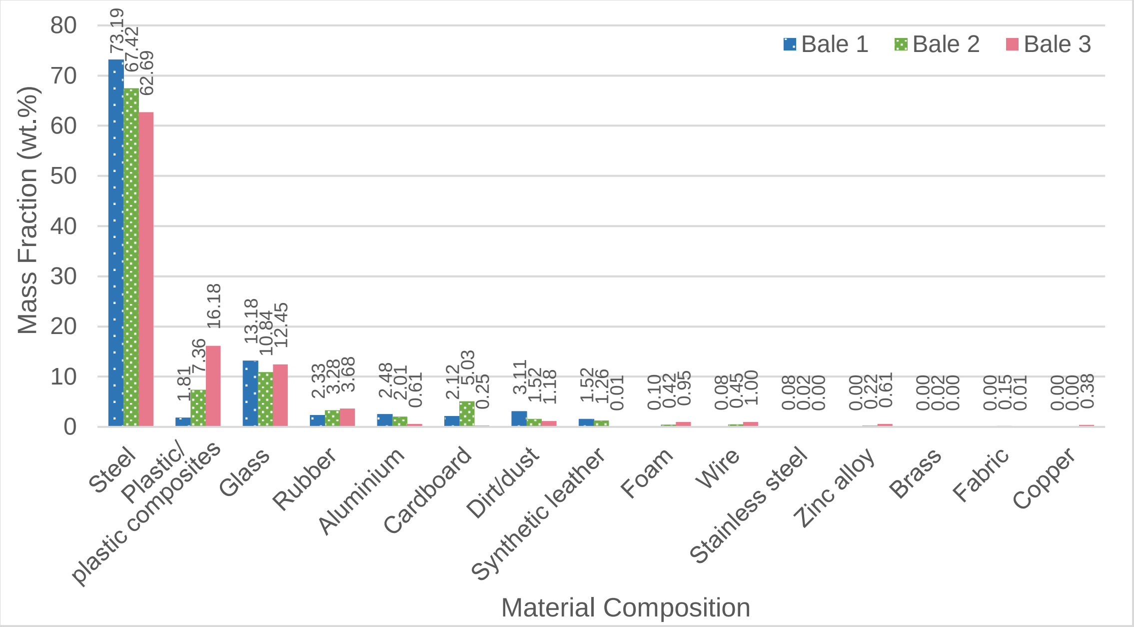


Figure 4-7: Material composition for different vehicle door bales.

The joining methods used to connect the vehicle door parts were assessed for a complete door representing each vehicle model, as seen in Table 4-8.

Table 4-8: Joining techniques used in different vehicle door models.

Joining Techniques	**Unit**	**Falcon**	**Commodore**	**Fiesta**	**Mazda 2**
MIG welding	m	-	0.46	0.27	0.47
Spot welding	unit	55	106	75	74
Rivet	unit	22	19	9	4
Screw/bolt	unit	21	50	40	45
Adhesive	m	7.18	16.18	10.20	9.57
Brazing	m	0.08	-	0.02	-
Plastic clip	unit	22	-	17	34
Plastic rivet	unit	6	2	46	22
Steel clip	unit	6	17	1	-

The data was then projected to represent the overall joining techniques in each bale by excluding joints associated with missing parts, as shown in Table 4-9. It is important to note that the joining audit for each bale is by no means representative of a car during that period. However, it provides quantitative information to understand the relationship between the joining techniques used and their associated impact on material separation efficiencies for different output streams.

Table 4-9: Overall joining techniques in different bales excluding missing part.

Joining Techniques	**Unit**	**B1**	**B2**	**B3**
MIG welding	m	-	8.65	8.83
Spot welding	unit	1153	2006	1635
Rivet	unit	460	319	180
Screw/bolt	unit	333	942	953
Adhesive	m	46.13	244.38	115.24
Adhesive/sealant—hemming	m	77.70	79.71	99.00
Brazing	m	1.68	-	0.11
Plastic clip	unit	157	-	619
Plastic rivet	unit	130	24	593
Steel clip	unit	126	84	7

4.4.2 Shredding Trial Procedures

The experiment carried out at the shredder facility, as shown in Figure 4-8, followed a rigorous set of procedures. The shredder facility was cleaned prior to the shredder trial. Containers and large industrial plastic sacks were placed at the 4 main output streams: ferrous (Fe), Non-ferrous (NF), stainless steel (SS), and ASR. The first bale was fed into the shredder during the initial start-up of the shredding process facility and all output streams were collected and labelled. The facility was run for an additional 10 minutes to ensure all materials from the first bale had reached their end points. The containers and plastic sacks were replaced at the output streams, and the second bale was fed in. The whole process was repeated for the third bale.

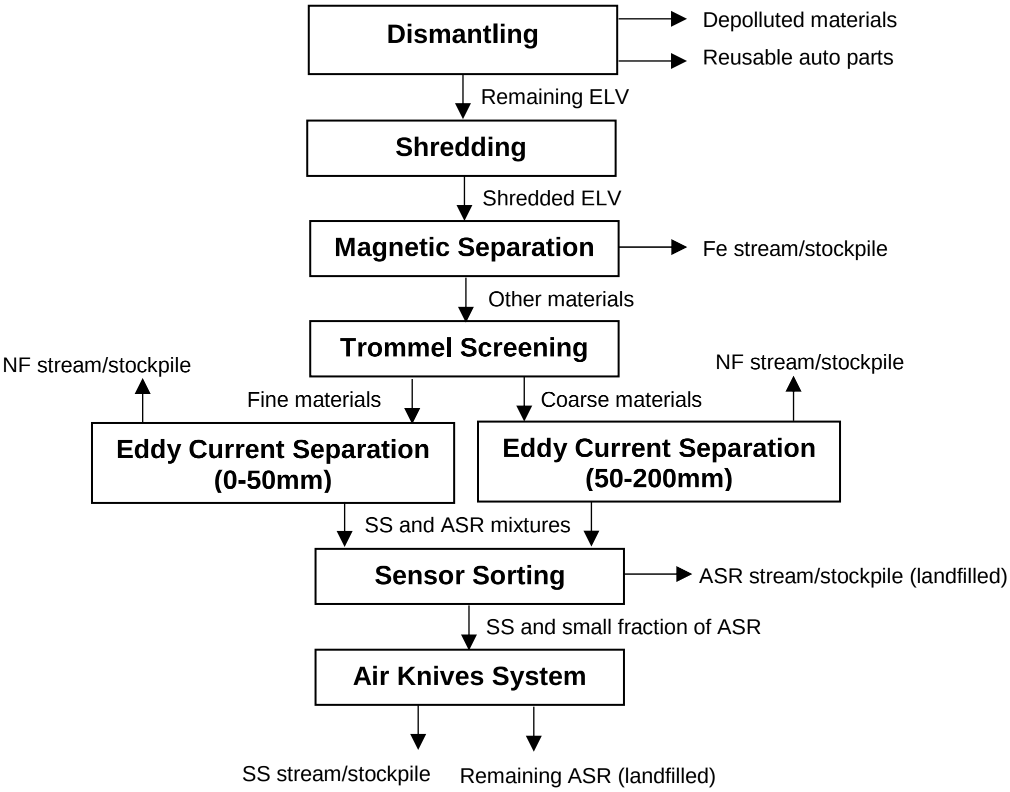


Figure 4-8: ELV material flows based on the current Australian recycling facility.

4.4.3 Sampling Method

The sampling method was conducted in accordance with the field sampling practice used in the Australian shredder facility. Samples were taken from the Fe and ASR output streams for each bale. Each sample was collected at random locations, and then mixed together for further analysis. The collected samples represented about 20% by mass of both the Fe and ASR stockpiles. All output materials from the NF and SS output streams were collected for analysis due to the relatively small output masses. The mass of samples collected for each output stream can be seen in Table 4-10. In this study, the SS stream was not further assessed due to the small amount of SS present in the vehicle door structure.

Table 4-10: Collected output samples for each recovered output stream.

Category	**Output Mass (kg)**				**Sampled Output Mass (kg)**			
	Fe	**NF**	**SS**	**ASR**	**Fe**	**NF**	**SS**	**ASR**
Bale 1 (B1)	274	8	0.3	64	66	8	0.3	18
Bale 2 (B2)	362	6	0.1	120	74	6	0.1	53
Bale 3 (B3)	294	2	0	124	56	2	0	24

4.4.4 Sample Analysis Procedures

The collected samples were sieved to different particle size classes using mesh sieves. A suitable size class range was chosen based on observations on the shredded particles' sizes for each respective output stream. Each particle was then sorted into 3 categories: liberated, liberated other material, and unliberated particles. Liberated particles consist of only one material type whereas, unliberated particles consist of at least two different materials that are still attached together. Liberated other material particles were particles of one material type that ended up in wrong stream due to separation errors. Unliberated particles were pulled apart, and the material types' composition was recorded with respect to mass. For cases where they could not be further disassembled, the mass of different material types was estimated based on the volume and material density. The number of joints causing impurities for each particle was recorded along with the joint type and characteristics.

To calculate the material recycling efficiencies for each output stream accurately, the mass of impurities was subtracted. The material recycling efficiency is defined by the following equations (Equations (3)-(5)).

$$Total\ impurities[x](kg) = Liberated\ other\ materials[x] + Unliberated\ impurities[x] \tag{3}$$

$$Recycling\ efficiency[x](wt.\%) = \frac{(Output[x] - Total\ impurities[x])}{Input[x]} \tag{4}$$

for which

$$x = \{Fe, NF\} \tag{5}$$

This step was also applied to the ASR stream to understand the fraction of valuable material losses given by Equation (6) and Equation (7).

$$\begin{aligned} Total\ material\ losses\ [ASR](kg) = {} & Liberated\ Fe[ASR] + +Liberated\ NF[ASR] + \\ & Unliberated\ Fe[ASR] + \\ & Unliberated\ NF[ASR] \end{aligned} \tag{6}$$

$$Valuable\ material\ losses\ [ASR](wt.\%) = \frac{Total\ material\ losses[ASR]}{Input[ASR]} \tag{7}$$

4.4.5 Relationship between Joint Input and Unliberated Joint Fraction

Based on the material and joint audit, only joints with dissimilar material types were considered. For example, steel screws used to connect two plastic parts were included in the number of screws input for the Fe stream. The fraction of unliberated joints was calculated for each respective joint type by extrapolating the sample results to represent the overall number in different output streams, as shown in Equation (8). The analysis was limited to the material combinations present in the vehicle door designs used in this case study.

$$Fraction\ of\ unliberated\ joint(x) = \frac{Number\ of\ unliberated\ joint\ output[x]}{Number\ of\ joint\ input[x]} \tag{8}$$

for which

$x = \{The\ respective\ types\ of\ joining\ techniques\}$

The Pearson product-moment correlation coefficient, *r* was used to determine the relationship between the joining techniques (total number of joint input) and the presence of impurities or material losses due to unliberated joints for different output streams, as shown in Equation (9). Although the amount of data used to calculate the correlation is small, the relationship provides an initial assessment to support the argument of joint types causing impurities or material losses in the output streams.

$$r\ (X,Y) = \frac{\sum(X-\bar{X})(Y-\bar{Y})}{\sqrt{\sum(X-\bar{X})^2(Y-\bar{Y})^2}} \tag{9}$$

for which

$X = \{Total\ number\ of\ Joint\ Input\},\ Y = \{Impurities/Material\ Loss\ in\ Output\ Streams\}$

4.5 Experiment Results

Data collection was conducted in a controlled environment to understand the material and joint inputs, and their corresponding outputs after the shredding trial. The joint types causing impurities and material losses were characterised. The relationship between the input joint audit data was plotted against the fraction of unliberated joints obtained from the output samples. This is to support the characteristics of joint types causing impurities and material losses observed in the output streams.

4.5.1 Impurities due to Joints in Fe Stream

From Figure 4-9, it is observed that most of the shredded particles were of larger sizes (more than 100mm), accounting for at least 77.9wt.% for each respective bale. Most of the other liberated materials were ASR such as fabric and foam. There is an increasing trend of unliberated particles with particle sizes greater than 100mm for newer designs. In contrast, liberated particles are showing a decreasing trend. This study focused on unliberated materials to understand the cause of the impurities due to joints.

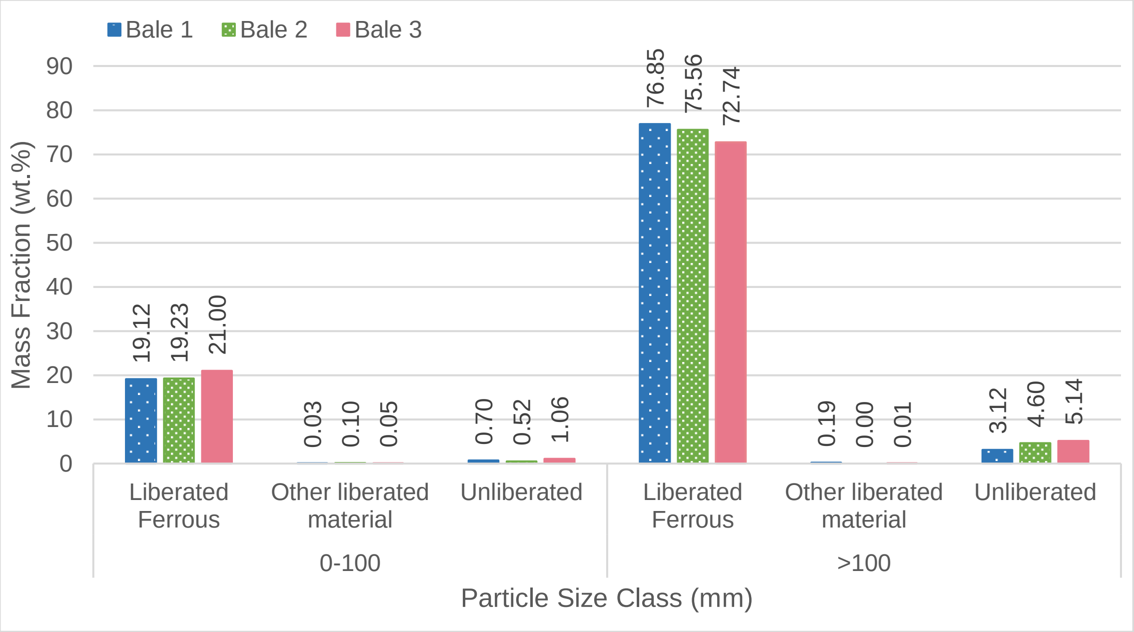


Figure 4-9: Liberation category for different particle sizes in the collected sample from Fe output stream.

The material combination types and the joining techniques contributing to the presence of impurities in the unliberated particles are shown in Figure 4-10. The design structure, material combinations and their associated joint types used have an impact on the increasing presence of impurities in the Fe stream.

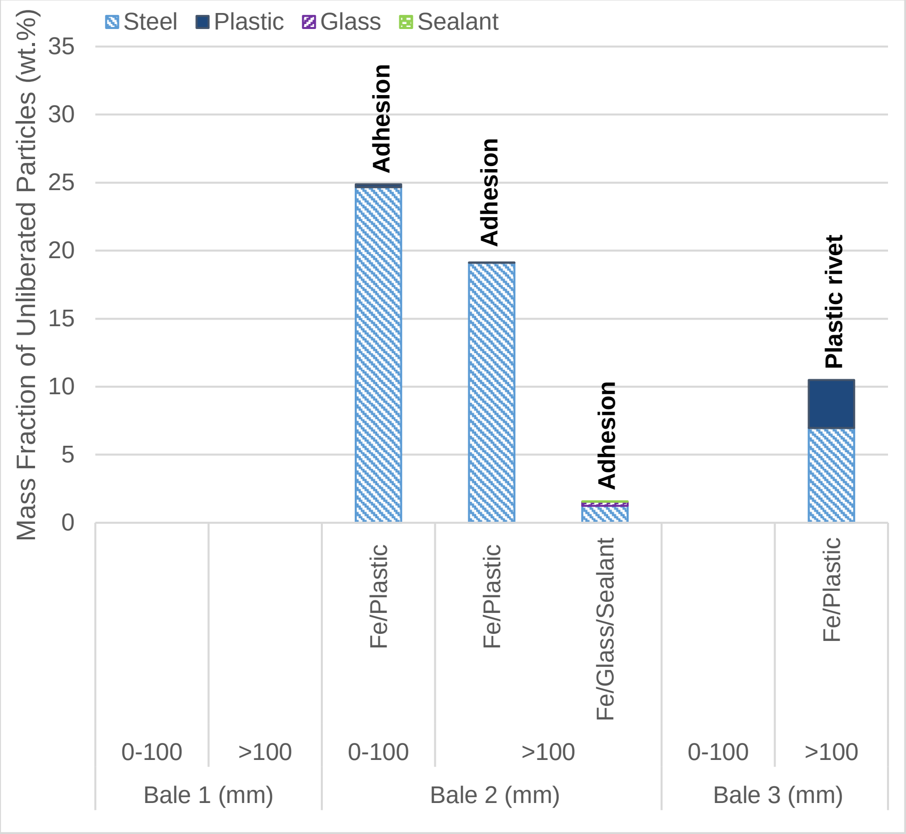


Figure 4-10: Material combination and joint types observed for unliberated particles in Fe output stream.

There were two types of joining techniques causing impurities in the Fe stream for Bale 2 and 3; adhesive bonding and plastic rivets. Adhesive surface bonding for Fe-plastic was the main joint type causing impurities for Bale 2. Additionally, unliberated Fe-glass-sealant particles caused by adhesion were observed in Bale 2 due to the sandwich layer design used on the side of the window glass attached to the window running channels. There were no impurities due to adhesive bonding for Bale 1 and 3 although this joining technique was observed in the joint audit. This is because a lap joint design was used for the metal-plastic combination, such as for door panel water shield and door trim, that was easily liberated. Plastic rivets used in newer vehicle door designs also caused Fe contaminations. Often, the plastic rivet itself was the source of impurities, as seen in Figure 4-11. The increasing use of door trim plastic rivets to attach inner door panel to the steel door frame has caused them to be less likely to be liberated. Although input joint types such as steel screws, steel bolts, steel rivets, steel clips, brazing, and plastic clips were used for different material combinations, observations at the Fe output samples showed no sign of these joining techniques causing impurities.

Figure 4-11: Steel particle with plastic rivet.

The structure of vehicle door part design also played a role in causing impurities in the Fe output stream although they were not bonded physically or chemically. Fe-Cu 'meatball' and Fe-rubber insertion were observed in the collected samples, as shown in Figure 4-12, mainly due to liberation errors. Particles with Fe-rubber combination were seen for all bales, and in both particle size classes. This was mainly due to the rubber materials used as bailey channel (door seal) to prevent rattling wind noise and guiding the window glass. They were fitted inside the upper door steel frame structure that resulted in steel particles with rubber insert after the shredding process. The Fe-Cu 'meatball' structure from the power motor of the window regulator was also recovered in the Fe stream. Cu impurities have a significant impact on the Fe scrap quality and cannot be easily removed during the smelting process.

(a) Fe/Cu "meatballs".

(b) Steel particles with rubber insert.

Figure 4-12: The presence of impurities in Fe output stream due to liberation errors.

The quantity of adhesive and plastic rivet joints causing impurities in Fe output stream is shown in Table 4-11.

Table 4-11: Quantitative joint data and their material combinations in Fe output stream.

Material Types	**Total Number of Input Joints**						**Total Number of Unliberated Joints**					
	Plastic Rivet (unit)			**Adhesive (m)**			**Plastic Rivet (unit)**			**Adhesive (m)**		
	B1	**B2**	**B3**	**B1**	**B2**	**B3**	**B1**	**B2**	**B3**	**B1**	**B2**	**B3**
Fe-Cbd-L	130											
Fe-Pl			251	27.3	101.6	14.2			11		10.9	
Fe-Rub				18.9	4.8	1.4						
Fe-Glass					9.5						3.9	
Total	130	0	251	46.2	115.9	15.6	0	0	11	0	14.8	0

Pl: Plastic; Rub: Rubber; L: Synthetic leather; Cbd: Cardboard

Joint audit data for all bales was plotted against the fraction of unliberated joints in the Fe output stream, as seen in Figure 4-13. There is no correlation between the number of input joints and the respective fraction of unliberated joints.

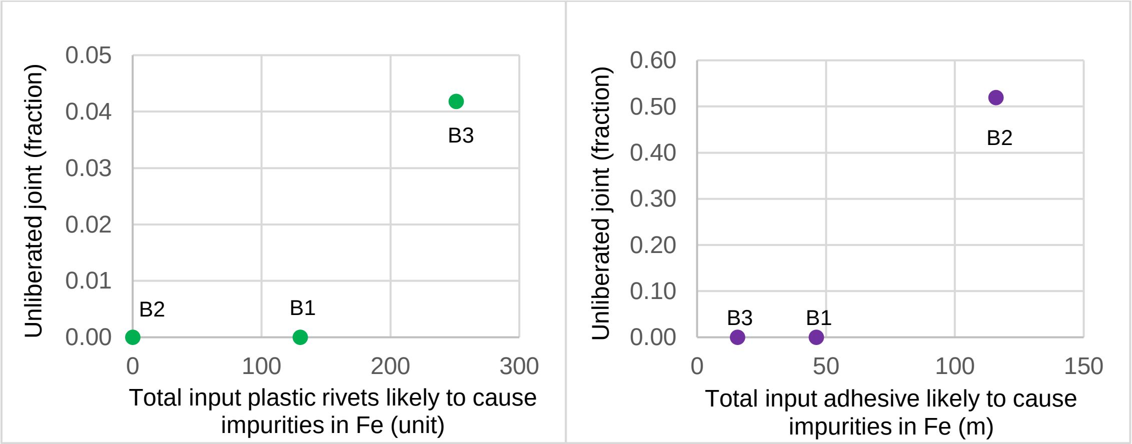


Figure 4-13: The relationship between different joint types and the fraction of unliberated joints in Fe stream.

4.5.2 Impurities due to Joints in NF Stream

The NF stream consisted of metals such as Al, Cu, Zn alloy, and brass. The different types of NF metals did not undergo further sorting processes in the facility but were exported in mixed form to developing countries. It is assumed that they were manually hand-sorted in other recycling facility.

Majority of the NF particles in Bales 1 and 3 were in the 0-50mm size range, 40.5% and 63.5% respectively, as seen in Figure 4-14. Most of the NF materials were used for narrow and small vehicle door parts, such as outer door belt moulding and car door handle mechanism. On the other hand, particles for Bale 2 were mainly in the size range of 100-200mm, about 40.8%. The particles in the 100-200mm category from Bale 2 originated from the car door handle mechanism and aluminium lift channels glued to the window glass. Other liberated materials consisted of ASR made up of mainly rubber, plastic, fabric, and foam. This liberation category represented the smallest mass fraction for particle size of more than 50mm.

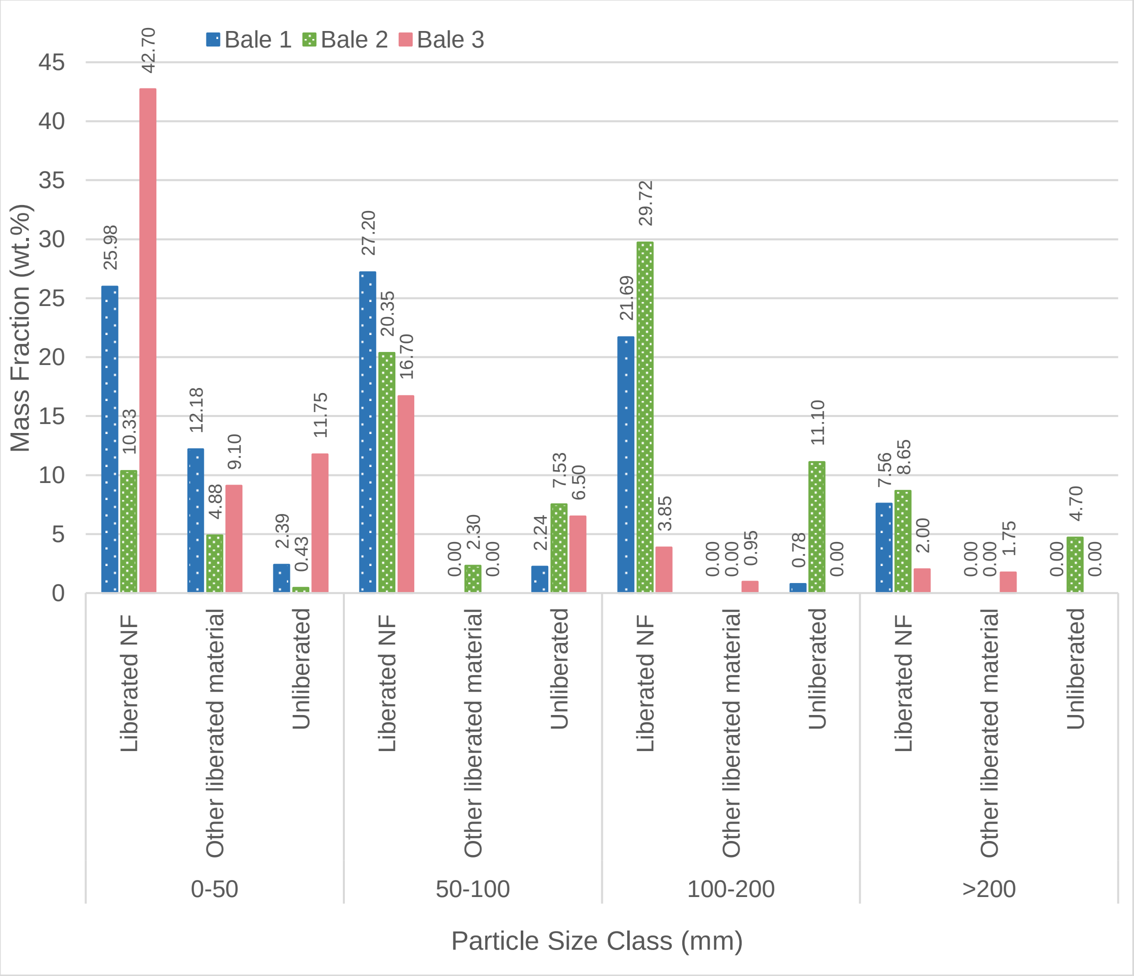


Figure 4-14: Liberation category for different particle sizes in the collected sample from NF output stream.

From Figure 4-15, it is observed that the joint types causing impurities in the NF stream were steel screws, rivets, and adhesive bonding. All impurities observed in Bale 1 and Bale 3 were caused by steel fasteners, such as machine screws and rivets, that were still attached to aluminium parts. The Fe parts attached to NF particles were not picked up by the magnetic separator due to the small amount of Fe present in the particles. These Fe impurities were largely caused by smaller joint size, and were situated at enclosed locations within the original doors. Small machine screws with 2-5mm diameter, and height of about 15-20mm attached to Al-Fe parts were seen in almost all particle size classes. Steel rivets contaminated the NF stream in Bale 1 only, since this joint type was largely used for Fe-plastic parts for Bale 2 and 3.

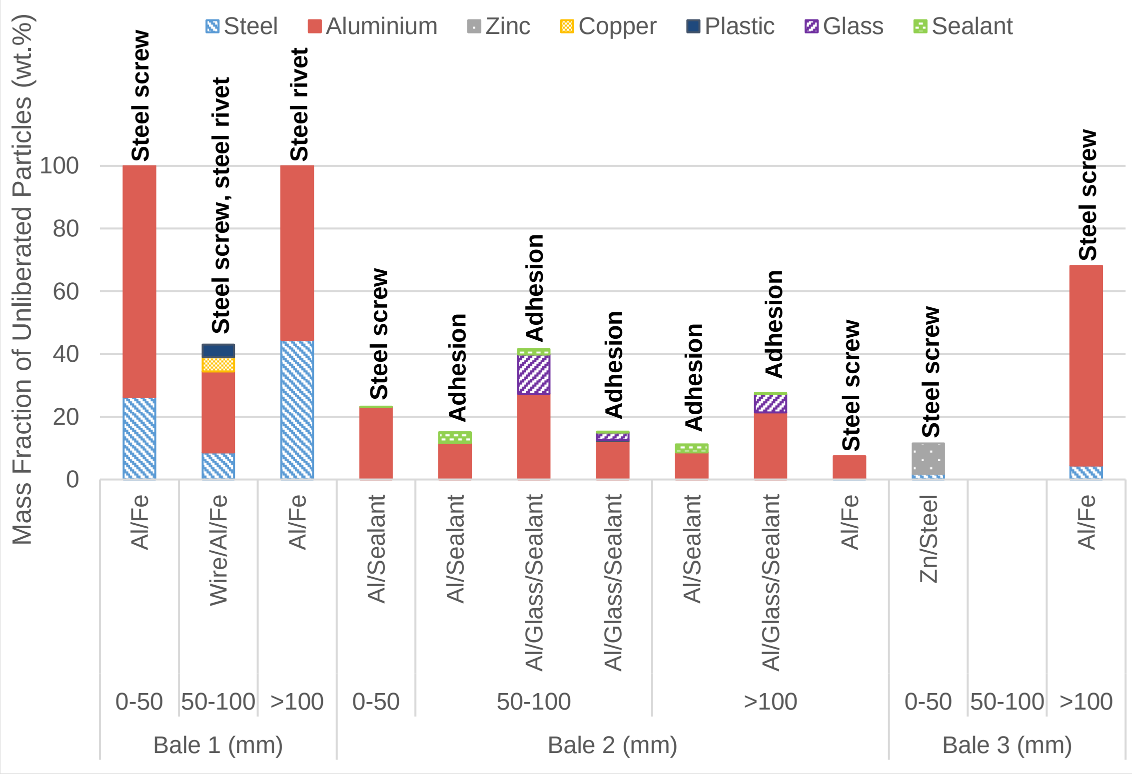


Figure 4-15: Material combination and joint types observed for unliberated particles in NF output stream.

Adhesive bonding was the main type of bonding technique contaminating the Al particles in Bale 2. The Al particles were mainly from aluminium lift channels glued to the window glass through a sandwich structure, as seen in Figure 4-16. This structure is less likely to be liberated regardless of different particles sizes. There was no trace of impurities due to adhesive bonding in Bale 1 and 3 in the NF output stream since this joining method was not used to bond NF materials to other material type.

Figure 4-16: Al particles with glass and sealant.

The quantity of steel screw/bolt, steel rivet and adhesive joints causing impurities in NF output stream is shown in Table 4-12.

Table 4-12: Quantitative joint data and their material combinations in NF output stream.

Material Types	**Total Number of Input Joints**								
	Steel Screw/Bolt (unit)			**Steel Rivet (unit)**			**Adhesive(m)**		
	B1	**B2**	**B3**	**B1**	**B2**	**B3**	**B1**	**B2**	**B3**
Fe-Al/Wire	98	57	14	57					
Br-Pl		30							
Al-Pl			112	18		35			
Al-Glass/Sealant								6.1	
Zn-Fe			7						
Total	98	87	133	75	0	35	0	6.1	0

Material Types	**Total Number of Unliberated Joints**								
	Steel Screw/Bolt (unit)			**Steel Rivet (unit)**			**Adhesive(m)**		
	B1	**B2**	**B3**	**B1**	**B2**	**B3**	**B1**	**B2**	**B3**
Fe-Al/Wire	11	1	1	5					
Br-Pl									
Al-Pl									
Al-Glass/Sealant								3.7	
Zn-Fe			1						
Total	11	1	2	5	0	0	0	3.7	0

Pl: Plastic; Br: Brass

Joint audit data for all bales was plotted against the fraction of unliberated joints in the NF output stream, as seen in Figure 4-17. The number of steel screws/bolts is highly correlated to the fraction of unliberated joints in the NF output. In contrast, there is no correlation between the total steel rivet and adhesive joints, and their respective fractions of unliberated joints.

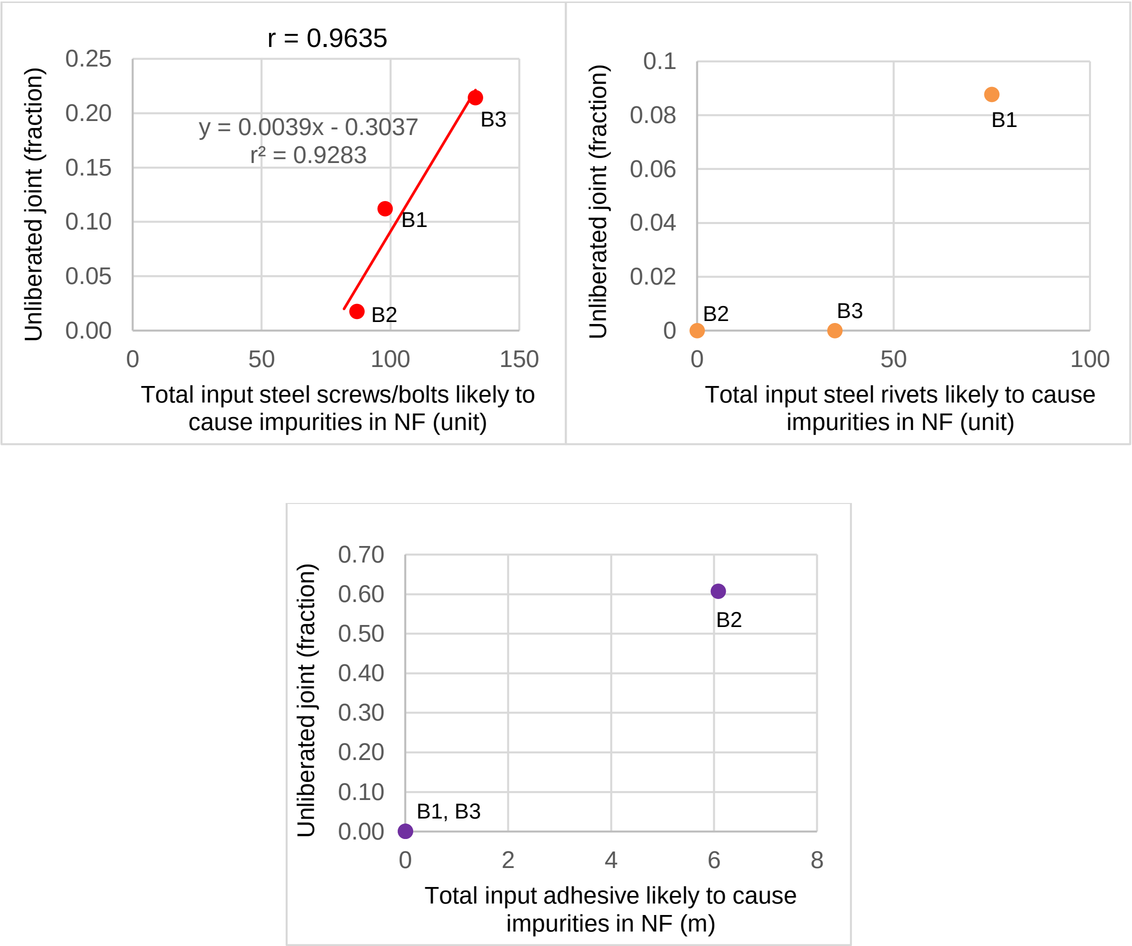


Figure 4-17: The relationship between different joint types and the fraction of unliberated joints in NF stream.

4.5.3 Valuable Material Losses due to Joints in ASR Stream

The ASR stream consisted of plastics, composites, rubber, glass, foam, and fabric that were landfilled. The mixture of ASR has a relatively small average particle size compared to other streams, as shown in Figure 4-18. ASR materials have lower densities, allowing them to easily fracture into smaller parts when undergoing the shredding and sorting processes. Thus, liberated ASR made up the highest fraction for the different particle size classes, and the majority were less than 10mm.

There were traces of liberated and unliberated valuable materials in the ASR stream, showing an increasing trend from B1 to B3. Liberated valuable materials consisted of steel, Al, Cu and others, whereas, most of the unliberated ASR were a combination of valuable materials and non-valuable materials. These valuable material losses were caused by the separation and liberation errors during magnetic and eddy current separation processes.

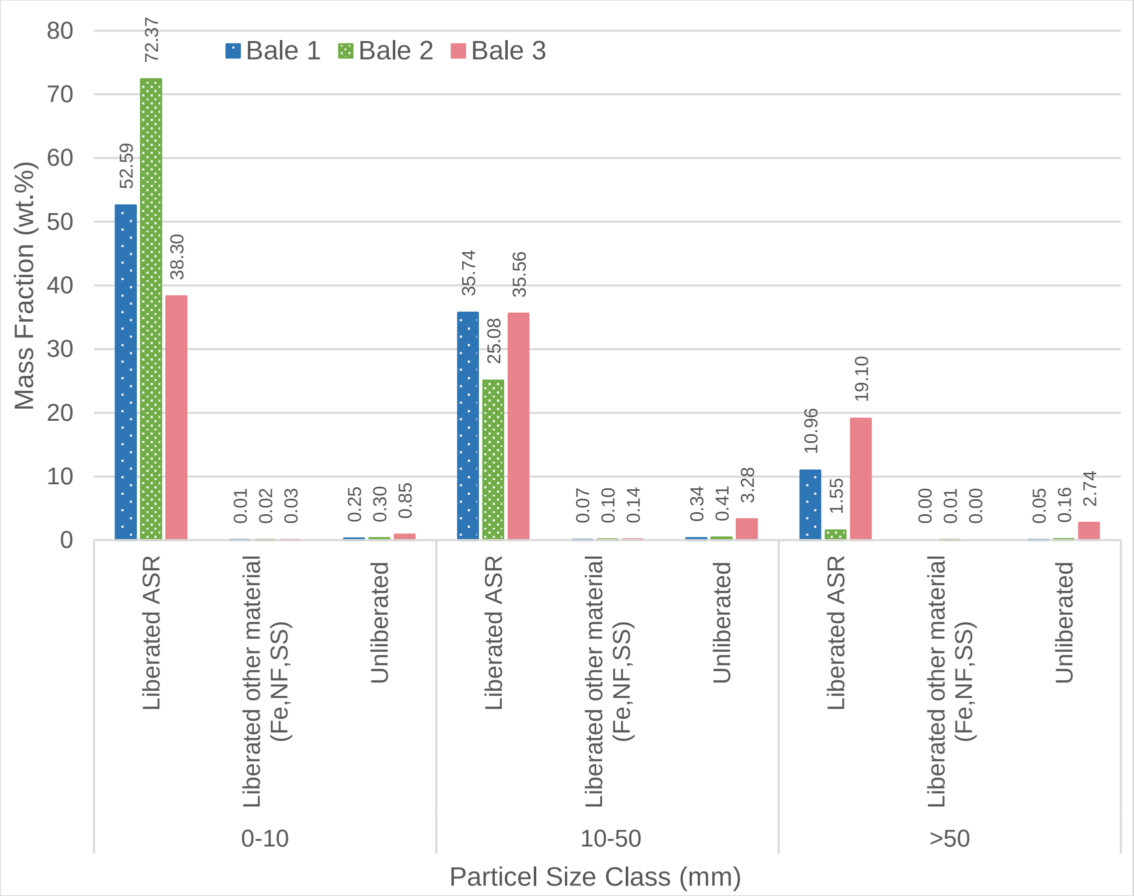


Figure 4-18: Liberation category for different particle sizes in the collected sample from ASR stream.

Figure 4-19 shows that the joint types causing the material losses in ASR were steel screws and plastic rivets. They were observed in the larger particle size class, more than 10mm. Most of the particles with impurities were due to joints made up of Fe-plastic combination connected through small steel screws or plastic rivets that were unliberated. In most cases, the mass fraction of Fe or Al was smaller in comparison to the fraction of plastics, resulting in higher likelihood of these particles ending in the ASR stream. Although magnetic separation method was effective in separating Fe materials, the ability to retrieve Fe that was still attached to other materials can be influenced by the Fe mass fraction in the particles and the location of the joints. Steel screws attached to plastic materials that were located at enclosed spots had low magnetic strength and were less likely to be separated by the magnetic separator, as seen in Figure 4-20.

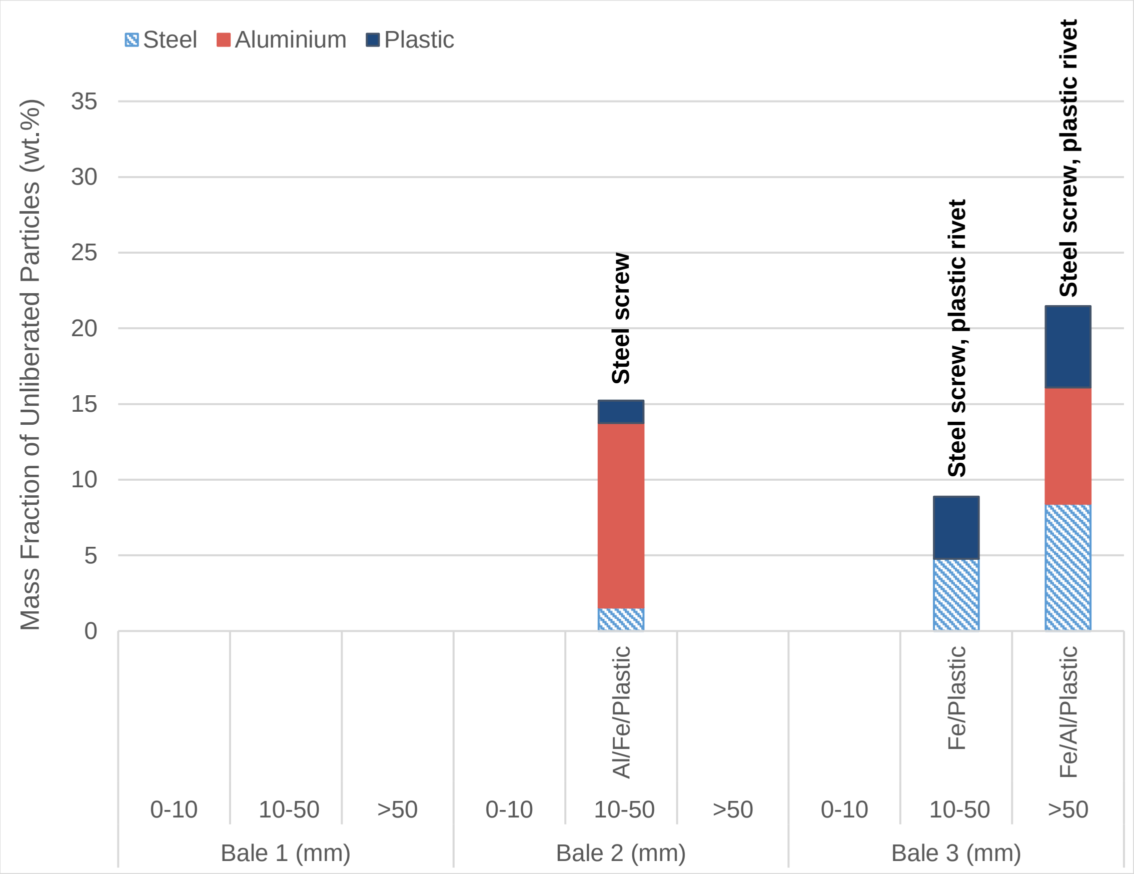


Figure 4-19: Material combination and joint types observed for unliberated particles in ASR output stream.

Figure 4-20: Particle with steel screw encapsulated in plastic.

The number of steel screw/bolt and plastic rivet joints causing material losses in ASR output stream is shown in Table 4-13.

Table 4-13: Quantitative joint data and their material combinations in ASR output stream.

Material Types	**Total Number of Input Joints**						**Total Number of Unliberated Joints**					
	Steel Screw/Bolt (unit)			**Plastic Rivet (unit)**			**Steel Screw/Bolt (unit)**			**Plastic Rivet (unit)**		
	B1	**B2**	**B3**	**B1**	**B2**	**B3**	**B1**	**B2**	**B3**	**B1**	**B2**	**B3**
Pl-Pl	116	369	376									
Fe-Rub	42											
Al-Pl			112									
Fe-F/L	9		21									
Br-Pl		30										
Fe/Al-Pl		42	351			251		2	52			10
Fe-Pl-Rub												
Al-Rub												
Fe-Cbd-L				130								
Total	167	441	860	130	0	251	0	2	52	0	0	10

Pl: Plastic; Rub: Rubber; Br: Brass; F: Foam; L: Synthetic leather; Cbd: Cardboard

Joint audit data for all bales was plotted against the fraction of unliberated joints in the ASR output stream, as seen in Figure 4-21. Similar to the NF output stream, there is a strong positive correlation between the number of steel screw/bolt joints and the fraction of unliberated joints. The material losses in ASR due to plastic rivet joints were only observed for Bale 3; thus, no correlation relationship is formed.

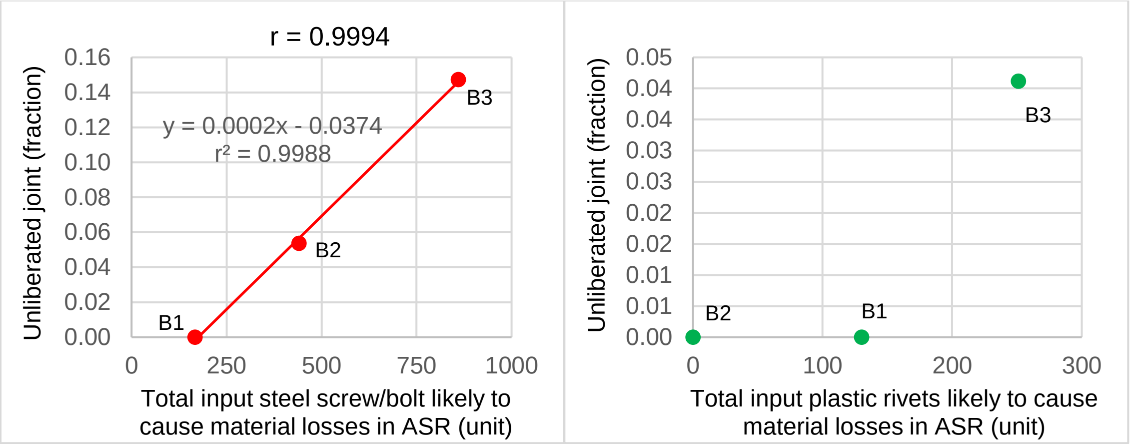


Figure 4-21: The relationship between different joint types and unliberated joints causing material losses in ASR.

4.6 Discussion

The positive correlations between steel screw/bolt joints and the fraction of unliberated joints are observed in different output streams except for Fe output. This is because the material liberation behaviour is strongly dependent on the types of material combinations. It was observed that steel screws and bolts were still attached to the Fe-Fe parts (as seen in Figure 4-22) in the Fe output stream; however, they were not considered as impurities. Moreover, majority of the steel screws and bolts were bonded to lower material density, such as Fe-plastic, Al-plastic or plastic-plastic parts. Plastics have lower densities compared to Fe, causing them to be easily liberated when centrifugal force is applied during the shredding process. For cases when the Fe-plastic parts were not liberated and the mass fraction of plastic was higher, they were more likely to end up in the ASR output stream. In addition to the types of material combinations, the joint designs also play a critical role. The impurities due to steel screws and bolts in NF stream were mostly contributed by the combination of Fe-Al parts. The commonly used lap joint design for steel fasteners to combine Fe-Al parts is at a liberation disadvantage due to the malleability and elasticity of Al. When force is applied, Al is easily deformed or bent compared to the steel-base material part and joint, making full material liberation more difficult. The increasing trend of multi-material designs will result in the growing use of mechanical fasteners to combine Fe to lightweight materials, such as Al and composites, leading to a greater likelihood of impurities or material losses due to screws and bolts.

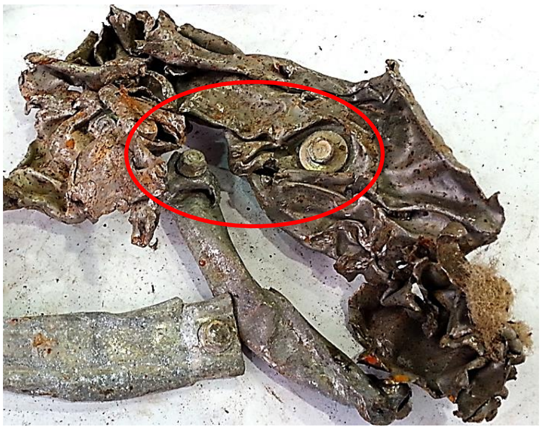


Figure 4-22: Steel particles with steel bolt screw.

Plastic rivet, steel rivet and adhesive joints have no correlation with their respective fractions of unliberated joints although they were observed in the different output streams for certain bales. However, the bale with largest number of plastic rivet, steel rivet or adhesive joints is likely to cause impurities in the different output streams. The changing material and joint designs have an influence on the presence of impurities or material losses in the output streams. The increasing use of plastic rivets to attach the inner door panels to the steel door frame has increased the likelihood of plastic impurities ending up in the Fe fraction. These Fe-plastic parts are more likely ending up in the Fe output stream when they passed through the magnetic separator due to the larger Fe mass fraction when unliberated. Another aspect that can influence where the unliberated particles ended up is the volume of different material types that are combined. For example, unliberated steel rivets used to join Fe-Al parts were more likely to end up in the NF output stream due to the larger mass fraction of Al. In most cases, the unliberated particles were more inclined to flow to the dominant material output stream. The increasing use of lightweight materials, such as plastics and composites, will lead to the higher probability of unliberated particles with larger proportion of plastics or composites flowing to the ASR output stream. Consequently, the fraction of valuable materials unliberated from the particles will be increasingly entering landfills.

Adhesive bonding was the main joint type causing impurities in Bale 2. The observations on the adhesive joint designs with respect to each bale indicated that the joint features have an impact on the presence of impurities. The semi rigid foam-based adhesions used to combine different materials in B3 have low strength and thus can be more easily liberated during the shredder process. In contrast, the adhesions in B2 were based on a sandwich joint design where the joint surface area was laminated within the combined materials. Moreover, the use of higher-strength adhesion type has caused the particles to be less likely to be liberated.

Observations on the shredder output samples showed that steel clips, plastic clips, and brazing were not the cause of impurities or material losses although these joining techniques were used. Steel clips were used to combine the speaker grill to the inner door panel, and to bond the Al-rubber parts of the outer door belt moulding. The surface area of steel clip joints was exposed and protruded which facilitate the material liberation during recycling processes. Plastic clips were largely used to attach the inner door panels to the steel door frame and can be easily liberated due to the protruded surface. Brazing joints with copper filler were used to combine the upper and lower door frame. The strength of the filler metal (Cu) was less compared to base metal (Fe), allowing them to be separated easily. Moreover, brazing often uses butt joint design with limited tensile strength that is strongly dependent on the amount of bonding surface, and the differences in the thickness of bonded material parts. Plastic clips, steel clips, and brazed joints can be easily liberated when force is applied during the recycling processes due to the low static and fatigue strengths.

The different joint types represent the varied joint characteristics that influence the presence of impurities or material losses in different output streams in the current Australian sorting processes. As shown in Table 4-14, the observations on the characteristics of unliberated joints in the shredded output samples collected from the case study can be further supported through the correlation between joint input and impurities or material losses for different output streams.

It is crucial to determine the specific attributional factors of joint types causing low quality secondary materials and high amount of material losses. The findings can be applied to a range of advanced joining techniques, such as hybrid joint. The characteristics of connection are strongly dependent on the part and the materials being joined, as listed in Table 4-15. It is important to note that the material separation efficiency may vary depending on the sorting processes. Nevertheless, the case study is representative of the initial phases of most current global ELV sorting practices.

Table 4-14: Summary of the characteristics of different joint types, and their impact on the impurities and material losses in different output streams.

Output Stream	Impurities/Material Loss	Joint Type	Observations	Correlation
Fe	Rubber, Cu, plastic, wire, glass, fabric	Steel screws, bolts and rivets	Fe-plastic parts were liberated due to larger differences in material densities. Fe-Fe parts were not liberated. Corroded joints could not be easily liberated	None
		Steel clips and plastic clips	Protruded steel and plastic clips assisted in liberation	None
		Brazing	Brazing utilised butt joint design with lower strength filler metal that ease liberation	None
		Plastic rivets	Low joint strength between door panel and steel door frame due to joint material type and thickness of materials being joined. The joint material type is often the source of impurities	None
		Adhesion	Highly dependent on the material combination types and joint strength. Sandwich layer design could not be liberated	None
NF	Glass, Fe, rubber, wire, plastic	Steel screws, bolts and rivets	Lap joint design for Fe-Al parts were not well liberated due to Al deformation	0.9635 (Steel screws)
		Adhesion	Highly dependent on the strength of adhesive used, and the joint design structure. Adhesion used had low joint strength	None
ASR	Wire, Fe, Al, circuit board	Steel screws, bolts and rivets	Small joints located in enclosed spots and corroded joints could not be easily liberated	0.9994 (Steel screws)
		Plastic rivets	Highly dependent on the volume of non-metal of the unliberated particles. Unliberated joints ended up in the dominant material types of the particles	None
		Steel clips and plastic clips	Protruded steel and plastic clips assisted in liberation	None
		Adhesion	Low joint strength when used to join non-metal to metal parts due to the difference in material density	None

Table 4-15: Joint characteristics that have an impact on the material recyclability.

Connection Characteristics	Preference for Material Separation
Joining Part	
Joint strength	Minimise static and fatigue strength without compromising the reliability during product usage
Area of bond contact (strength)	Minimise the area of bond contact without compromising the reliability during product usage
Temperature resistance	Minimise the temperature resistance at joints to ease liberation without compromising the reliability during product usage
Joint location	Place joints at accessible location on the surface area of bonded materials
Joint material type	Use joints with similar and compatible material types
Degradation over time due to moisture effect	Minimise joint material type such as steel that degrade due to moisture, or use joints with corrosion resistance coatings
Degradation over time due to heat effect	Use joint types that are likely to degrade over time due to heat without compromising the reliability during product usage
Fastener diameter and size	Minimise the use of fasteners with small diameter and length
Protrusion level	Use joint types that create uneven geometry at joining area to ease liberation
Material Part	
Material density	Encourage the use of material combinations with larger differences in material densities to ease breakage
Material thickness	Encourage the use of material combinations with unequal thickness to ease breakage and liberation

The findings from this study were limited to the joining techniques used to connect different materials for the respective vehicle model and part. Welding techniques, such as spot and MIG welding, were mostly used for similar material connection (Fe-Fe part) that did not cause impurities in the output stream. Further investigation needs to be carried out for welded joints with different material combinations. Nevertheless, the joint characteristics for weld can be used to identify the likelihood of causing impurities in the valuable output streams.

The quality of recycled materials is determined by the types of impurities present in the respective output stream. For instance, Al impurities in the Fe output stream can be easily removed during the secondary material production phase. In contrast, when Fe impurities are found in Al output stream, they cannot be easily removed and thus need to be diluted with more high quality primary materials to achieve the desired material quality.

In this case study, the correlation coefficients for different joining techniques are used to further support the observations in the output streams, and they serve as an initial assessment of the causal relationship. To validate the correlation between the variables, further experimental work will need to be carried out in the future through a well-designed and controlled experiment targeting specific variables with larger sample analysis. Nevertheless, the characteristics of joint types more likely to cause impurities and material losses as observed through this study can be used as the first step to link the complexity of joints during product design with other variables, such as material and joining choices, and liberation behaviour during shredding. This is crucial to provide a realistic design for recycling guidelines that optimises the quality and separation efficiencies for the valuable outputs based on current sorting practices.

4.7 Concluding Remarks

This study shows that steel screws and bolts cause more impurities and material losses in the output streams of traditional recycling facilities compared to other joining techniques. With the increasing use of these joining techniques to connect steel with other lightweight materials (e.g. Al and composites) in the automotive industry, the impurities in Fe output stream are predicted to grow although they were not observed at the shredded output. This is due to the limited types of material combination with lower material densities that ease breakage during sorting processes. Therefore, the joint characteristics are also influenced by the attributes of the materials being joined. Some of the characteristics of these joining methods include strong joint strength with a relatively large area of bond contact causing them to be less likely liberated. The observation can be further supported by the high positive correlation between the input joint data and the fraction of unliberated joints for different output streams. In contrast, joint types with more surface area exposure, such as steel and plastic clips, were easily liberated when force was applied. The protrusion at the joints also assisted in the likelihood of full liberation during the shredding process.

The joint type, size, diameter, and location also influence the material recyclability. Full material liberation at joint is possible when the particle size is smaller than the joint size. Most of the particles with impurities due to joints had a smaller joint size in comparison to the different particle size classes for each respective material output, and were located at enclosed spots that further hinder full liberation. Therefore, the joint characteristics play a crucial role in determining the liberation of particles, and thus, the amount of impurities and material losses in the different output streams. The lack of understanding on how the characteristics of joints for different joining methods have an influence on material separation efficiencies has caused ineffective vehicle design decisions to optimise material recyclability in a closed-loop system. This work serves as an initial step to investigate effective choice of joining techniques based on their characteristics.

In the following chapter, the influence of joints on the presence of impurities in the output streams is investigated through an industrial trial based in Europe. The case study is crucial to identify the types of joining techniques affecting perfect material liberation for different recycling approaches.

Chapter 5

The Influence of Joints on Advanced Vehicle Recycling

European Case Study

Publications relevant to this chapter:

Soo VK, Peeters J, Compston P, Doolan M, Duflou JR. Comparative Study of End-of-Life Vehicle Recycling in Australia and Belgium. *Procedia CIRP* 2017; 61:269-274.

Soo VK, Peeters J, Paraskevas D, Compston P, Doolan M, Duflou JR. Sustainable Aluminium Recycling of End-of-Life Products: A Joining Techniques Perspective. *Journal of Cleaner Production* 2017; 178:119-132.

5.1 Introduction

This chapter demonstrates the influence of stricter EoL treatment strategies for ELV on the presence of impurities in valuable output streams based on the European scenario. The first section provides the comparative material recycling and recovery efficiencies for different ELV management systems. The following section investigates the influence of joints on more advanced recycling technologies and to what extent the impurities due to unliberated joints are affecting the valuable output streams.

The ELV recycling of depolluted car hulks in Australia and Belgium is compared to provide context on the effect of different recycling approaches on material recycling and recovery efficiencies. The recycling system in Belgium is reflective of the European scenario that utilises more rigorous post-shredder separation processes. Industry data collected from these two countries allow comparison on ELV management systems adopted in different regions. The findings are essential for understanding the barriers and opportunities to improve material recycling of different recycling approaches from the legislative boundaries.

Next, an industrial trial is conducted to investigate the cause of impurities present in one of the valuable output streams (Al fractions) through an advanced recycling technology in Europe. The experiment aims to understand the impact of strict vehicle legislation on the quality of recycled valuable materials. The findings are essential to understand the sensitivity of the fraction of unliberated joints on the material quality recycled through more rigorous recycling processes. The types of joints that cause impurities are explored to support the findings from the Australian case study (Chapter 4). Furthermore, the characteristics of joints that influence the material recycling efficiency observed from the European case study are presented. A life cycle analysis is then performed to evaluate the environmental impacts due to dilution and quality losses during the recycling of different Al scrap qualities. The observations from the European case study are limited to the output streams only. Although the European case study is carried out under different conditions and scopes in comparison to the Australian case study, general conclusions can still be made using the exploratory research method for multiple case studies (Yin, 2007).

5.2 ELV Recycling and Recovery Efficiencies

The implementation of stricter vehicle recycling legislation influences the adoption of recycling approaches. This is reflected in the material recycling efficiency of the recycling processes used in Australia and Belgium. In this section, the material recycling and recovery efficiencies of depolluted car hulks for two recycling facilities using different approaches are compared and discussed.

The Belgian recycling facility utilises more rigorous separation processes, as shown in Figure 5-1. This has resulted in higher ELV recycling efficiency in comparison to the Australian recycling plant (see Table 5-1). The overall material recycling and recovery rates in Belgium is 94.33% whereas in Australia, the recycling efficiency is 71.61%. The efficiency of the Belgian recycling facility is lower than the set target of 95% because the reused ELV parts were not included.

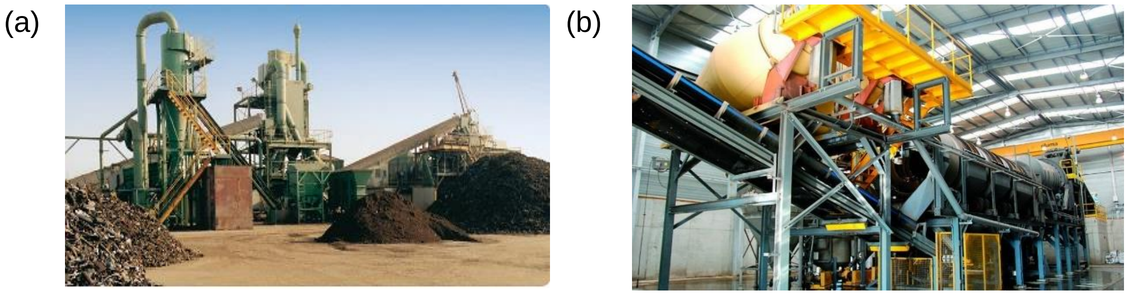


Figure 5-1: Material separation processes in the Belgian recycling facility. (a) Shredder facility; (b) Density separation.

Table 5-1: Post-shredder waste landfilled, and the recycling and recovery efficiencies of depolluted car hulks for the Australian and Belgian recycling facilities.

Output Stream	Australia (%)	Belgium (%)
Material recycling	71.61	90.26
Energy recovery	-	4.07
ASR landfill	28.39	5.67

The material recycling efficiencies for both recycling facilities are significantly contributed by the amount of metals recovered from ELV. In the Belgian recycling facility, the use of more rigorous separation processes has led to higher recycling rates for different metal types, with a minimum 91.76%, as shown in Table 5-2. Fe has the highest recycling efficiency in both facilities; nevertheless, there is potential for the Australian recycling facility to further increase it by 3%. The recycling efficiencies for NF materials in the Australian facility are comparatively low, ranging from 4.11% to 45.55%. This is due to reduced focus on NF retrieval, and a reliance on eddy current separation.

Table 5-2: Material recycling efficiencies of ELV in the Australian and Belgian recycling facilities.

ELV Materials	Australia (%)	Belgium (%)
Fe	96.13	99.97
Al	45.55	97.52
Cu	4.11	91.76
Zn	36.45	98.24
Pb	-	97.08
PP	-	89.5
PE	-	89.5
PMMA	-	0.32
ABS	-	83.36
PET	-	0.4
EPP	-	0.58
PP-EPDM	-	0.32
PU	-	0.69
Rubber	-	1.94
Textile	-	0.83
Glass	-	79.4

ASR that would be landfilled in the Australian recycling facility undergo further treatment processes in the Belgian recycling facility. The post-shredder treatment utilises density separation to further segregate the non-metallic materials and heavy metals. Plastic recycling is the focus in this process, and the recovered plastics are further sorted to different plastic types to improve purity and thus increase the value of secondary plastics. However, the recycling efficiencies varied vastly from one plastic type to another. PP and PE have the highest recycling efficiencies in the Belgian facility, at 89.5%, followed by ABS, which is about 83.4%. These plastic types are widely used in vehicle production. Conversely, other plastic types such as PMMA, PET, expanded polypropylene (EPP), polypropylene blended with ethylene propylene elastomer (PP-EPDM), and PU each have recycling efficiencies of less than 0.7%.

One of the major similarities between both recycling facilities is the focus on recycling valuable materials for financial gain. The types of recycled materials are strongly influenced by the materials' market value to fully optimise revenue. Both recycling facilities opted for the shredder-based recycling technology that has been proven to be cost-effective for ELV recycling (Ferrão and Amaral, 2006a; Soo et al., 2017). The Australian recycling facility has a relatively high Fe recycling efficiency compared to other metals due to the high demand to provide enough stock for their affiliated steel mill company. In Belgium, high recycling efficiencies of different metals are achieved to maximise profit, and to abide by the strict ELV legislation implemented in Europe.

Material recycling efficiency is strongly related to the adoption of recycling technologies. In the Belgian recycling facility, post-shredder technologies are used to recover plastics, and to further segregate the different types of metals. Moreover, the advancement in post-shredder technologies will ensure the recyclability of future vehicles abides by the strict recycling targets. In Australia, the material recycling efficiency is relatively low due to inefficient recycling processes. Although the adoption of more advanced recycling technologies can further improve the material recycling efficiencies particularly for metals, revenues from recovered materials and strict policy play a significant role to actualise the transition.

In the following section, the environmental impacts of dilution and quality losses during the recycling of secondary materials are assessed through LCA. An industrial trial was conducted in the Belgian recycling facility to investigate the types of joining techniques causing impurities in the Al output streams when advanced recycling technologies are applied. Impurities due to joints are identified to understand to what extent they are affecting the collected Al streams. The observations are then expanded to assess the linkage between the presence of impurities due to specific joint types, and the different particle liberation sizes. Based on the case study data, a life cycle analysis is performed to evaluate the environmental impacts of recycling different Al scrap qualities. This study assists manufacturers and designers to promote closed-loop recycling by mitigating the source of impurities through effective joining technologies during the initial design stage that caters for current recycling practices. In addition, recyclers and policy-makers can target effective recycling processes and standards to ensure perfectly liberated joints for high purity Al to minimise the loss of valuable material streams.

5.3 Recycling Aluminium from ELV

Al is increasingly used in vehicle manufacturing due to its high strength-to-weight ratio, good formability, and high corrosion resistance. The global demand for Al has seen significant growth, leading to the importance of sustainable metal management. The amount of Al used globally has been increasing since 1950, as can be seen Figure 5-2, and this trend is projected to continue (Cullen and Allwood, 2013; Martchek, 2006). One of the major concerns is the continuous energy-intensive extraction of primary Al to supply for the growing demand worldwide. This activity has contributed significantly to the global CO_2 emissions (Norgate et al., 2007). Although Al is one of the highly recycled metals, offering significant energy saving during secondary production, the benefits of Al recycling are influenced by the purity level of scrap sources (Liu and Müller, 2012).

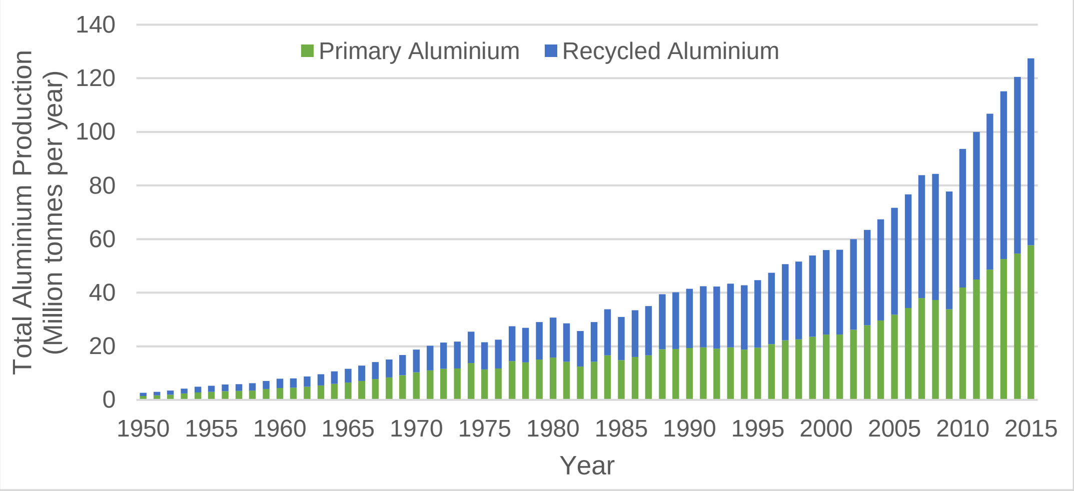


Figure 5-2: Amount of primary and recycled Al used globally (Adapted from (International Aluminium Institute, 2009)).

The transportation industry is one of the major consumers of Al worldwide and is responsible for 35-40% of the overall Al consumption (Nappi, 2013). In recent years, the focus on producing lightweight vehicles has led to the increasing use of high purity Al in vehicle design to replace conventional steels (Goede et al., 2008). Multi-material design concepts have been progressively adopted by vehicle manufacturers due to the emphasis on reducing vehicle mass, thereby lowering the vehicle carbon footprint (Cui et al., 2011; Miller et al., 2000). Al or Al alloys are among the most suitable material category candidates for the manufacture of multi-material car bodies for automotive applications such as BIW, chassis components, doors closure, and outer panels (Carle and Blount, 1999; Hirsch, 2011; Volkswagen Group, 2009).

Complex vehicle designs and their associated joining techniques have led to the increasing challenges for Al recycling during EoL phase. As a result, lower grades or qualities of recyclates are retrieved due to the presence of impurities that lead to cascade recycling (Paraskevas et al., 2015) and the loss of valuable material streams. This is particularly the case for recycling Al scrap that has more limitations during metallurgical recycling in comparison to other metals such as iron and Cu (Nakajima et al., 2010). One of the main reasons is the relatively low melting point of Al, which makes it difficult to remove impurities or tramp elements during the secondary Al smelting and refining processes. The most common strategies used to address this challenge are either dilution using primary Al or down-cycling to lower grade Al alloys that are associated with additional environmental burden (Castro et al., 2004; Paraskevas et al., 2015). The ability to retrieve high quality Al with low impurities increases the scrap value for recyclers; however, the extra recycling costs need to be justified by the volume of different scrap qualities.

5.4 Industrial Experiment

The types of scrap sources as considered in the studied Belgian recycling facility are shown in Table 5-3. The high content of Al in different scrap sources has made it one of the most intensely recycled metals besides steel. Most of the Al scrap is contributed by the ELV and household waste streams. The Al content in the ELV and household waste accounts for 4.9wt.% (Muchová and Eder, 2010; RDC Environment, 2015) and 4.7wt.% (Muchová and Eder, 2010) respectively. The Al content in demolition and building scrap is relatively low, less than 1wt.% (Muchová and Eder, 2010). Since ELV is the major scrap source with higher Al content, the collected Al samples were representative of Al recovered from ELV recycling. Moreover, observations made during the segregation of Al samples indicated a high likelihood of the Al scrap originated from ELV components and parts.

Table 5-3: The sources of Al scrap in the Belgian recycling facility.

Scrap sources	Relative share of total scrap stream (%)
Depolluted vehicle hulks (ELV)	30
Demolition scrap	30
Household waste	20
Building scrap	20

The material process flow specific to Al is shown in Figure 5-3. The processes involved in Al recycling can be categorised into three main clusters: Al sorting, refinement of sorted Al, and particle size sorting. For Al sorting, density separation is the first step to retrieve Al from the mixture of scrap. Subsequently, other major processes, such as eddy current separator, optical separator, and head pulley magnet, are used to further separate Al from other material types.

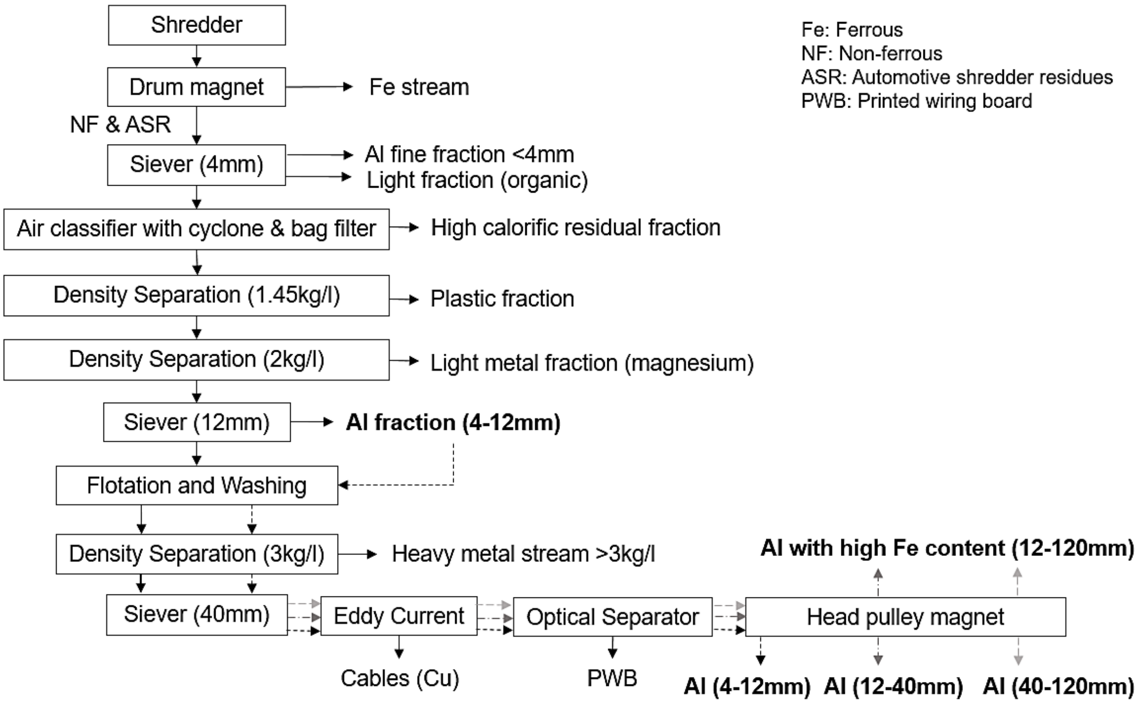


Figure 5-3: Al material flows in the Belgian recycling facility.

The sorting process targeting Al begins with the density separation after the shredding and magnetic separation. Density separation sorts different materials based on their material densities. It typically starts with separating lighter material fractions (e.g.

plastics, foam, rubber, etc.) and is followed by the sorting of materials with higher density. Through density separation at 3kg/l, Al alloys float and can be separated from materials with higher density, such as Cu, Zn, and other heavy metals, that sink to the bottom. In some other recycling facilities, Al retrieval through eddy current separation is carried out (Gaustad et al., 2012).

An air classifier is used to remove fine shredder residues targeted for energy recovery before the density separation. This allows the fine mixture of dust, metals, glass, and polymers to be removed before the first density separation for lighter material fraction. Other separation techniques, such as sieves, are also used. The material flow is sorted to different particle sizes based on the sieve sizes used at various screening stages. This is a common practice in the recycling industry in Europe to segregate different material grades based on the particle sizes (Cui and Forssberg, 2003).

An eddy current separator, optical separator, and head pulley magnet are used to further sort unwanted materials that are still present in the Al flow. The remaining cable wires that did not sink during earlier density separation are further sorted using the eddy current separator. Through this process, an electrical current is induced within the conductive metal flow, and all metals are repelled through the rotor that produces an external magnetic field. Since Al and Cu have a different conductivity, and thus produce varying eddy currents, they are ejected to different distances from the rotor. An optical separator is then utilised to further sort the commonly green coloured PWB from the grey coloured Al. To further remove small particles with Fe content from the Al flow, a very strong head pulley magnet with a deeper magnetic field is used.

5.4.1 Sampling Method

The different Al fraction categories recovered from the facility are shown in Table 5-4. These categories were chosen for sampling to understand the effect of particle sizes on the purity level of various Al fractions, and the extent of impurities due to joints in the different particle sizes. Sampling was also carried out for Al with high steel content. The collection of a minimum of 10 samples from each Al fraction was performed in accordance with the field sampling guidance for shredded scrap by the United States Environmental Protection Agency (USEPA) (Bethel et al., 1993). The field sampling guidance provides information on different sampling methods, estimated sample size, and the statistical analysis methods to accurately approximate the impurity level of different Al fractions. These guidelines were based on previous case studies carried out at different shredder sites.

Table 5-4: Amount of Al samples from each category, and the generated annual amount in the Belgian recycling facility.

Category	Particle Size Class (mm)	Number of Samples	Mass Range of Each Sample (kg)	Overall Sample Mass (kg)	Annual Amount (ton)
Al with high steel content	12-120	10	2.685-3.737	32.689	644
Al fraction	40-120	20	2.290-3.896	61.363	6132
Al fraction	12-40	10	1.506-2.408	19.210	4147
Al fraction	4-12	10	1.494-1.947	16.662	1114

There are different field sampling methods for shredded metal scraps on-site based on the guidelines by USEPA. Stockpile sampling, as explained in Figure 5-4, was chosen in this case study to obtain a more representative sample of the normal shredder output (Bethel et al., 1993). Al samples were taken from the Al stockpile warehouse where different qualities and particle sizes were stored separately. The bucket used to collect the samples has a diameter of 27.5cm with a height of 22.5cm. Each sample taken only filled up half the bucket. First, Al samples were collected at the edge of pile (location 1) at notch 1 and notch 2. The two notches were then dug to equal depth with the help of a front-loader truck. Finally, samples were gathered at locations 2 to 5 for notch 1 and 2. In total, there were 10 buckets of samples collected for each targeted Al output stream. 20 samples were taken only for the Al fraction 40-120mm to ensure a good representation of the stockpile, since it is the largest fraction produced in the facility.

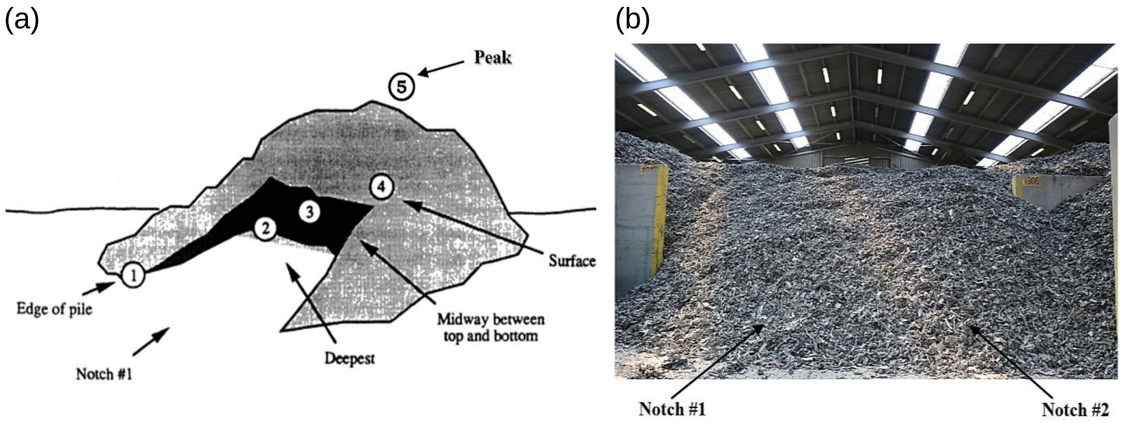


Figure 5-4: Stockpile sampling of different Al fractions. (a) Sampling location for each Al stockpile; (b) Location of notches made for each Al stockpile to carry out sampling.

5.4.2 Sample Analysis Procedures

The Al with high steel content fraction was sieved through a 40mm mesh sieve to separate particles to two particle size categories: 12-40mm and 40-120mm. This step was carried out to allow comparability with the observations made for the Al fractions of similar particle size classes.

Each particle was weighed and hand-sorted according to the different liberation classifications, as shown in Figure 5-5 and as follows.

- Liberated Al samples consisting of Al only (Figure 5-5(a)).
- Liberated impurities were particles consisting of a single material type other than Al (Figure 5-5(b)).
- Unliberated impurities were particles consisting of material combinations other than Al (Figure 5-5(b)).
- Unliberated Al samples were particles consisting of Al that was still attached to other material types without the presence of a joint (Figure 5-5(c)).
- Unliberated Al samples due to joint were particles consisting of Al that was still attached to other material types with the presence of a joint (Figure 5-5(d)).

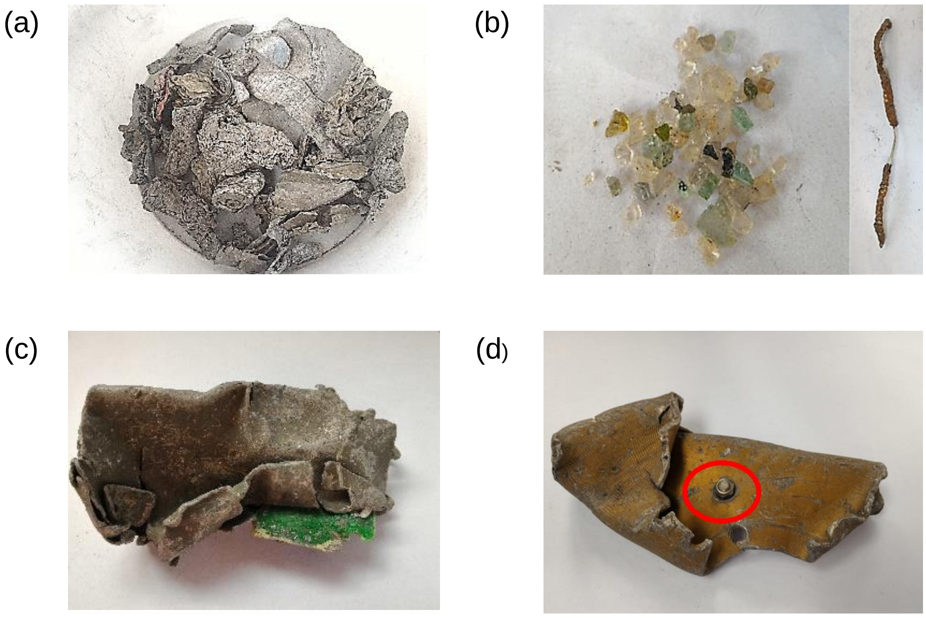


Figure 5-5: Examples of liberation classification for particles in the Al output streams. (a) Liberated Al samples (Al particles only); (b) Liberated/unliberated impurities (liberated glass and unliberated Cu-Fe particles); (c) Unliberated Al sample not due to joint (PWB inserted in Al particle); (d) Unliberated Al sample due to joint (screw and bolt attached to Al particle).

Unliberated particles were further separated into their individual materials. The mass of each material was recorded. For cases where further material separation was not possible due to entanglement or rust, the mass of individual materials was calculated using their volumes and material densities. The types and characteristics of joints causing impurities were observed, and the range of joint sizes, joint material liberation, and the number of rusty joints were recorded quantitatively.

5.4.3 Environmental Impact Assessment

To evaluate the environmental impacts associated with the quality of different Al scrap fractions collected from the case study, LCA was carried out to assess the dilution and quality losses in remelting the scrap to be reused as Al 6061 alloy (AA6061). During remelting, dilution losses occur due to the need to dilute the residual element concentration (e.g. Fe) with primary Al, and quality losses occur due to the addition of alloying elements (e.g. Si and Cu) (Paraskevas et al., 2015). The environmental impact assessment only takes into consideration the secondary Al processing of the defined system boundary shown in Figure 5-6. The wrought Al 6061 was chosen as the target secondary alloy since it is widely used in automotive applications and thus, likely to be close to the average composition of the Al scrap retrieved from ELV. To compare the environmental impacts of smelting different Al scrap, the functional unit is defined as Al recycling to achieve 1 tonne of AA6061. The calculations for the required primary Al for dilution purposes and the additional alloying elements (Si and Cu) are attached in Appendix A. The credits for subsequent recycling of by-products, such as dross and salt slag, were also taken into consideration.

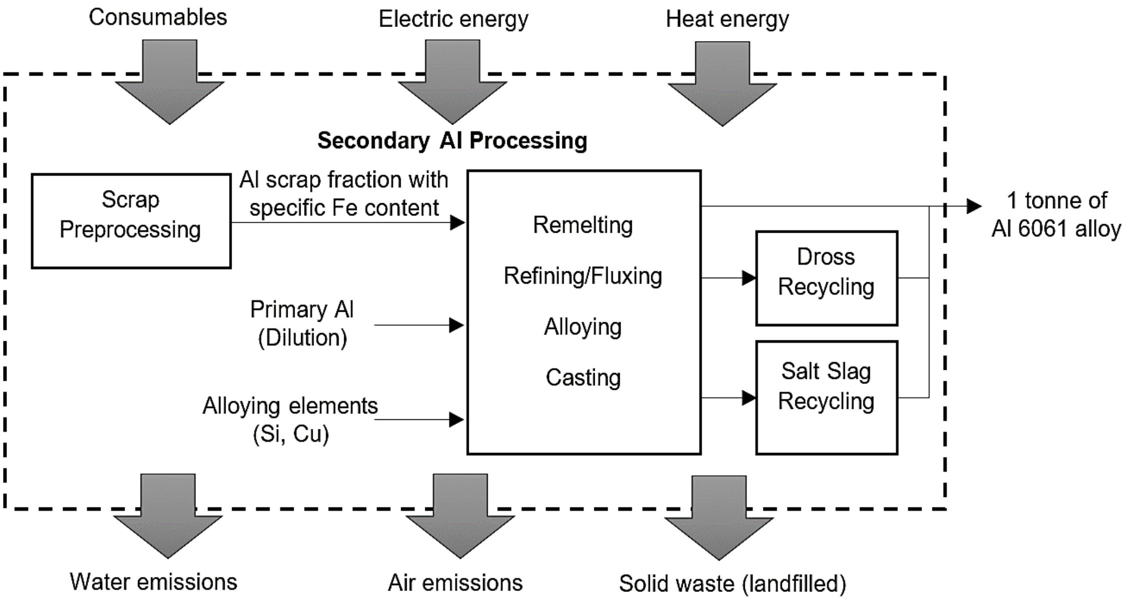


Figure 5-6: System boundary and functional unit of secondary Al processing for different Al scrap fractions.

GaBi software was used to model all the processes and resources involved during the secondary Al processing. The life cycle inventories were obtained from GaBi Professional database v6.115 and a previous comprehensive report from the Aluminium Association (The Aluminium Association, 2013), as detailed in Table 5-5.

Table 5-5: The life cycle inventory data and sources for materials and recycling processes.

Process	**Source**	**Description**
Al scrap preprocessing	(The Aluminium Association, 2013)	The dataset includes scrap collection, separation, cleaning, and preprocessing
Al scrap remelting	(The Aluminium Association, 2013)	The dataset includes remelting, refining, alloying, and casting of secondary Al
Primary Al ingot	GaBi Professional Database v6.115	The dataset includes cradle-to-gate inventory for primary Al ingot production in Europe
Primary Cu	GaBi Professional Database v6.115	The dataset includes cradle-to-gate inventory for primary Cu (99.999%) in Germany
Primary Si	GaBi Professional Database v6.115	The dataset includes cradle-to-gate inventory for primary Si (99%) in global context. The chemical composition is approximated based on Si-2202 (BAIDAO, 2007; SINOGU, 2016)
Dross and salt slag recycling	(The Aluminium Association, 2013)	The dataset includes crushing, milling, screening, remelting, refining, and casting of secondary Al
Electricity	GaBi Professional Database v6.115	The average electricity consumption mix in Europe

The environmental performance was calculated based on the midpoint categories of the International Reference Life Cycle Data System (ILCD recommendations v1.09). These recommendations were based on the ILCD handbook in accordance with the ISO

14040 series (European Commission et al., 2010; ISO, 2006). Following this method, the midpoint results were normalised to person-equivalent unit (the environmental impact caused by an average European annually) to allow comparison of the overall environmental performance for different Al scrap fractions to achieve 1 tonne of AA6061.

5.5 Experiment Results

The liberation categories of the collected Al samples from different fractions were studied. The average Al purity of each fraction was determined. The presence of impurities due to joints was further analysed, and the types of joining techniques causing impurities were characterised. Based on the impurity levels obtained from the case study, a life cycle analysis was carried out to compare the environmental performance for different Al scrap fractions.

5.5.1 Al Sample Analysis

The mass distribution of particles in the different liberation categories is shown in Figure 5-7. Liberated and unliberated impurities were mainly caused by separation errors during the recycling processes, and can be characterised as fine particles (<4mm); materials with similar density range to Al; small and longitudinal heavy metal particles; and materials with density less than Al (<2kg/l). The types of impurities consisted of ferrosilicon fines, glass, PWB, Cu, Fe, wires, plastics, and other light fraction of non-metals. Ferrosilicon fines are an example of fine particles easily trapped in Al samples during the density separation. Glass and PWB have a density range of 2.47-2.54kg/l (Malone and Dolter, 2008) and 1.5-2.89kg/l (Bizzo et al., 2014; Zhang and Forssberg, 1997) respectively that can be similar to Al density. Small heavy metal particles, such as Fe and wires, with thin and long shapes caused them to be entangled between Al particles during the density separation. Plastics, rubber, fabric, fibrous materials, and foam are examples of impurities that were not well separated through density separation at earlier stages. Unliberated Al samples both with or without the presence of joints have higher Al content in the particles by mass and therefore, they were more likely to end up in the Al streams.

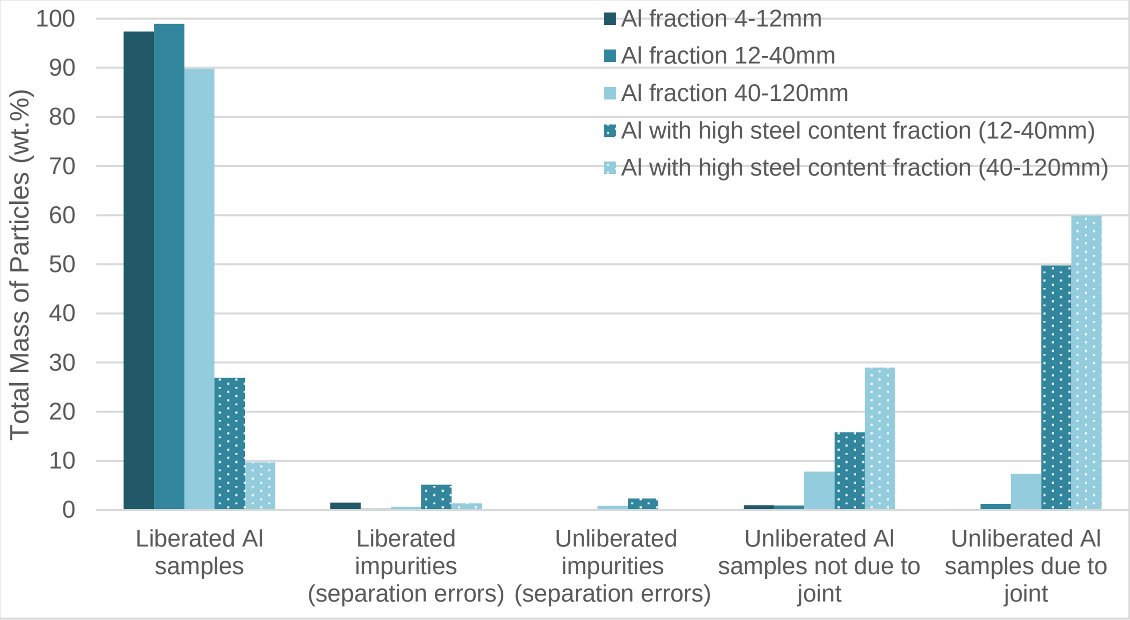


Figure 5-7: Liberation categories for particles in different Al fractions.

From Figure 5-7, the total mass of unliberated Al samples both with and without joints is showing an increasing trend when the particle sizes are larger. This observation is valid for both the Al fraction and Al with high steel content fraction. To understand the purity level of Al samples for different particle sizes, the mass fraction of impurities was calculated, and the result is shown in Table 5-6.

Table 5-6: Al purity for different Al fractions with 95% confidence interval.

Category/Fraction	**Particle Size Class (mm)**	**Al Purity (wt.%)**
Al with high steel content	40-120	82.07 ± 3.86
Al with high steel content	12-40	80.75 ± 3.38
Al fraction	40-120	98.66 ± 0.58
Al fraction	12-40	99.57 ± 0.29
Al fraction	4-12	98.11 ± 0.58

In general, the quality of recycled Al can be separated into two classes: Al purity more than 98%, and Al purity less than 83%. Al purity less than 83% consisted of Al with high steel content fractions that were separated through a strong head pulley magnet as the final separation process in the recycling facility.

Based on the analysis of the shredded samples, smaller particle sizes do not indicate higher Al purity. Al with high steel content fraction (40-120mm), and Al fraction (12-40mm) have higher Al purity values in their respective categories. The geometry, joint size, and material types of the combined parts also affect the purity level of Al fractions in different particle sizes. For instance, when a large number of small steel screw fasteners (i.e. steel screw with diameter and length of 2mm and 4mm respectively) are used, the likelihood of Fe impurities due to screw fasteners present in the Al fraction in smaller particle sizes is quite high with respect to mass.

The material types of impurities were identified to understand the extent of contamination in the Al samples. Some of the impurity types can be removed easily during the secondary Al production whereas others, such as Fe, require a dilution process using primary Al. As seen in Table 5-7, the types of impurities are Fe, Cu, organic, and inorganic. It can be observed that the smaller particle size fraction, 4-12mm has a higher impurity level than the 12-40mm fraction due to the material types and the physical characteristics of impurities. These impurities are largely contributed by ferrosilicon fines (consisting of Fe and Si), thin and long-shaped wires (consisting of Cu and plastics), small pieces of shattered glass (Si) and plastics that typically have small dimensions or high brittleness. Fe impurities are one of the most undesired tramp elements during Al recycling (Cho et al., 2015; Paraskevas et al., 2015) due to their detrimental effect on the mechanical properties of Al alloys (Belov et al., 2002). Therefore, this case study focused on the source of Fe impurities in unliberated samples due to joints to understand the impact of joining choices on the purity level of recycled Al.

Table 5-7: Types of impurities present in the Al output streams in the Belgian recycling facility.

Category/ Fraction	**Particle Size Class (mm)**	**Average Mass Percentage (wt.%)**			
		Fe Impurities	**Cu Impurities**	**Organic Impurities**	**Inorganic Impurities**
Al with high steel	40-120	11.32	0.27	5.82	0.42
Al with high steel	12-40	9.82	1.38	6.40	1.56
Al	40-120	0.36	0.25	0.71	0.05
Al	12-40	0.03	0.13	0.23	0.06
Al	4-12	0.14	0.26	0.96	0.43

5.5.2 Observations on the Joint Type Causing Impurities

From the collected Al samples, it was observed that mechanical fastening and adhesive bonding were the two main types of joining techniques causing impurities. The amount of unliberated Al samples due to adhesive bonding was extremely small. They were mostly combinations of Al and lower density materials, such as Al-plastic and Al-foam particles, using lap joint. Lower density materials assisted in breakage during the shredding process due to centrifugal force, and hence, were less likely to cause impurities in the Al samples.

In contrast, mechanical fasteners were the major type of joining method contributing to the presence of Fe impurities in the Al stream, since they are typically made of steel. They were further classified to understand the different types of mechanical fasteners, and how their characteristics contributed to the presence of impurities. Figure 5-8 shows the various types of mechanical fasteners that were observed in the unliberated Al samples due to joints.

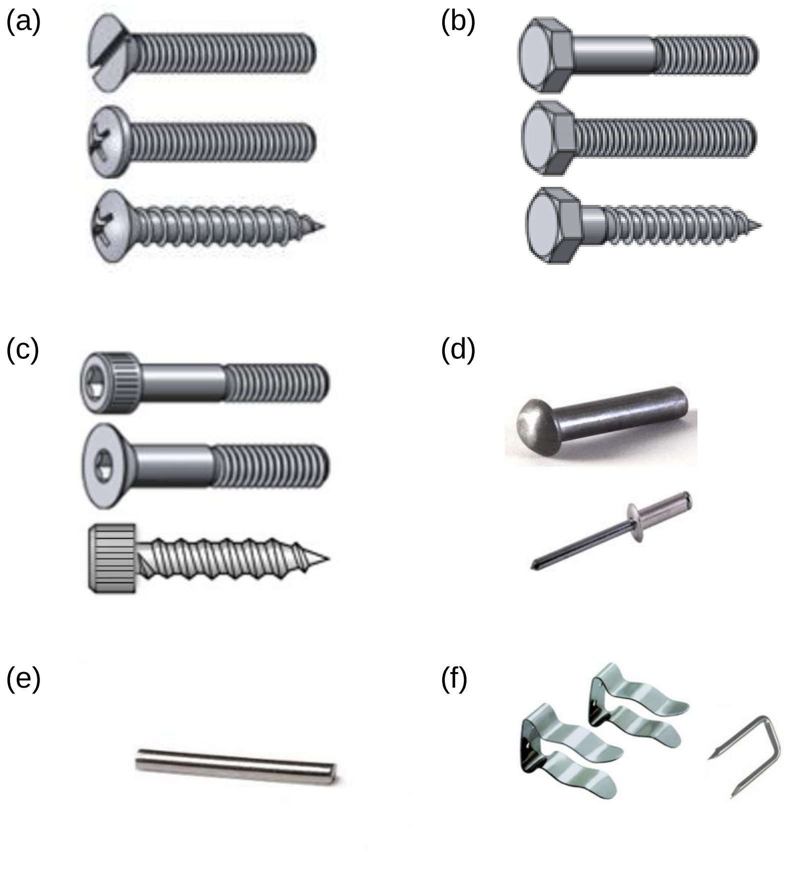
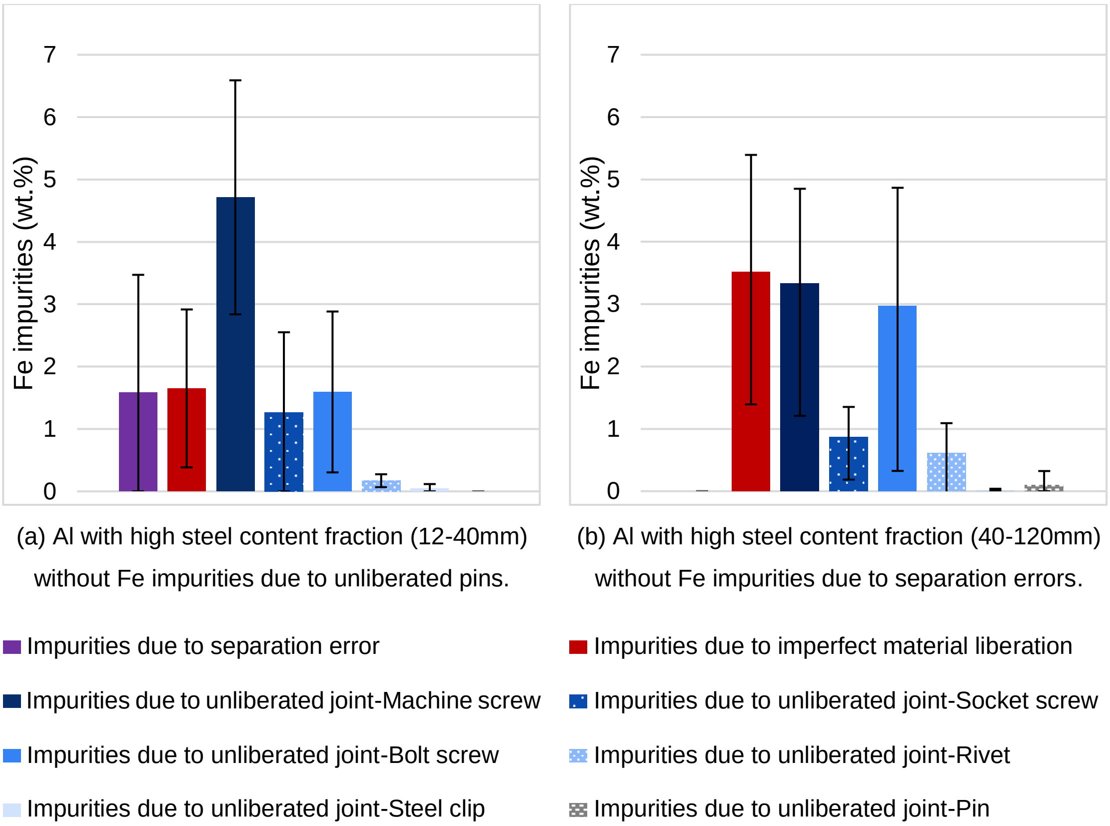


Figure 5-8: Classification of different mechanical fastening joining methods (Bolt Depot, 2013). (a) Machine screw; (b) Bolt screw; (c) Socket screw; (d) Rivet; (e) Pin; (f) Steel clip.

5.5.2.1 Al with High Steel Content Fraction (12-120mm)

In Figure 5-9, it can be observed that the likelihood of Fe impurities due to separation errors decreases for larger particle sizes in the Al with high steel content fraction. Fe impurities that were larger in size have higher likelihood of being separated by the magnetic separator after the shredding process. On the other hand, impurities due to imperfect material liberation were largely caused by structural design, such as enclosures (parts surrounded by different material types) and entanglement (parts that were twisted together or caught in), after the shredding process. Therefore, the likelihood of Fe impurities due to imperfect material liberation increases for larger particle sizes in the Al fraction.



(a) Al with high steel content fraction (12-40mm) without Fe impurities due to unliberated pins.

(b) Al with high steel content fraction (40-120mm) without Fe impurities due to separation errors.

Figure 5-9: Fe impurities present in the Al with high steel content fraction with 95% confidence intervals.

There were a variety of mechanical fastener types causing Fe impurities in the Al with high steel content fractions. Fe impurities observed in smaller particle sizes were caused by unliberated machine screws, socket screws, bolt screws, rivets, and steel clips. No pins were observed for this fraction possibly due to the smoother joining surface that allowed them to be well liberated when shredded to smaller particle sizes. The types of mechanical fasteners causing Fe Impurities in the larger particle sizes were machine screws, socket screws, bolt screws, rivets, steel clips and pin. For both fractions, machine screws were more likely to cause impurities when compared to other mechanical fastener types.

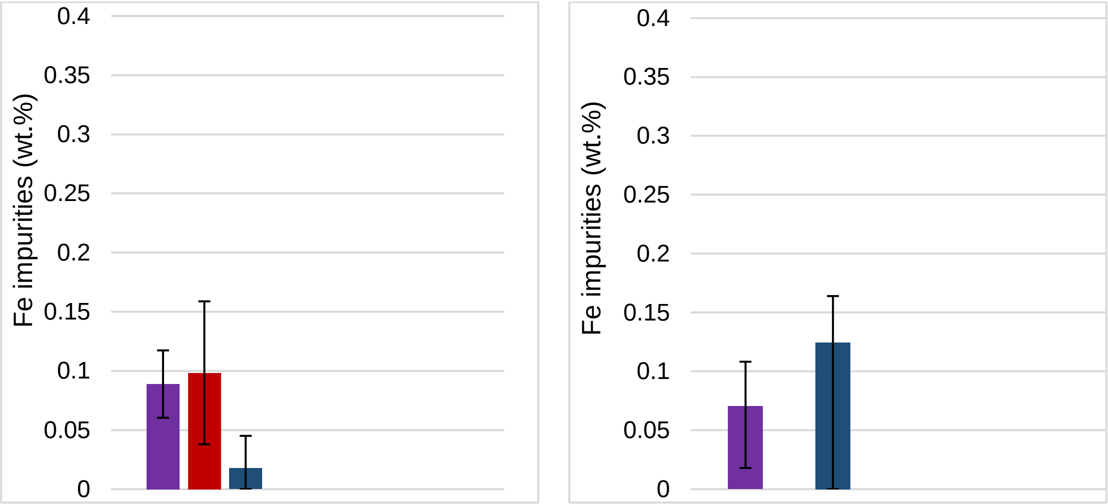
The types of mechanical fasteners causing impurities were further characterised through observation of their physical attributes, as shown in Table 5-8. The percentages are with respect to the total number of each joint type. It is observed that the number of mechanical fasteners (for each joint type) in the larger particle sizes was higher compared to the smaller particle sizes except for machine screws and steel clips. Moreover, the fraction with larger particle sizes has a wider range of fastener sizes when compared to smaller particle sizes. However, the number of fastener sizes with diameter and length more than 6mm and 10mm respectively (large fastener sizes) is similar for both particle size classes. Partial liberated joints, those with more than 50 wt.% of the joint material liberated, were more likely for threaded fasteners such as machine screws and bolt screws. In most cases, the fasteners' head was liberated due to protrusion. Rusty threaded fasteners were also more likely to cause impurities in the Al samples.

Table 5-8: Characteristics of joints causing Fe impurities in Al with high steel content fractions.

Joint Types	**Total (unit)**	**Fastener Size (mm)**		**Large Fastener Size (%)**	**Partially liberated (%)**	**Rust (%)**
		Diameter	**Length**			
12-40mm						
Machine screw	101	2-10	3-30	12	9	86
Socket screw	11	4-7	9-36	27	0	64
Bolt screw	16	4-10	8-50	56	0	94
Rivet	13	4-5	3-13	0	0	46
Steel clip	19	2-3	10	0	0	0
40-120mm						
Machine screw	94	2-12	2-30	12	4	76
Socket screw	20	3-9	10-60	30	0	85
Bolt screw	39	3-14	7-125	52	8	76
Rivet	48	5-6	3-50	1	0	48
Steel clip	2	2-3	12	0	0	0
Pin	1		10	0	0	0

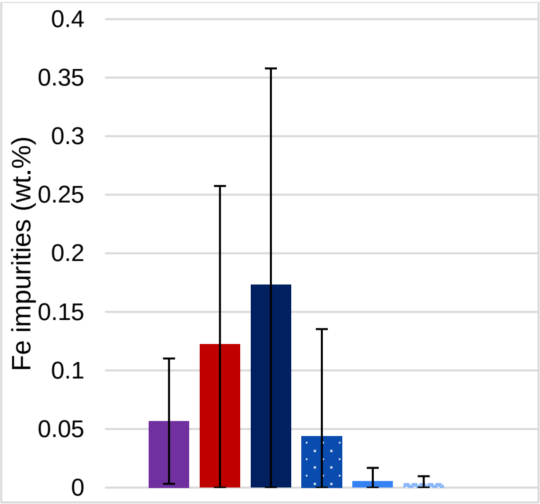
5.5.2.2 Al Fraction (4-120mm)

Similar to Al samples with high steel content, the likelihood of Fe impurities due to separation errors decreases for larger particle sizes in the Al fraction, as seen in Figure 5-10, since they can be easily sorted through magnetic separation. In contrast, impurities due to imperfect material liberation could potentially be higher for larger particle sizes, although they were not observed in the Al fraction (12-40mm).



(a) Al fraction (4-12mm) with Fe impurities due to separation errors, imperfect material liberation, and unliberated machine screws.

(b) Al fraction (12-40mm) with Fe impurities due to separation errors and unliberated machine screws.



(c) Al fraction (40-120mm) with Fe impurities due to a variety of unliberated joint types.

🟪 Impurities due to separation error
🟥 Impurities due to imperfect material liberation
■ Impurities due to unliberated joint-Machine screw
▨ Impurities due to unliberated joint-Socket screw
🟦 Impurities due to unliberated joint-Bolt screw
▨ Impurities due to unliberated joint-Rivet

Figure 5-10: Fe impurities present in the Al fraction with 95% confidence intervals.

The likelihood of Fe impurities due to mechanically fastened joints in the Al fraction is higher for larger particle sizes. There was more variety of mechanical fastener types that contribute to the Fe impurities in the Al fraction (40-120mm). Machine screws were the only type of joint causing impurities in the smaller particle sizes, whereas machine screws, socket screws, bolt screws, and rivets were observed in Al fraction (40-120mm). Despite the use of a strong head pulley magnet to remove small Fe content, machine screws contaminating the different Al fractions were still present.

Table 5-9 shows the attributes of mechanical fasteners causing Fe impurities in the different Al fractions. The number of machine screws observed in Al fraction (40-120mm) was larger compared to the fraction containing the smaller particle sizes. However, there was still a small number of machine screws present in this smaller particle size fraction. This was due to the lower magnetic force experienced by small screws located at enclosed spots despite the use of a strong head pulley magnet. In contrast, the presence of mechanical fasteners other than machine screws (socket screws, bolt screws, and rivets) was only seen in Al fraction (40-120mm). Socket screws and bolt screws have a more protruded head compared to machine screws that facilitate liberation during the shredding process. On the other hand, rivets have a smooth surface that allows them to be easily set free when shredded into smaller particle sizes. The likelihood of impurities due to larger fastener sizes or of partial liberation is higher for larger particle sizes particularly for the machine screw fastener type.

Table 5-9: Characteristics of joints causing Fe impurities in Al fractions.

Joint Types	**Total (unit)**	**Fastener Size (mm)**		**Large Fastener Size (%)**	**Partially liberation (%)**	**Rust (%)**
		Diameter	**Length**			
4-12mm						
Machine screw	2	3-4	8	0	0	100
12-40mm						
Machine screw	1	5	20	0	0	100
40-120mm						
Machine screw	17	3-8	5-25	18	12	50
Socket screw	1	4	18	0	0	0
Bolt screw	2	4	11-12	0	0	50
Rivet	2	5	7	0	0	0

5.5.3 Environmental Impact Assessment Results

The share of environmental impact associated with the recycling, dilution, and quality losses for different Al scrap fractions to achieve 1 tonne of AA6061 is shown in Figure 5-11. Based on the LCA results, the total environmental impact for Al with high Fe scrap fractions (both particle sizes) has increased by at least 28 times in comparison to the Al scrap fractions (4-12mm, 12-40mm, and 40-120mm) due to the higher concentration of Fe, Si, and Cu, which can be considered as impurities rather than useful alloying elements for the production of AA6061. The contribution of different midpoint impact categories for the different Al scrap fractions to produce 1 tonne of AA6061 is provided in Appendix B. The use of primary Al for dilution is the major contributor to the environmental impact for Al scrap with high steel content with an impact share of at least 92%, as supported in other studies (Amini et al., 2007; Paraskevas et al., 2015). To achieve higher purity wrought Al alloy, a substantial amount of primary Al is required for the dilution of these streams, and alloying elements are added to meet the compositional limits. This results in scrap underutilisation. The use of primary Al for dilution can be minimised by using other high purity scrap streams and optimised Al scrap blending (Paraskevas et al., 2015).

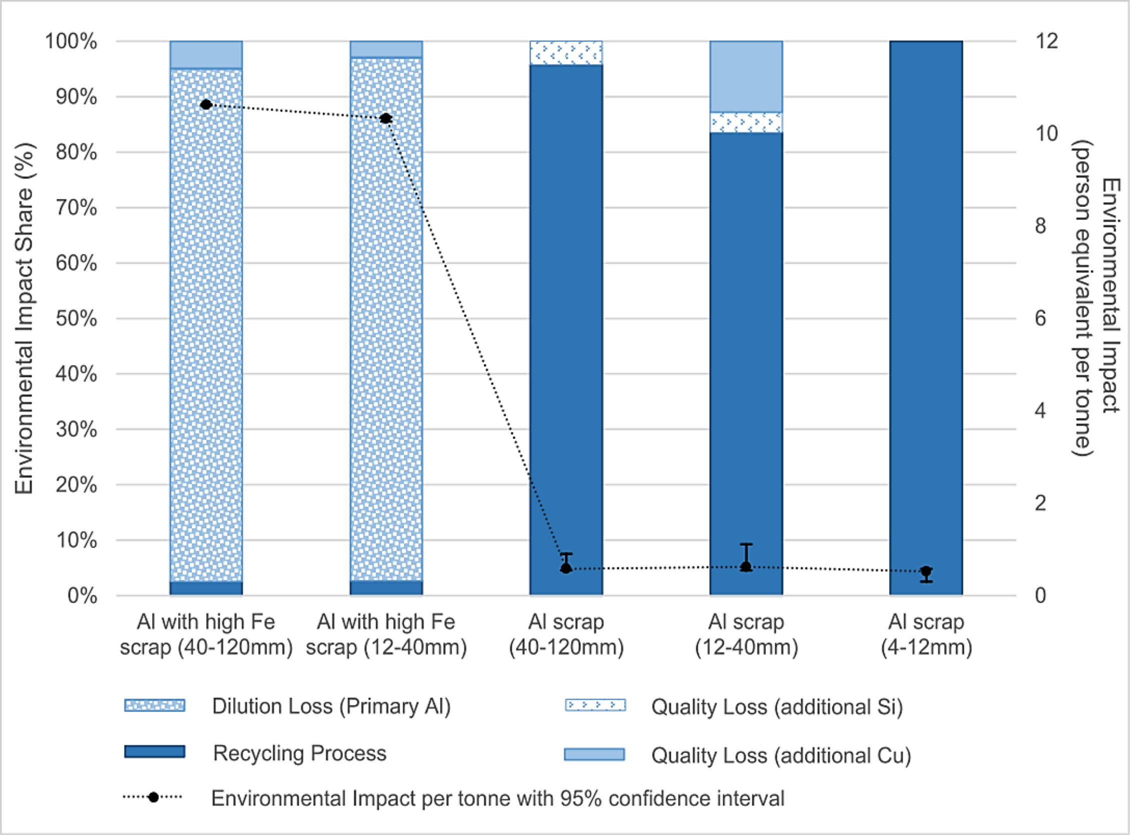


Figure 5-11: Total environmental impact and the percentage share of recycling, dilution, and quality losses for different Al scrap fractions to achieve 1 tonne of AA6061.

A sensitivity analysis was carried out to assess the influence of varying impurity levels for different Al scrap fractions. The range of values for Fe, Si and Cu impurities are shown in Table 5-10. As can be seen from Figure 5-11, the total environmental impact is sensitive to the range of impurity levels of Fe, Si, and Cu for different Al scrap fractions. It is shown that the margin of error for the total environmental impact can be up to ±0.5 person equivalent per tonne. However, the trend of the total environmental impact for the range of impurity levels is largely unaffected. The total environmental impact for Al scrap fractions is largely contributed by recycling process and quality losses. In spite of that, the negative impact is insignificant compared to Al scrap with high steel content.

Table 5-10: The range of values for impurities present in the different Al scrap fractions with 95% confidence interval.

Category	**Particle Sizes (mm)**	**Fe (wt.%)**		**Si (wt.%)**		**Cu (wt.%)**	
		min	**max**	**min**	**max**	**min**	**max**
Al with high steel fraction	40-120	9.95	12.69	0	0.94	0	0.46
Al with high steel fraction	12-40	7.12	12.53	0	3.51	0.51	2.24
Al fraction	40-120	0.03	0.68	0	0.11	0.06	0.46
Al fraction	12-40	0	0.06	0.03	0.09	0	0.28
Al fraction	4-12	0.07	0.20	0.27	0.54	0.14	0.38

As can be seen from Figure 5-12, about 70% of the total impact share of dilution losses for Al scrap with high steel content is caused by unliberated joints. Dilution losses due to material separation errors can only be observed for Al with high Fe scrap in smaller particle sizes due to the presence of Si from the shattered glass. The environmental evaluation based on the case study data shows that the dilution and quality loss impacts are tightly-linked to the quality or purity level of the recovered Al streams resulting from the degree of material liberation. The high Fe content that is significantly contributed by unliberated joints and imperfect material liberation has become a limiting factor for the recyclability of the Al streams. It is worth noting that the environmental performance may vary according to the efficiency of recycling technologies used in different countries.

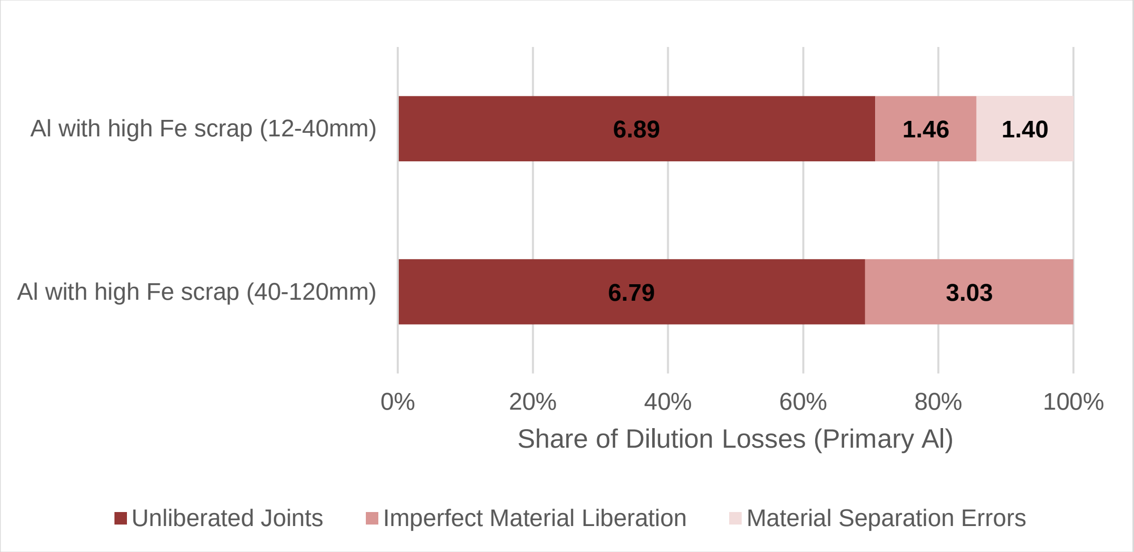


Figure 5-12: The percentage share of dilution losses (primary Al), and the environmental impact (person equivalent per tonne) due to liberation categories.

5.6 Discussion

The annual Al output streams in the Belgian recycling facility are shown in Table 5-11. The material composition in each Al stream is estimated from the performed sampling, and subjected to the variation based on the 95% confidence interval. Despite the large variance for certain tramp elements in different Al output streams, the impact on the environmental performance is insignificant. Al fractions (12-40mm) and (40-120mm) are the two largest fractions with high Al purity levels of 99.57% and 98.66% respectively, whereas the Al with high steel content fraction has the lowest annual amount with low Al purity level of 81.28% (combination of both particle sizes). With the increasing complexity of multi-material designs, particularly in the automotive sector which is one of the largest consumers of Al, it is projected that the Al with high steel content fraction will be growing and thus, lead to the reduction of the Al fraction with higher purity (Soo et al., 2016, 2015).

Table 5-11: Estimated material composition for the Belgian recycling facility's annual Al output streams based on the extrapolation of sampling results.

Material Type	**Al with High Steel Content (12-120mm)**		**Al Fraction (40-120mm)**		**Al Fraction (12-40mm)**		**Al Fraction (4-12mm)**	
	ton	***wt.%***	***ton***	***wt.%***	***ton***	***wt.%***	***ton***	***wt.%***
Al	523.5	81.28	6048.5	98.66	4128.6	99.57	1093.0	98.11
PWB	2.09	0.32	3.14	0.05	1.45	0.03	6.04	0.54
Wire	4.21	0.65	18.8	0.31	2.41	0.06	2.72	0.24
Cu	0.62	0.10	7.6	0.12	4.24	0.10	0.61	0.06
Plastic/ composite	12.13	1.88	19.44	0.32	3.87	0.09	3.57	0.32
Rubber	18.26	2.84	6.71	0.11	2.67	0.06	0.2	0.02
Steel	75.82	11.77	21.39	0.35	0.73	0.02	1.29	0.12
Foam	0.57	0.09	0.46	0.01	0.21	0.01	0	0
Fabric	2.19	0.34	2.16	0.04	0	0	0	0
Synthetic leather	0.28	0.04	0	0	0	0	0	0
Glass	0	0	0	0	0	0	5.06	0.45
Fibrous material	2.66	0.41	0	0.41	0	0	0.4	0.04
Ferrosilicon fine	1.7	0.26	3.86	0.06	2.8	0.07	1.16	0.10
TOTAL:	**644**	**100**	**6132**	**100**	**4147**	**100**	**1114**	**100**

From the analysed samples, most of the Fe impurities were due to unliberated joints particularly for Al with high steel fractions, and Al particles of larger sizes, as seen in Table 5-12. Particles with unliberated joints in the Al with high steel fractions have contributed at least by 69% to the total Fe impurities. When the particle sizes for different Al fractions decrease, the total Fe impurities due to unliberated joints decrease by at least 33%. Therefore, smaller particle sizes can assist in reducing Fe impurities due to unliberated joints. However, the proportion of Fe impurities due to separation errors or imperfect material liberation is higher for Al fractions with smaller particle sizes. The presence of these impurities is strongly influenced by the material structural design, fastener size used, and the efficiency of the recycling processes in sorting small to fine particles. Thus, additional loops in Fe impurity removal or adjustment of the installation with strong magnets could assist in reducing material separation errors for smaller particle sizes.

Table 5-12: The proportion of Fe impurities due to separation errors, imperfect material liberation, and unliberated joints.

Category/Fraction	**Particle Size Class (mm)**	**Total Fe Impurities (wt.%)**		
		Separation Errors	**Imperfect Material Liberation**	**Unliberated Joints**
Al with high steel	40-120	0	3.52	7.88
Al with high steel	12-40	1.41	1.47	6.94
Al	40-120	0.04	0.08	0.24
Al	12-40	0.03	0	0.01
Al	4-12	0.06	0.07	0.01

5.7 Concluding Remarks

The findings from this chapter support the observations on the joint types affecting the material recyclability in the Australian case study (Chapter 4). Despite the rigorous recycling processes used in Europe, the joint types causing unliberated particles were similar. This study shows that the amount of tramp elements presence in the different recovered streams has a significant influence on the scrap quality; thus, the environmental impacts of dilution and quality losses during metal scrap recycling need to be integrated into LCA for better-informed decisions towards closed-loop recycling.

The main type of joining techniques causing impurities in the Al streams are mechanical fasteners, such as machine screws, socket screws, bolt screws and rivets, which are commonly used for assembling Al with other materials. Although adhesive bonding was also observed to cause impurities in the Al particles, these were relatively small and almost negligible when compared to the effects of mechanical fastening joints.

Based on the observations of the collected samples, machine screws were the major type of mechanical fasteners causing Fe impurities in different Al fractions due to their joint characteristics. This was consistently observed for various particle sizes. Machine screws are normally less protruded compared to other mechanical fasteners, such as bolt screw and socket screw. A higher level of protrusion eases joint liberation during the shredding process. In addition, machine screws that were smaller in size, and corroded due to moisture have caused more challenges for particle liberation. There were also cases of partial liberation due to the threaded structure that have further hindered full material liberation.

Unliberated Al samples due to the presence of joints are less likely for smaller shredder output fractions with respect to the total mass of particles. It was shown that smaller particle sizes ease liberation of Fe impurities from the joints. However, when considering the Al purity level for different particle sizes, they do not indicate a higher purity level for smaller particle sizes. This was largely caused by the increasing proportion of Fe impurities due to separation errors and imperfect material liberation. Although sorting of Al scrap into different fractions is proven to be effective in obtaining high quality Al in most European countries, it is important to understand the quality of recycled Al scrap in high consumption countries, such as in China (RBC Capital Markets, 2015), from a global perspective.

Based on the LCA results of recycling different Al scrap qualities, Al with high steel fractions have a more significant environmental impact in comparison to the Al fractions due to the use of primary Al for dilution. Particles with unliberated joints in the Al with high steel fractions have contributed significantly to the total impact share of dilution losses, at least by 69%. This shows that the liberation of joints is critical in determining the purity level of different Al fractions.

In conclusion, the choice of joining techniques during the design phase has a significant impact on the environmental performance during the ELV recycling phase. This is consistently observed for different recycling approaches adopted in different countries. In the next chapter, the relationship between the changing vehicle designs and their associated joining techniques, and the long-term effect on material recycling from the life cycle perspective is explored. Based on the observations from case studies, the dynamic behaviours of the vehicle recycling systems are explained.

Chapter 6

The Impact of Joints on Vehicle Recycling Systems

Publication relevant to this chapter:

Soo VK, Compston P, Doolan M. The Impact of Joining Choices on Vehicle Recycling Systems. *Procedia CIRP* 2018; 69:843-848.

6.1 Introduction

This chapter addresses the influence of joining choices on the material recycling efficiencies through current recycling practices using the System Dynamics (SD) approach. The dynamic behaviours of the vehicle life cycle analysis due to joint effects are observed from different recycling approaches based on the case studies presented in Chapter 4 and Chapter 5. Although the commonly used LCA method is effective in assessing the environmental impacts associated with each vehicle life cycle stage (see Section 4.3 and Section 5.5.3), there is a lack of consideration for the changing material and joining trends, and their delayed impact on the ELV recyclability. The vehicle life cycle analysis only provides the environmental performance that is representative of a point in time. As highlighted in Section 3.4.2, the temporal effects between vehicle designs and recycling phases can be accounted for using the SD approach to produce dynamic vehicle recycling models. The behavioural patterns of the vehicle recycling systems, emphasising the life cycle impact of different joining choices on vehicle recyclability, can then be characterised to well known system archetypes.

In the first section, an overview of the model conceptualisation process is provided to discuss the integration of system archtypes into the SD modelling approach. The next section articulates the dynamics between the joining choices for new vehicle designs and their impact on vehicle recycling based on the observations from case studies and historical trends. This is followed by the description of the main feedback loops lead to the use of joining techniques that have an influence on the vehicle life cycle impact through time delay. Based on the formulated dynamic hypothesis, the intended behaviour and system reaction loops are then combined to interpret the vehicle recycling models that highlight the effect of joints on material recycling efficiencies. Finally, the characteristics of the vehicle recycling models are explained based on the basic structures of widely known system archetypes to present the emerging behavioural patterns over time.

6.2 Model Conceptualisation Process

The SD modelling process used in this thesis is shown in Figure 6-1. System archetypes—generic structures used to describe insights in terms of system structure and behavioural patterns over time—were integrated during the modelling process to assist in translating the observed problems to mental models (Corben, 1994; Dowling et al., 1995; William, 2002). The steps taken for the model conceptualisation process are detailed in Section 6.3 to Section 6.8.

Figure 6-1: Integration of system archetypes into the framework for model conceptualisation in SD modelling process (Adapted from (Corben, 1994; Sterman, 2010)).

6.3 Problem Articulation

The first step taken to build the automotive recycling models was to clearly define the recycling problem. Through observation of the current vehicle industry, it is shown that the increasing multi-material vehicle designs has led to the growing fraction of unliberated joints that reduces the material recycling efficiencies during EoL phase (see Chapter 4 and Chapter 5). Moreover, the growing amount of impurities due to unliberated joints in the valuable recovered fractions has led to dilution or quality losses (see Section 5.5.3). Valuable materials are also increasingly entering landfills due to imperfect material liberation. Consequently, primary non-renewable resources are continuously extracted for the dilution of impurities present in the valuable output streams, and the replacement of valuable materials lost in ASR. Observations from the case studies have shown that the choice of joining techniques has an influence on the presence of impurities and the loss of valuable materials in the different output streams (Section 4.5 and Section 5.5.2). Therefore, the dynamic interaction between new vehicle designs and vehicle recyclability was investigated from a joining techniques perspective.

6.3.1 Model Boundary

To set the boundary of the modelled problem, key variables were determined. The model boundary chart in Table 6-1 outlines the scope of the model to three main categories: endogenous, exogenous, and excluded during the first iteration. The categorisation of variables may change during the iterative process for cases such as the expansion of model boundary (Richardson, 2011; Trimble, 2014). For example, excluded variables can be considered as a part of the model expansion, and exogenous variables can be upgraded to endogenous variables (Trimble, 2014). As noted by (Sterman, 2002), model boundary charts are used to assist in expanding the boundaries of mental models, and to highlight the limitations of the simulated models. The different categories of variables are explained as follows.

Endogenous variables generate the dynamics in the system, and involve dynamic variables that are driving the feedback loops of the system (Sterman, 2010). The endogenous variables driving the studied vehicle recycling systems were mainly the variables in the balancing and reinforcing loops.

Exogenous variables are external conditions that influence the endogenous variables, and their values are not directly affected by the system (Sterman, 2010). These variables are essential to set the external conditions that drive the system behaviour. Based on the vehicle recycling model, the total vehicle environmental impacts were also affected by the material extraction and vehicle manufacturing phases although the recycling system focused on the effect of vehicle use and recycling phases.

Excluded variables do not contribute, or have little contribution to the model behaviours of the defined scope. Thus, these variables are not taken into consideration (Sterman, 2010). It is crucial to identify the excluded variables to understand the limitations of the system, and the potential areas for model expansion.

Table 6-1: Vehicle recycling model boundary chart. Excluded variables in italics are variables that can be part of the endogenous or exogenous variables.

Endogenous Variables	**Exogenous Variables**	**Excluded Variables**
Lightweight multi-material fraction Vehicle mass Vehicle CO_2 emissions Vehicle life cycle environmental impact Vehicle emission target Mass of impurities due to joints Mass of recyclable materials in ASR due to joints Material recycling efficiency Vehicle recycling environmental impact Vehicle recycling target Dilution environmental impact Material loss replacement environmental impact	Vehicle extraction and manufacturing environmental impact Vehicle fuel consumption (petrol fuel) Time frame for new multi-material vehicle designs Time frame for vehicle reaching EoL stage	Alternative fuel consumption Fuel consumption of new powertrain *Cost of raw materials* *Valuable material price* *Recycling cost* *Scrap price*

The conceptualisation of the SD models is limited by the following dynamics that are beyond the scope of this study:

- Adoption of alternative fuels, such as electricity, diesel, natural gas, and biodiesel.
- Adoption of new advanced powertrain technologies, such as hybrid electric and plug-in hybrid electric.
- Variation for different vehicle class sizes, such as sport utility vehicle and sports vehicle.
- Variation in the raw material prices and recycling costs.
- Variation in consumer behaviours driving the vehicle use patterns in different regions.

Since the variables in the recycling models were based on the data collected from case studies of actual recycling scenarios, the economic aspects were indirectly influencing the recycling systems. For instance, the changing fraction of lightweight materials was determined through the data collected on vehicle material composition. In the actual scenario, the higher cost of lightweight materials in comparison to conventional materials limits their widespread use in vehicle production. Although the variable for raw material cost was not included in the model, the changing fraction of lightweight materials has reflected the effect of cost indirectly. Similarly, the recycling costs are reflected through the material recycling rates obtained from the case studies based on the various recycling approaches adopted in different countries.

The time horizon considered in the conceptualised models is from 1980 till 2028. The period allows the predicted model behaviours to be extended far enough to capture the delays and effects of emerging new vehicle designs on the vehicle recyclability. For example, new multi-material vehicles made in 2013 will only reach the EoL stage in 2023-2027 based on the estimated vehicle use life of about 10-14 years (Australian Bureau of Statistics, ABS, 2013; Inghels et al., 2016; Messagie et al., 2010).

6.3.2 Reference Modes

To elicit key reference modes of the dynamic behaviours observed through the different vehicle recycling systems, the historical trends for important variables were obtained from the literature. The behaviour of the models' key variables was hypothesised and projected based on the past historical trends and observations from literature data (Albin, 1997; Saeed, 1998). In this section, the historical and projected behaviours for vehicle CO_2 emission, average vehicle mass, and lightweight multi-material fraction were provided. The joining trends and their effect on the presence of impurities and material losses were hypothesised based on literature. The overall observations from literature were then used to create the reference mode for the total vehicle life cycle environmental impact that includes exergy losses.

The significant contribution of the transportation sector to the GWP has led to the implementation of a series of CO_2 emission targets in Europe. For the past 20 years, stricter vehicle emission targets have been legislated, as can be seen in Table 6-2. In 2012, the average vehicle CO_2 emission achieved the target set for 2015. Vehicle manufacturers are still improving the vehicle fuel efficiency to reach the emission target required by 2021.

Table 6-2: European Union legislations on CO_2 emission targets for passenger vehicles (European Commission, 2014; Mock, 2016).

Standard	**Target Year**	**Emission Target (g CO_2 km)**
1999/125/EC	2008	140
(EC) No 443/2009	2015	130
(EC) No 333/2014	2021	95
(EC) No 333/2014 (proposed)	2025	68-78

As shown in Figure 6-2, the enactment of vehicle CO_2 emission policy in Europe is effective in driving the production of vehicles with high fuel efficiency. The average vehicle CO_2 emissions in Europe is lower compared to Australia where there are no mandatory regulations. In recent years, the Australian government is looking for opportunities to further reduce the vehicle emissions through effective policy (Climate Change Authority, 2014). It is projected that the average vehicle CO_2 emissions for both countries or regions will continue to decrease based on the annual improvement rate or stricter emission targets.

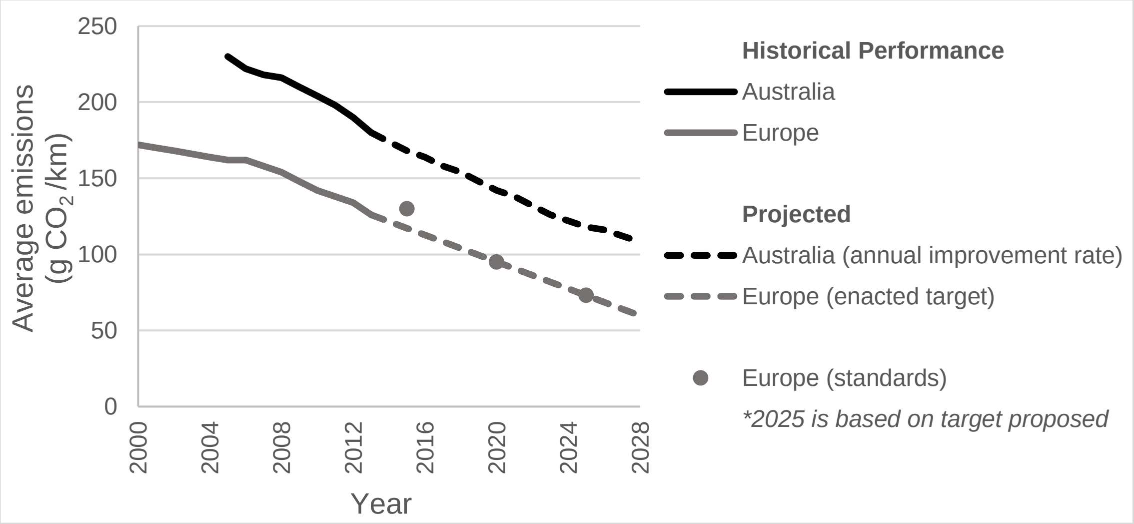
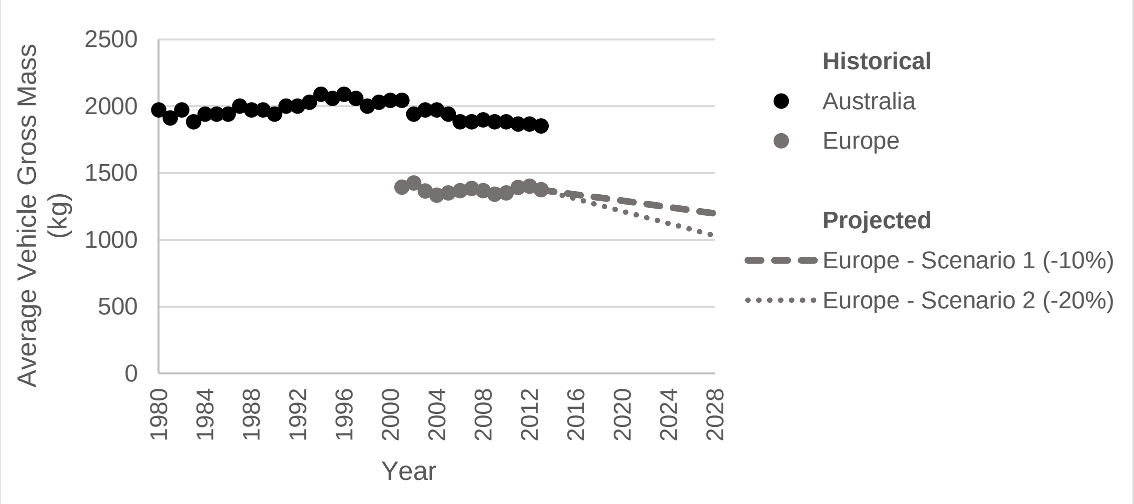


Figure 6-2: The historical average CO_2 emissions of passenger vehicles in Australia and Europe normalised to European drive cycle (NEDC), and the projected average CO_2 emissions based on annual improvement rate or vehicle emission targets (Adapted from (Climate Change Authority, 2014)).

As discussed in Chapter 2, one of the most effective measures to improve the vehicle's fuel efficiency is through vehicle mass reduction. The average gross mass for passenger vehicles has shown a decreasing trend, and this is projected to continue in Australia and Europe. The decreasing mass of average vehicle depends on the mass reduction potential as shown by the projected values for different scenarios in Figure 6-3.



The projected value for Europe is based on two scenarios (Kühlwein, 2016):

i. Scenario 1: An average reduction of vehicle mass by 10% based on current technologies.

ii. Scenario 2: A maximised vehicle mass reduction potential by 20%.

Figure 6-3: The historical average vehicle gross mass in Australia and Europe, and the projected average vehicle gross mass in Europe (Adapted from (Bureau of Infrastructure, Transport and Regional Economics (BITRE), 2014; European Environment Agency, 2013; Kühlwein, 2016)).

To optimise the vehicle mass reduction potential, lightweight materials and multi-material vehicle designs are increasingly used. Since 1980, there is a significant growth in the percentage of lightweight materials used for multi-material designs, as can be seen in Figure 6-4. Stricter emission targets will continue to encourage the increasing use of lightweight materials in future.

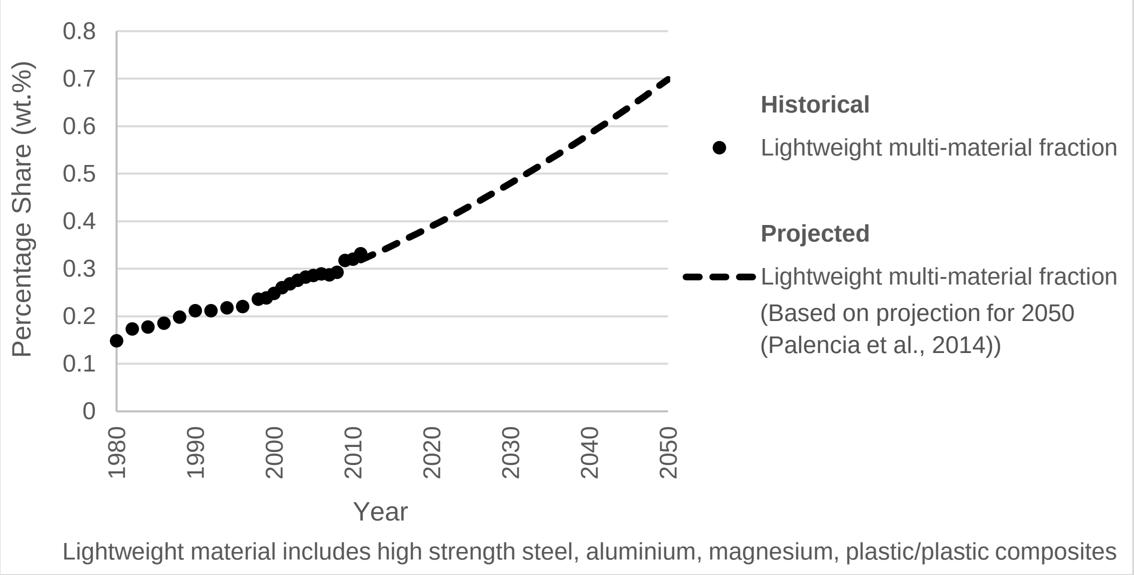


Figure 6-4: The historical and projected percentage of vehicle lightweight multi-material fraction. The projected value is adjusted based on the lightweight vehicle composition in 2050 (Adapted from (American Automobile Manufacturers Association et al., 1994; Palencia et al., 2014; U.S Department of Energy, 2013)).

The varying multi-material vehicle designs have led to the changing trends in joining techniques. The combination of different material types limits the number of applicable joining methods, often restricting to mechanical fasteners and adhesive bonding that hinder material liberation. Consequently, the increasing use of these joining techniques has caused the growing amount of impurities present in the different recovered fractions. As shown in Figure 6-5, the mass percentages of impurities in valuable output stream and the valuable material losses in ASR stream due to unliberated joints are projected to show similar growth due to the limitation of current shredder-based recycling process.

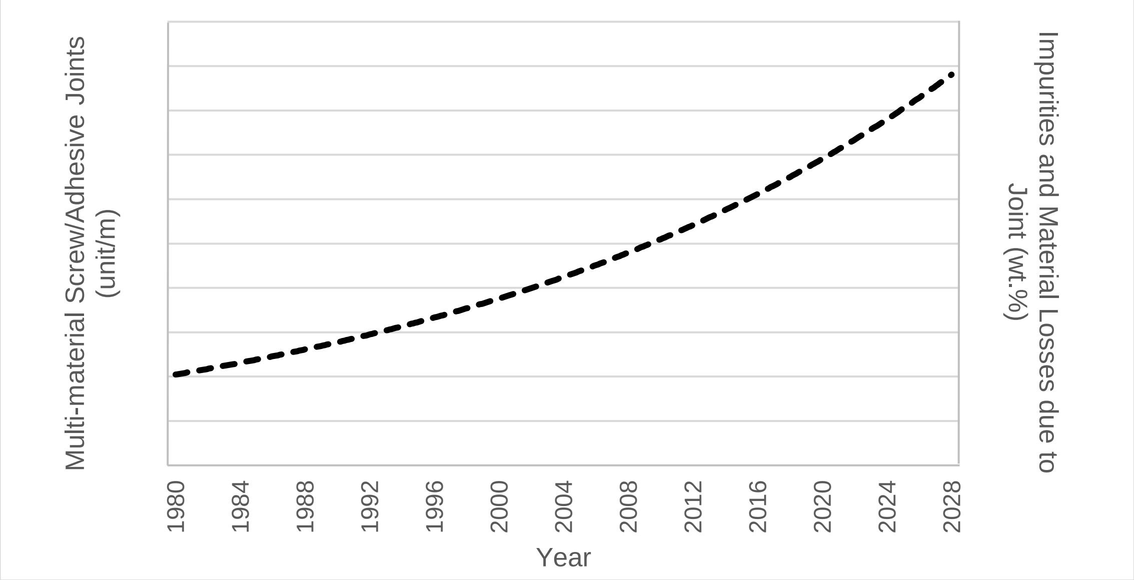


Figure 6-5: The hypothesised trend for screw and adhesive joints with different material combinations, and their impact on the impurities and material losses due to joints (Grote and Antonsson, 2009).

The environmental impact of each life cycle stage can be inferred based on the historical and projected trends in multi-material vehicle designs and their associated joining trends, as can be seen in Figure 6-6. The exergy losses through dilution and additional alloying elements were included in the recycling phase to account for a closed-loop recycling system.

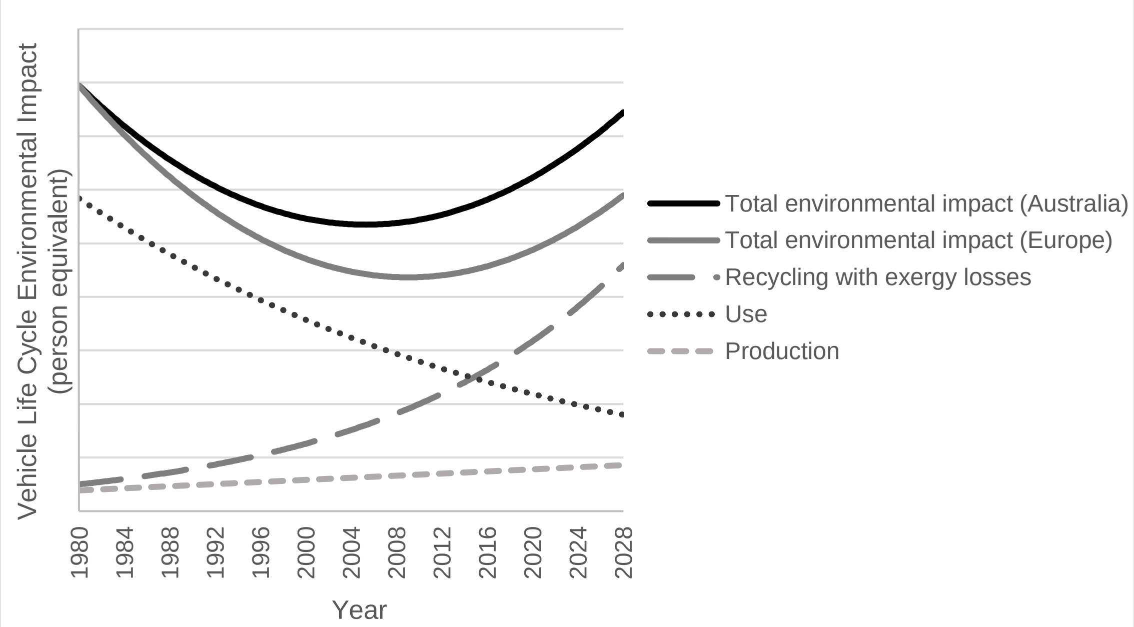


Figure 6-6: The hypothesised trends for the vehicle life cycle environmental impact in Australia and Europe based on the different life cycle stages (Soo et al., 2016, 2015).

The vehicle life cycle environmental impact in Europe is predicted to be lower compared to Australia due to the implementation of ELV Directive. The Directive 2000/53/EC set targets for reuse, recycling, and recovery, as shown in Table 6-3. Despite the strict minimum targets to be achieved based on mass percentage, there are no standardised procedures to calculate the actual material recycling efficiencies (i.e. taking into consideration the impurities present in the recovered output streams). The ELV regulation has driven the improvement of recycling technologies over time; however, exergy losses persist when considering a closed-loop system to obtain the required material quality. This is because the shredding process, that caused the imperfect material liberation, is still utilised.

Table 6-3: ELV regulatory framework in Europe (E. U. Directive, 2000).

Description	**Target by 2006 (wt.%)**	**Target by 2015 (wt.%)**
Reuse and recycling	80	85
Reuse and recovery	85	95

6.4 Dynamic Hypothesis

Observations from past historical trends on material and joining techniques used in vehicle industry (see Chapter 2), and the case study data on vehicle recycling (see Chapter 4 and Chapter 5) were used to generate the dynamic hypothesis: the increasing use of joining techniques, such as mechanical fasteners, for multi-material vehicle designs has led to the decreasing material recycling efficiencies that are caused by the growing amount of impurities and material losses due to unliberated joints. This hypothesis describing the recycling problem focuses on how critical the choice of joining techniques for multi-material vehicle designs is in determining the actual material recycling efficiencies—mass percentage of collected output streams excluding impurities. The choice of joining techniques can influence the amount of impurities in different valuable output streams, and the amount of valuable material losses in ASR entering landfills.

6.4.1 Formulating the Dynamic Hypothesis

To formulate the dynamic hypothesis of the current vehicle industry, intended behaviours were specified (i.e. the increasing use of lightweight vehicles has shown significant improvement in fuel efficiency). The system reactions caused by the actions implemented to drive the intended behaviours were identified (i.e. the increasing use of lightweight vehicles has led to the changing vehicle material composition and multi-material designs). These behaviours were described through the main feedback loops in the vehicle recycling systems.

In this section, the balancing and reinforcing loops driving the level of vehicle life cycle environmental impact are explored using Causal Loop Diagrams (CLD) (Sterman, 2010). CLD are often used to map the causal structures and formulate the dynamic hypothesis through negative causal link (when the cause increases, the effect decreases or vice versa), and positive causal link (when the cause increases, the effect increases or vice versa), as can be seen in Figure 6-7. The relationship between the variables in a closed cycle loop connected to a series of causal links can be described based on the balancing and reinforcing loops. Balancing loop (also known as negative loop) is a situation when the current state is changed to the desired state through a push in the opposite direction that is often determined through odd number of negative relationships. On the other hand, the reinforcing loop (also known as positive loop) is a situation wherein the action leads to the growth of the result that in return increases the same action through self-reinforcement. The reinforcing loop can be determined through either zero or even number of negative relationships.

6.4.2 Main Feedback Loops in Vehicle Recycling Systems

The balancing loop through the use of vehicle with lower CO_2 emissions is first described, followed by a discussion of the reinforcing loop caused by the increasing complexity in vehicle designs. The implementation of strict impurity levels for material recycling is then explained through another balancing loop at the EoL stage.

Figure 6-7 shows that the approach taken to limit the increasing vehicle CO_2 emissions during vehicle design stage has created a balancing loop. Vehicle LCA results from previous studies often conclude that the contribution of CO_2 emissions during use phase is the major contributor to the environmental impact. Strict vehicle emission targets are imposed to limit the vehicle CO_2 emissions in some countries, particularly in the European region. Voluntary vehicle emission targets are implemented in Australia as a guideline to vehicle manufacturers. Therefore, the increasing use of lightweight materials, such as high strength steels, aluminium, and reinforced polymer composites, has been the focus in vehicle designs. The combination of different lightweight materials has led to the growth of multi-material designs to further optimise the vehicle mass reduction potential. When the vehicle mass decreases based on the reference vehicle mass, the fuel consumption is reduced significantly for a specific fuel reduction potential in addition to the fuel efficiency improvements from enhanced vehicle powertrain technologies. The reduced fuel consumption will then correspond to the lowered vehicle CO_2 emissions that consequently results in a decreased GWP for the vehicle LCA results.

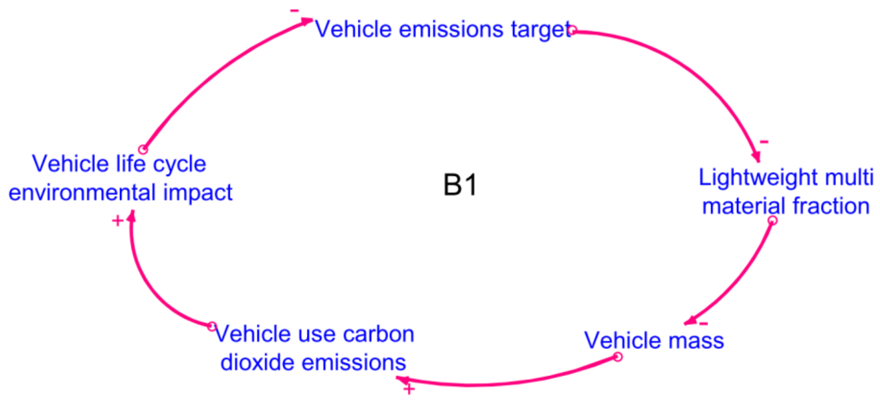


Figure 6-7: The effect of vehicle CO_2 emissions during use phase. The positive link (+) shows that when the cause increases, the effect increases (or vice versa). The negative link (-) shows that when the cause increases, the effect decreases (or vice versa).

The reinforcing loops (R1 and R2) in Figure 6-8 show the implication of standard vehicle LCA without exergy losses. The focus on achieving the vehicle emission targets during use phase has led to the increasing use of multi-material designs. Despite the negative effect on the recycling phase, highly complex vehicle designs are still implemented due to the limitations of standard LCA to account for a closed-loop recycling environmental impact. A high material recycling efficiency is often assumed during the vehicle recycling phase of life cycle analysis but this does not reflect the current recycling processes. The reinforcing loops highlight the limitations of standard LCA to account for the exergy losses during ELV recycling.

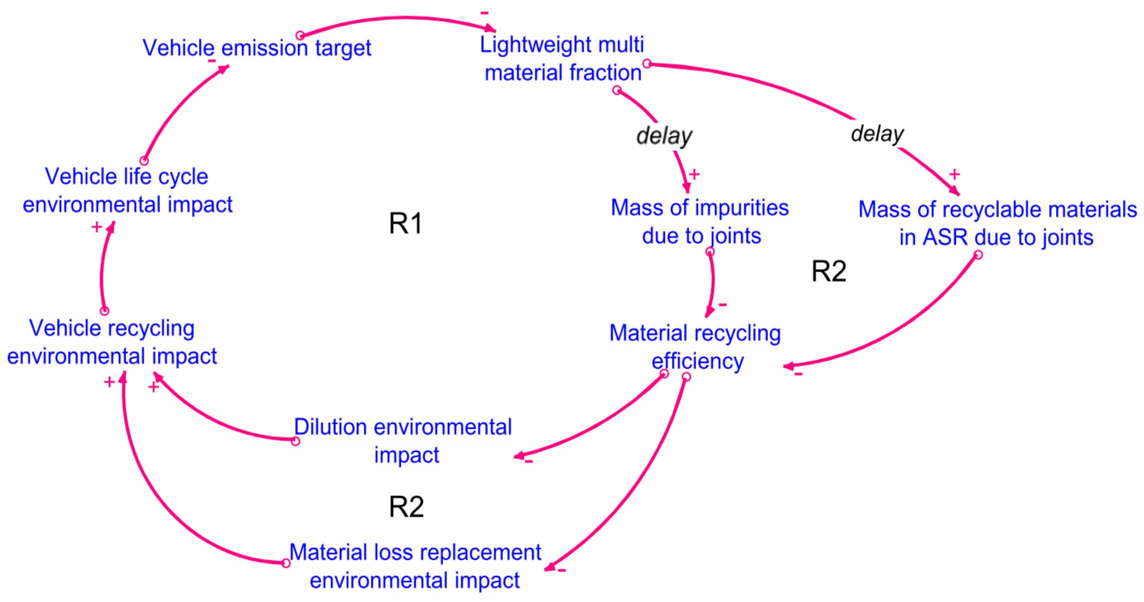


Figure 6-8: The focus on vehicle use phase and its effect on vehicle recyclability through the implementation of standard vehicle LCA.

The complexity of multi-material designs has led to the increasing challenges in recovering materials with high purity through the current recycling practices. The shredder-based recycling processes commonly used in ELV recycling are incapable of liberating the different materials efficiently particularly at joints. Joining techniques that introduce additional materials, such as mechanical fasteners and adhesive bonding, are increasingly used due to their ease in combining varied materials. The joining trends for new vehicle designs have consequently caused the increase of impurities in valuable output fractions during the recycling phase, as denoted by the R1 loop. This impact is only seen after a delayed period of about 10-14 years when the vehicle reaches the EoL phase.

The observations from case studies have shown that certain joint types are strongly correlated to the amount of impurities present in the different valuable fractions. For example, mechanical fasteners, particularly mechanical screws and bolts, have a strong relationship with the increasing impurities present in the NF output stream. Consequently, the actual material recycling efficiency—mass percentages of valuable output materials excluding impurities—has been decreasing over time. When the material recycling efficiency decreases due to the presence of impurities, the amount of primary resources used as dilution agent for secondary material production will increase significantly from a closed-loop perspective. The dilution process contributes to the additional environmental impact that is often overlooked in the standard vehicle LCA.

The loss of valuable materials in ASR due to joints has a similar recycling effect that needs to be accounted for in a closed-loop system. Valuable materials that end up in landfill need to be replaced with primary resources for a continuous production. Thus, the R2 loop in Figure 6-8 illustrates the additional environmental impact due to the replacement of primary resources for the material losses over a delayed period.

It is arguable that the material recycling efficiency is relatively high in some countries, particularly in the European region, when strict ELV legislations are implemented. However, the recycling rate calculation lacks actual interpretation of the complex vehicle designs (Van Schaik, 2004). The balancing loop (B2) in Figure 6-9 highlights the need for stricter targets on the impurity levels for the different types of material recycled to achieve a closed-loop system. Through the implementation of low mass percentage of impurity levels in different output streams, the mass of impurities and material losses due to joints will decrease and thus, the overall material recycling efficiency can be increased effectively. When the material recycling efficiency is improved from the closed-loop perspective, the vehicle recycling environmental impact, including exergy losses, will decrease. This will then reduce the vehicle life cycle environmental impact that accounts for exergy losses.

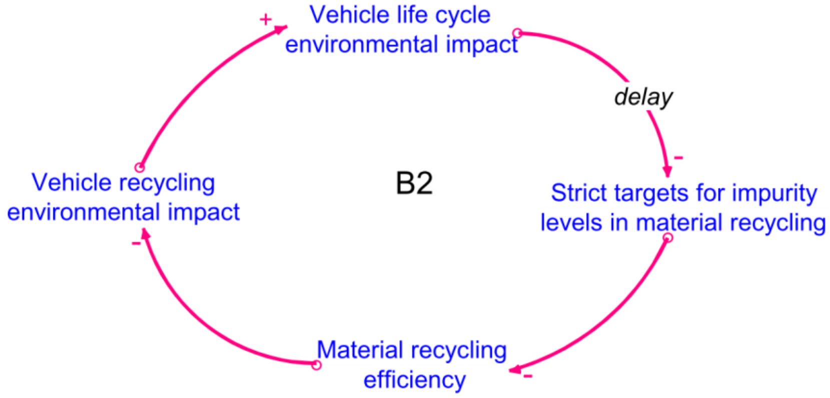


Figure 6-9: The effect of strict impurity levels during material recycling phase.

6.5 Integration of System Archetypes

By combining the intended behaviour loops with the system reaction loops, base archetypes were created. This step was carried out to illustrate the defined boundary of the dynamic problem through mental models, which was then used as a specific case to be matched with the well-known system archetypes. The application of system archetypes to describe the behaviours of the mental models is a highly effective tool for organisations to diagnose the underlying problem, and to identify potential loopholes of the implemented policies at an earlier stage (Maliapen, 2007).

Two widely known archetypes, “Fixes that Fail” and “Shifting the Burden” introduced by Senge (1990), were explored to highlight the quick fix for the environmental impact during vehicle use phase through multi-material vehicle design trends, and its effect on the ELV recyclability observed through the life cycle analysis. This section describes the basic structural templates, the similarities and differences for both archetypes. An example using the road congestion problem is then used to illustrate how the system archetypes can be applied to describe an issue.

“Fixes that Fail” archetype is used to describe the situation wherein the fix to a problem has shown a short-term effective solution; however, there is a build-up of unintended consequences when the same fix is used over time (Dowling et al., 1995; Senge, 1990a). The balancing loop (B) through the fix is dominating at the initial phase leading to the temporary improvement. When the reinforcing loop (R) through the unforeseen consequences is more influential in the system after a time delay, the problem arises again and possibly worsens. The behavioural pattern and key variables of the archetype through the balancing and reinforcing loops can be seen in Figure 6-10.

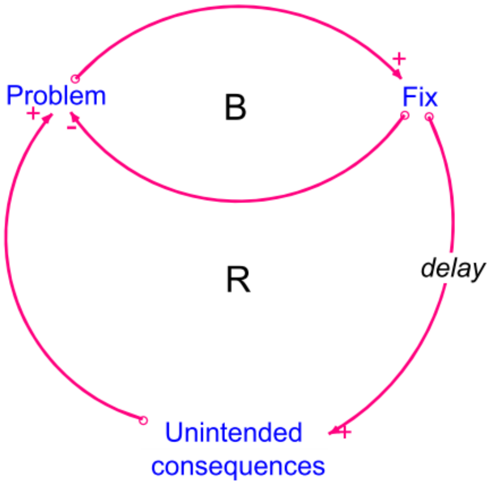


Figure 6-10: Basic archetype of “Fixes that Fail” (Senge, 1990b).

“Shifting the Burden” archetype is used to describe the fix of a problem through short-term solution, also known as symptomatic solution. However, a side effect of this solution is that it hinders the application of fundamental solution to solve the underlying problem (Dowling et al., 1995; Senge, 1990a). The symptomatic solution can be applied to reduce the problem immediately and thus, make it more attractive than the fundamental solution that requires a time delay to reduce the problem to a greater extent. As a result, the problem is not solved in the long term due to the atrophy of fundamental solution. The gap between the short-term and long-term solution can be described through the reinforcing side effect loop (R). The symptomatic solution through the balancing loop (B1) is dominating at the initial phase leading to the slight improvement in the problem. The balancing loop (B1) and reinforcing loop (R) for "Shifting the Burden" are similar to the variables that drive the balancing and reinforcing loops in "Fixes that Fail". The major difference is the additional balancing loop (B2) that describes the application of fundamental solution to reduce the problem symptom. Over time, the problem may persist, and a fundamental solution through the balancing loop (B2) is needed to solve the underlying problem effectively. The balancing and reinforcing loops that describe the "Shifting the Burden" behavioural pattern can be seen in Figure 6-11.

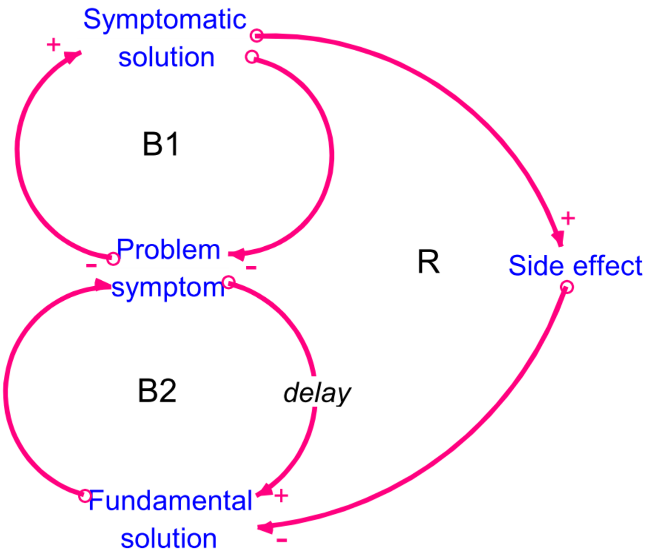
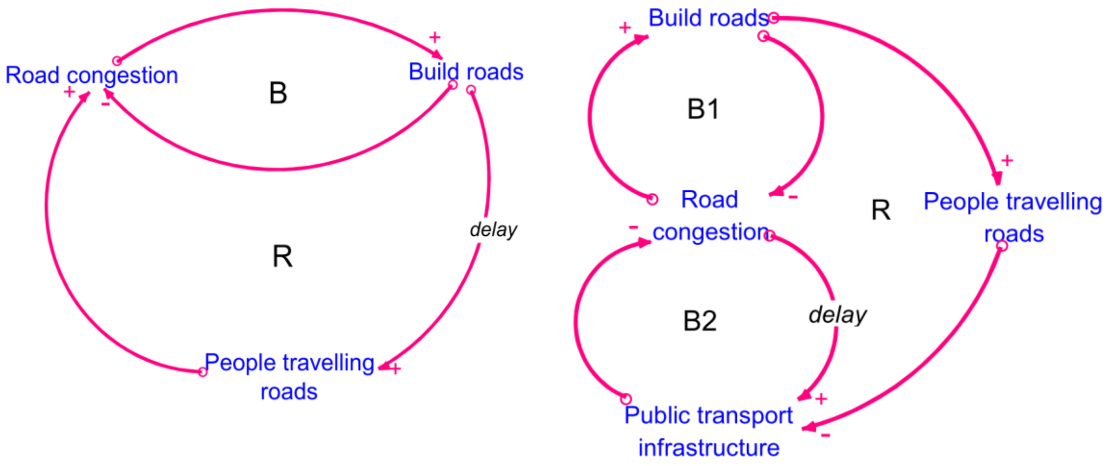


Figure 6-11: Basic archetype of "Shifting the Burden" (Senge, 1990b).

"Shifting the Burden" archetype system behaviour is often described as an extension of the "Fixes that Fail" archetype (Kim and Anderson, 1998; Senge, 2006). This can be illustrated through the road congestion problem as shown in Figure 6-12. Road congestion is often solved by building more roads. When more roads are built over time, the improvement in road transport infrastructure will encourage people to travel more via roads, causing a rebound effect. Hence, the initial road congestion problem is not solved and may rise to a higher level. This scenario can be represented through the "Fixes that Fail" archetype. When the unintended consequences are known, the issue can be elaborated through the "Shifting the Burden" structure. Effective public transport system, such as trains and buses, would have provided a better fundamental solution to reduce the use of personal cars and thus, solve the underlying road congestion problem.



(a) Fixes that Fail (b) Shifting the Burden

Figure 6-12: Road congestion problem interpreted through the “Fixes that Fail” archetype, and extended to the “Shifting the Burden” archetype (Truman, n.d.).

In this study, the behaviours of the vehicle recycling systems were explored based on both archetypes. This is because the system archetypes have close resemblance in terms of the action taken in response to the problem symptom without thorough investigation of the underlying problem, and the consequences that arise from it (Kim and Anderson, 1998). The major difference is whether the action has caused unexpected consequences over a delayed period, or the application of a short-term fix leading to the rise of the same problem (William, 2002).

6.6 Vehicle Recycling Models

The CLD interpreted through the standard vehicle LCA were used as the foundation for the choice of system archetypes. This allows the central problem of a complex system, such as a vehicle, to be articulated clearly based on the combination of behavioural loops. “Fixes that Fail” and “Shifting the Burden” archetypes were used as the “lenses” to describe the dynamic vehicle recycling systems from a joining techniques perspective, as observed from the case studies. The behaviours of the critical variables in the vehicle recycling systems are then matched to the reference modes of the adopted archetypes. This provides a qualitative first pass of the vehicle recycling models that can be used to generate quantitative simulation models in future based on the collected case study data. In this study, only qualitative mental models were simulated to gain insights from the observed structural patterns from which the archetypal behaviour emerges. Prescriptive actions to prevent the unintended behavioural systems were provided based on the generic guidelines for specific types of archetypes.

6.7 “Fixes that Fail” Perspective

This section describes the dynamic vehicle recycling model based on the “Fixes that Fail” archetype. A qualitative first pass of the model is then performed and compared to the reference mode of “Fixes that Fail”, as shown in Figure 6-6. Finally, prescriptive policy actions are provided with reference to the case study observations.

6.7.1 Model Development

The CLD based on the vehicle recycling systems, and the observations from case studies can be represented through the “Fixes that Fail” archetype, as illustrated in Figure 6-13. The short-term effective reduction in vehicle environmental impact through multi-material structures has consequently created a long-term side effect on the material recycling efficiencies due to unliberated joints. Therefore, the lightweight multi-material fraction is the key variable to drive the balancing and reinforcing loops.

At present, much of the effort to decrease the vehicle environmental impact is focusing on the potential to reduce CO_2 emissions during the vehicle use phase, as shown in the balancing loop (B1). The vehicle mass is tightly-linked to the amount of CO_2 emissions; therefore, manufacturers are driven to design environment-friendly cars through vehicle mass reduction. Lightweight materials combined with multi-material structures are increasingly used to optimise the overall vehicle mass without compromising the safety features. When cars get lighter, CO_2 emissions are reduced and thus, the environmental impact is significantly decreased.

Conversely, the corrective action through the increasing use of multi-material designs has caused unintended consequences on the environmental impact, as denoted by the reinforcing loops (R1 and R2). Multi-material designs are resulting in the use of more lightweight metals and plastic composite materials. Joint types for these material combinations are often limited to non-welding types (e.g. mechanical fasteners and adhesive bonding) especially for metal and non-metal combinations. These joint types increase the difficulty in recovering materials at the EoL phase. Therefore, the recycling efficiency of valuable materials is reduced and more waste is produced. When the presence of impurities in valuable materials and the amount of valuable material losses increase, the environmental impact that was initially reduced is negated. This is largely due to the loss of valuable materials and the need for high purity metals to dilute impurities present in the valuable streams to obtain the required material quality during secondary production.

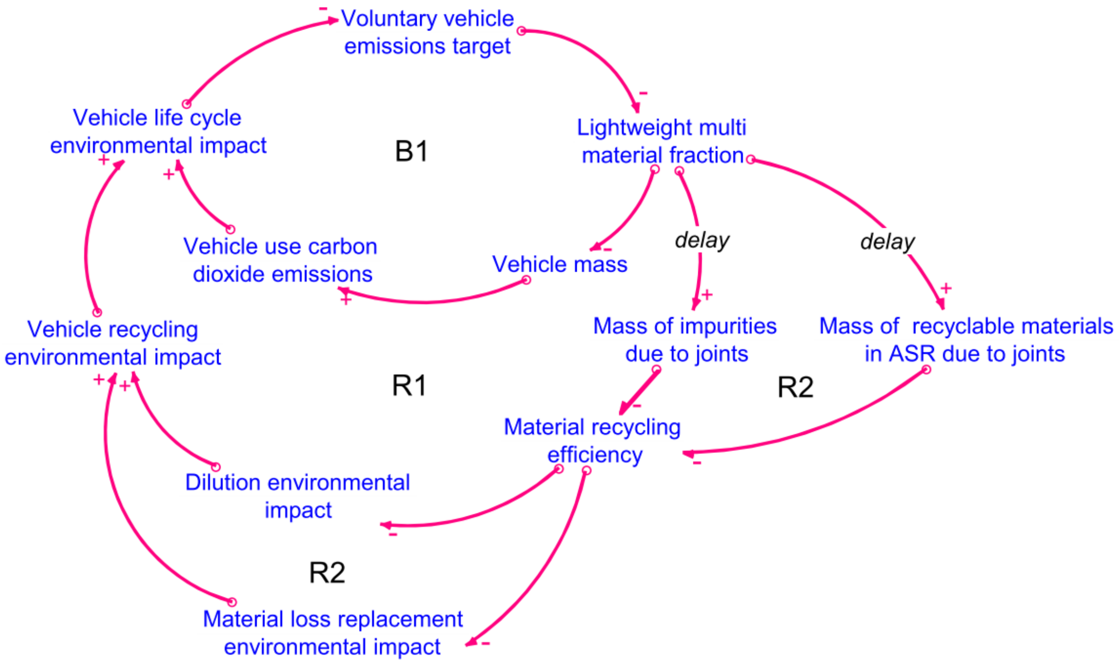


Figure 6-13: The balancing loop of CO_2 emissions during use phase, and the reinforcing loops of reducing material recycling efficiencies. The CLD adheres to “Fixes that Fail” archetype that is reflective of the Australian automotive industry.

The “Fixes that Fail” scenario was used to describe the Australian recycling systems due to the lack of strict regulations for ELV recycling. Vehicle manufacturers are the major driver for the increasing complexity in vehicle designs; however, their impact on the EoL phase using current recycling practices is not a critical aspect that is considered by the manufacturers. It is often assumed that the use of recyclable materials in vehicle production will assist in material recycling, and the ELV recycling efficiency is solely the responsibility of auto recyclers. Additionally, there are limited preventive measures that require manufacturers to take responsibility of the EoL of their products. Therefore, the rebound effect on the ELV recyclability based on current recycling practices in Australia is treated as an “unintended consequence” due to the low awareness among vehicle manufacturers to create highly recyclable vehicles that can be reused in a closed-loop system. The data measurement units from the Australian case study (see Chapter 4) can be used to represent the different variables in the “Fixes that Fail” scenario, as shown in Table 6-4.

Table 6-4: The data measurement units representing different variables based on the Australian case study.

Variables	Measurement Unit
Vehicle life cycle environmental impact	person equivalent
Voluntary vehicle emission target	kg CO_2-equivalent/km
Lightweight multi-material fraction	mass percentage (wt.%)
Vehicle mass	kilogram (kg)
Vehicle use CO_2 emissions	kg CO_2-equivalent
Mass of impurities due to joints	mass percentage (wt.%)
Mass of recyclable materials in ASR due to joints	mass percentage (wt.%)
Material recycling efficiency	mass percentage (wt.%)
Dilution environmental impact	person equivalent
Material loss environmental impact	person equivalent
Vehicle recycling environmental impact	person equivalent

6.7.2 Testing

The predicted vehicle recycling system behaviour in Australia based on the “Fixes that Fail” situation can be seen in Figure 6-14. It resembles the reference mode for the vehicle life cycle environmental impact based on the Australian scenario, as seen in Figure 6-6.

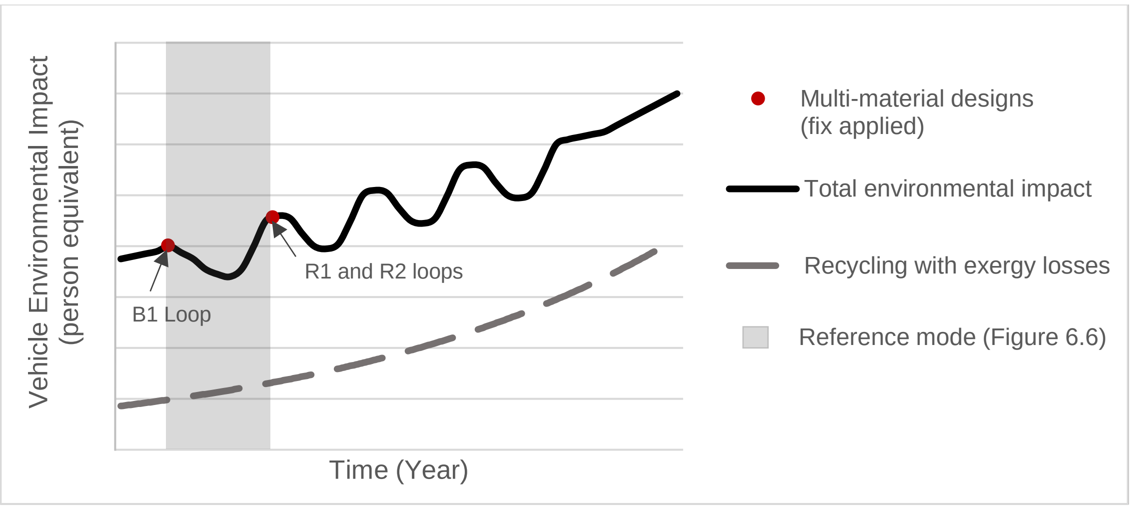


Figure 6-14: The predicted vehicle recycling system behaviour over time in Australia based on the “Fixes that Fail” archetype (Adapted from (Kim and Lannon, 1997; Senge, 2006)).

6.7.3 Prescriptive Policy Actions

Based on the “Fixes that Fail” archetype, prescriptive actions to prevent the escalating problem symptom for vehicle life cycle environmental impact are as follows (Kim and Anderson, 1998; William, 2002).

- Identify the potential consequences of the actions taken to improve the vehicle CO_2 emissions during use phase.
- Identify the consequences of the increasing multi-material designs and their associated joining techniques during vehicle production on other vehicle life cycle phases to remove the underlying cause that contributes to the vehicle life cycle environmental impact.
- Mitigate the cause of vehicle recycling environmental impact through effective choice of joining techniques for multi-material vehicle designs to optimise the reduction of vehicle environmental impact for different life cycle phases.

It is critical to identify the delay between the fix through multi-material vehicle designs and the unintended consequences during ELV recycling. In most cases, the effectiveness of changing vehicle designs to improve the fuel efficiency is more apparent since it appears at an earlier life cycle stage. The lack of interaction between vehicle manufacturers and recyclers has also widened the gap in understanding the effect of changing vehicle designs on the current recycling practices.

6.8 “Shifting the Burden” Perspective

This section describes the dynamic vehicle recycling model based on the “Shifting the Burden” archetype. The developed vehicle recycling model is then compared to the reference mode of “Shifting the Burden”, as shown in Figure 6-6, to provide a qualitative first pass of the model. This is then followed by a discussion on the prescriptive policy actions used to prevent the vehicle recycling problem based on the case study observations.

6.8.1 Model Development

“Shifting the Burden” archetype is used to illustrate the vehicle recycling systems and the observations from case studies when there is an awareness of the unintended consequences of complex vehicle designs on ELV recycling. However, the varying recycling efficiencies caused by the increasing complexity in vehicle designs are not well-addressed in the standard vehicle LCA that is often used to assist vehicle manufacturers in decision-making. This scenario is depicted through the CLD shown in Figure 6-15. The stricter vehicle emission legislations have pressured the manufacturers to come up with short-term solution to abide by the targeted CO_2 emissions. However, the burden to achieve the regulated recycling and recovery targets is shifted to ELV recyclers. This is reflected through the high material recycling efficiencies that are often estimated for the respective materials during the life cycle analysis of EoL phase. The long-term rebound effect of complex vehicle designs on the current material recovery efficiency is not well considered. In most cases, the environmental impacts of additional primary resources used during secondary material production are not accounted for in the standard vehicle life cycle analysis.

The tension between the short-term solution through the reduction of CO_2 emissions during vehicle use phase, and the long-term solution through closed-loop vehicle life cycle consideration is denoted by the balancing loops. The short-term solution through multi-material designs has been proven to be effective for reducing the CO_2 emissions during use phase as represented through the balancing loop (B1). However, the action only shifted the environmental issue from the use phase to the recycling phase, as illustrated in the reinforcing loops (R1 and R2). The impurities and material losses due to joints will consequently reduce the efficiency of material recycling, leading to the need for strict impurity targets for different output streams, as denoted by the second balancing loop (B2). Through the implementation of policies that incorporate closed-loop system, vehicle manufacturers and recyclers will be held responsible to achieve the stringent material recycling targets.

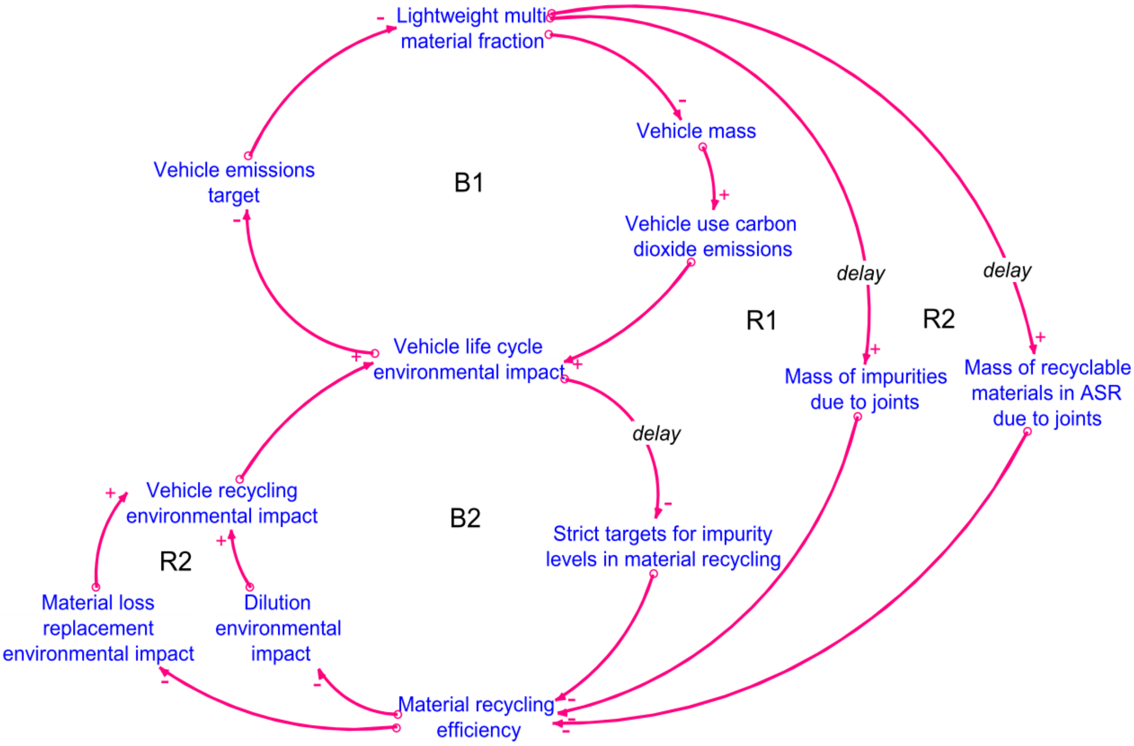


Figure 6-15: The balancing loops of vehicle CO_2 emissions during use phase and the strict impurity levels during ELV recycling, as well as the reinforcing loops of reducing material recycling efficiencies. The CLD adheres to “Shifting the Burden” archetype that is reflective of the European scenario.

The “Shifting the Burden” archetype resembles the vehicle recycling systems in Europe, where strict vehicle CO_2 emission and recycling regulations are implemented. However, the vehicle environmental burden is gradually shifting from the vehicle manufacturers to the recyclers. It is undeniable that new vehicle designs are needed to address the increasing global warming issue; however multi-material designs focused on CO_2 emissions reduction fail to provide the long-term remedy. Nevertheless, it provides time for vehicle manufacturers to come up with multi-material structures that are not just low-emission, but also highly recyclable from the closed-loop perspective. The focus on vehicle use phase will lead to the importance of understanding the rebound effects, such as the exergy losses in the vehicle recycling environmental impact. When the exergy losses are taken into consideration, the focus on vehicle use phase will decrease, leading to the emphasis on optimised vehicle designs that improve both use and recycling phases to reduce the long-term environmental impact. The balancing loop (B2) shows that deep understanding of the cause and effect for different life cycle stages is critical.

The data measurement units from the Belgian case study (see Chapter 5) that can be used to represent the different variables in the “Shifting the Burden” scenario are shown in Table 6-5.

Table 6-5: The data measurement units representing different variables based on the Belgian case study.

Variables	**Measurement Unit**
Vehicle life cycle environmental impact	person equivalent
Vehicle emissions target	kg CO_2-equivalent/km
Lightweight multi-material fraction	mass percentage (wt.%)
Vehicle mass	kilogram (kg)
Vehicle use CO_2 emissions	kg CO_2-equivalent
Mass of impurities due to joints	mass percentage (wt.%)
Mass of recyclable materials in ASR due to joints	mass percentage (wt.%)
Material recycling efficiency	mass percentage (wt.%)
Dilution environmental impact	person equivalent
Material loss environmental impact	person equivalent
Vehicle recycling environmental impact	person equivalent
Strict targets for impurity levels in material recycling	mass percentage (wt.%)

6.8.2 Testing

The predicted vehicle recycling system behaviour in Europe based on the “Shifting the Burden” situation can be seen in Figure 6-16. It resembles the reference mode for the vehicle life cycle environmental impact based on the European scenario, as shown in Figure 6-6.

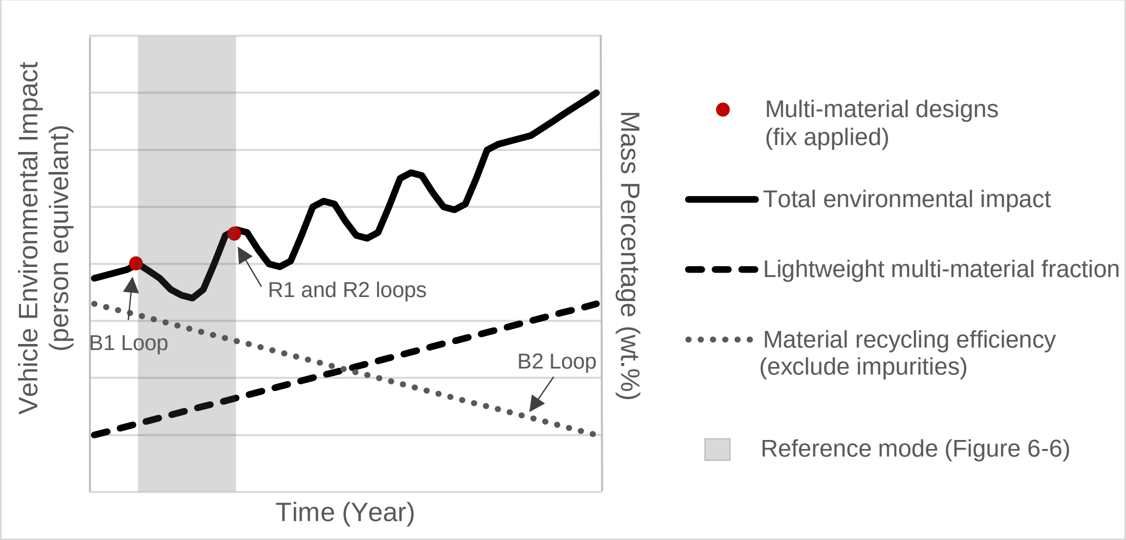


Figure 6-16: The predicted vehicle recycling system behaviour over time in Europe based on the “Shifting the Burden” archetype (Adapted from (Kim and Lannon, 1997; Senge, 2006)).

6.8.3 Prescriptive Policy Actions

Based on the “Shifting the Burden” archetype, prescriptive actions to prevent the escalating problem symptom for vehicle life cycle environmental impact are as follows (Kim and Anderson, 1998; William, 2002).

- Identify the potential side effects of the actions taken to improve the vehicle CO_2 emissions during use phase.
- Optimise the reduction potential for vehicle environmental impact during vehicle use phase (multi-material vehicle designs) and vehicle recycling phase (material recycling efficiency considering impurity levels in different output streams, and material losses in ASR).
- Identify the consequences of the increasing multi-material designs and their associated joining techniques during vehicle production on other vehicle life cycle phases to remove the underlying cause that contributes to the vehicle life cycle environmental impact.
- Mitigate the cause of vehicle recycling environmental impact through effective choice of joining techniques for multi-material vehicle designs to optimise the reduction of vehicle environmental impact for different life cycle phases.
- Create strict recycling policies that focus on closed-loop material recycling system, such as strict impurity levels for different recovered output streams.

- Vehicle manufacturers and recyclers need to cooperate to ensure the new vehicle designs have low emissions level while remain highly recyclable through the current recycling processes from the closed-loop perspective.

This scenario depicts the shifting of environmental burden from vehicle manufacturers to recyclers due to the widening gap between vehicle designs and the efficiency of material liberation through current recycling approaches. It is crucial to understand that the increasingly complex vehicle designs have led to the choice of joining techniques that cannot be liberated well in the shredder-based recycling processes. The challenges during ELV recycling continue to persist despite the adoption of more advanced recycling technologies, as observed from the Belgian case study.

6.9 Discussion

The Australian vehicle recycling system interpreted through the “Fixes that Fail” archetype has a close resemblance to the European vehicle recycling system described through the “Shifting the Burden” archetype. It is shown in Figure 6-14 and Figure 6-16 that the predicted behavioural patterns for the vehicle life cycle environmental impact over time are similar. Despite the adoption of different vehicle policies and regulations in Australia and Europe, the environmental burden of exergy losses during recycling phase continue to exist due to the presence of unliberated joints. This has consequently led to increasing waste produced and natural resource consumption in both countries or regions. Although strict vehicle legislations are implemented in Europe to prevent or limit ELV waste, impurities and material losses due to unliberated joints are still observed in the different output streams, which are not well reflected in the current material recycling efficiency. The enactment of strict ELV regulations only prolongs the delay in material down-cycling impact, and valuable material losses in ASR. This shows that the current ELV recycling systems and policies are unable to solve the underlying ELV waste problem in the long term, particularly with the proliferation of complex multi-material designs and their associated joining techniques to produce lightweight vehicles. Therefore, the choice of joining methods, particularly mechanical fastening types, during initial design phase plays a key role in determining the material liberation level through the different recycling approaches.

The difference between the vehicle recycling models illustrated through both archetypes is the application of a fundamental solution in the form of an additional balancing loop to impose strict ELV policies that focus on closed-loop recycling system. Such measure provides a standardised definition of the ELV recycling rate to capture the material degradation issue, and to assist in decision-making for joining choices that ease recycling at earlier design phase. This scenario is reflected in the European vehicle recycling system interpreted through the “Shifting the Burden” archetype where the environmental burden is progressively shifted from the vehicle use phase to the vehicle recycling phase despite the implementation of strict ELV recycling targets. It is important to note that the fundamental solution should not be framed as the “right” or only action to solve the underlying problem (Kim and Anderson, 1998). There are multiple fundamental solutions that can be generated when looking from different perspectives.

The qualitative vehicle recycling models in Australia and Europe are produced through the combinations of different behaviour loops from a joining techniques perspective. These models serve as the first step to build the quantitative models using stock and flow diagrams. The associated data collected from the case studies can then be computed into the recycling models to verify the system behaviours. Through the simulation of working models, more intensive testing can be carried out, such as model robustness under extreme conditions, and sensitivity analysis for different policy interventions (Sterman, 2010).

6.10 Concluding Remarks

The current automotive industry has seen a vast improvement in the vehicle life cycle environmental impact through the optimisation of vehicle mass using lightweight materials and multi-material designs. This has consequently led to the increasing use of joining techniques, such as mechanical fasteners, to cater for different material combinations. The commonly used LCA method to assess the environmental impacts of vehicles is unable to capture the delayed life cycle impact of joining choices on material recycling efficiencies during ELV recycling. Observations from case studies (as presented in Chapter 4 and Chapter 5) have shown that the use of mechanical fasteners, particularly machine screws, is causing impurities and material losses in different output streams. The standard LCA is often limited to the lack of consideration for impurities present in different valuable output streams that have an impact on the quality of materials recovered. The common practice in standard LCA assumes that the recyclable materials, particularly for metallic secondary materials, are reused in a closed-loop cycle. This is not the case for materials recycled from vehicles in current recycling practices due to the complex material combinations. Similarly, the environmental impacts of replacing valuable materials lost in ASR need to be accounted for in a closed-loop system. From these points of view, the limitations of standard LCA have led to an incomplete interpretation of the environmental impacts associated with the EoL phase. The increasing complexity of vehicle designs and their associated joining choices has led to the delayed increase of impurities and material losses due to joints during ELV recycling. Therefore, the automotive industry adheres to the “Fixes that Fail” archetype due to the unintended consequences arise from the initial fix for the vehicle life cycle impact, as can be seen from the Australian vehicle recycling system.

“Shifting the Burden” scenario happens when the vehicle manufacturers apply a short-term solution to reduce the vehicle life cycle environmental impact, but may not necessarily address the underlying cause of problem in the long term. This is because the identification of the fundamental issue involves greater time delay and additional costs before the initial problem can be alleviated. The reduction of environmental burden during vehicle use phase through multi-material designs and their associated joining choices is progressively offset by the increasing environmental impact during recycling phase. This is caused by the inability of the current recycling practices to liberate the joints with different material combinations. The symptomatic solution through increasing multi-material vehicle designs has effectively alleviated the vehicle life cycle impact during use phase, and reduced the pressure to implement the fundamental solution that is more beneficial in the long term. It is important to note that the fix through multi-material designs is essential to reduce the environmental impacts of vehicles during the initial stages; however, the side effects of joining choices on material recycling efficiencies need to be accounted for through an optimised approach. The fundamental solution through the enactment of ELV recycling policies targeting the optimisation of closed-loop system can provide an initial assessment of joint effects on ELV recyclability. This can assist manufacturers in choosing the appropriate joining techniques during vehicle design phase. Therefore, the system behaviour of the European vehicle recycling system adheres to the “Shifting the Burden” archetype. Despite the implementation of strict vehicle recycling regulations, the material degradation issues due to joint effect is not well captured in the current life cycle analysis, causing the shift of vehicle environmental burden from one phase to another.

This chapter shows that the environmental burden associated with the life cycle impact of joining choices continue to exist despite the adoption of different vehicle policies and ELV regulations. Although the Australian and European vehicle recycling systems are represented through two different system archetypes: “Fixes that Fail” and “Shifting the Burden”, the systems’ behavioural patterns are similar. The only difference is the prolonged delay impact of material degradation and valuable material losses due to unliberated joints, as can be seen from the European recycling system representing the “Shifting the Burden” archetype. Therefore, the life cycle impact of different joining choices on ELV recycling needs to be accounted for a closed-loop material cycle.

Chapter 7

Discussion

7.1 Introduction

This chapter summarises the research results based on the observations from case studies, and the observed dynamic behaviours of joint types used on the vehicle life cycle analysis through time delay. An overview of the research findings is provided. This is followed by a discussion on the research contributions both in theory and practice to draw out the implications of the main findings in relation to other research. The limitations of the research are then addressed to explore more advanced recycling technologies and their feasibility. Finally, the place of this work towards true vehicle sustainability is discussed in view of the constraints and opportunities faced in the vehicle industry.

7.2 Summary of Research Findings

Joining methods play a significant role in determining the material liberation level that subsequently affect the material quality and the amount of valuable material losses in ASR, as presented in Chapter 4 and Chapter 5. The shredding industrial trials carried out in Australia and Belgium have shown that the use of mechanical fasteners, particularly machine screws, to join different material types cannot be perfectly liberated (see Section 4.5 and Section 5.5). This type of joining technique is more likely to cause impurities and material losses in different output streams despite the use of more rigorous recycling approaches. One of the major similarities between the two case studies is the use of shredding process to reduce the particles' size. Therefore, the liberation efficiency of the shredder in releasing the connected parts of different material combinations is one of the key factors to assist in perfect material liberation.

Further observations on the unliberated joints showed that the characteristics of joints (joining and material parts) play a critical role in assisting material liberation through the shredding process. From the Australian case study, the attributes of the joining methods used on different material parts before entering the recycling facility were determined, and their likely liberation behaviour after going through the recycling processes were characterised (see Section 4.6). These characteristics are further supported by the observations made in the Al output from the Belgian case study (see Section 5.5.2). The characteristics of a joint that have an impact on the material recyclability are joint strength, joint location, joint material type, joint size, fastener diameter or length, joint surface smoothness, area of bond contact, temperature resistance, protrusion level, and joint degradation over time due to heat and moisture. Based on these characteristics, the preferences for material separation are detailed as follows.

- A low joint strength, low joint temperature resistance, and a small area of bond contact between joined materials assist in material liberation due to the centrifugal force and heat generated during shredding process. Precautionary measures need to be taken to ensure the product use phase is not compromised. These features need to be optimised for both vehicle use and recycling phases.
- Reduce the number of mechanical fasteners with small diameter and length to assist in joint liberation from the vehicle designs perspective. It is arguable that fine shredding can assist in material liberation for small joints; however, more material losses will occur during the recycling process due to the moving of fine particles through the conveyor system.
- Choose joints with compatible material types to prevent material degradation from the perspective of metallurgical processing. Otherwise, encourage the use of active fasteners with low-cost material disassembly to optimise material recycling potential.
- Place joints at easily accessible locations, such as the exposed surface rather than sandwiched between the materials being joined. Protruded joints with uneven geometry can also assist in material liberation due to the force applied during shredding process.
- Reduce joints that degrade due to moisture, such as corroded steel, and encourage the use of joint types that degrade due to heat, such as adhesive bonding. Corroded joints cannot be easily liberated whereas joints that degrade with heat can be more easily liberated during the shredding process.
- Mechanical fasteners with smoother joining surface, such as pins, rivets, and steel clips, can be easily released compared to threaded fasteners, such as machine screws, bolt screws, and socket screws. Threaded fasteners are more likely to experience partial joint liberation.

The characteristics of materials being combined also have an influence on the joint liberation (see Section 4.5, Section 5.5.1, and Section 5.5.2). In general, material combinations with large differences in material densities or unequal thickness can assist in the liberation of joints. Therefore, the efficiency of material liberation can vary depending on the material and joining parts. A general material recyclability rating based on the joint characteristics for dissimilar metals, similar metals, metals to non-metals, and dissimilar non-metals bonding can be seen in Appendix C. It is worth noting that the material recyclability rating for certain joining techniques, such as welding, is approximated based on their characteristics since they are not largely observed from the case studies.

Besides integrating the joint characteristics into the ecodesign guidelines to assist in designing highly recyclable vehicles, it is essential to quantitatively measure the influence of joints to optimise a closed-loop material recycling. The impurities and material losses due to joints can be assessed through ELCA to account for the dilution, quality, and material losses during secondary material production (see Section 5.4.3). The extension of standard LCA with exergy losses provides information on how the different impurity levels affect the overall environmental impact. This approach can address the challenges of recycling complex vehicle designs that are not well considered in the standard LCA commonly used by vehicle manufacturers. By understanding the joint effects on current recycling practices using life cycle analysis, the interaction between vehicle design and recycling phases can be more accurately interpreted. ELV recycling policies targeting the optimisation of closed-loop system can then be imposed, such as setting the concentration limits for impurities in the different recovered output streams.

The use of lightweight materials and multi-material concepts in vehicle manufacturing has shown significant environmental improvement during the vehicle use phase; however, the delayed consequences during ELV recycling through the commonly used shredding process are not well addressed in the current analysis (see Chapter 6). The increasing complexity in vehicle designs and their associated joining techniques has led to the increasing amount of impurities and material losses due to joints during ELV recycling with a time delay. In the long term, more primary resources are required to dilute the presence of impurities or to replace the valuable materials lost in ASR. An SD approach in LCA was used to illustrate the temporal effect on vehicle life cycle analysis to investigate the challenges associated with the material recycling efficiencies due to unliberated joints. The trends observed from the vehicle life cycle analysis can be described based on two widely known archetypes: “Fixes that Fail” and “Shifting the Burden”. It is shown that the Australian vehicle recycling system adheres to the “Fixes that Fail” archetype due to the lack of strict recycling targets, and the relatively low landfill cost. Conversely, the implementation of strict ELV policies and high landfill levy in the European vehicle recycling system has shifted the environmental burden from the vehicle use phase to the recycling phase through a longer delay. This scenario can be resembled through the “Shifting the Burden” archetype, which is an extension of the “Fixes that Fail” archetype. Based on the dynamic behaviours observed through different vehicle recycling systems, the key factors to reduce the vehicle life cycle environmental impact are optimisation of the environmental burden for different life cycle phases, and awareness of the rebound effects (i.e. the influence of joining choices on material recycling efficiencies) associated with an implemented action or policy.

It is crucial to acknowledge that the vehicle recycling models used to represent the different recycling systems by no means predict the future behaviour of the systems, or indicate the need to reduce the focus on vehicle use phase. The representation of the recycling models through system archetypes was used to indicate the dynamics of joint impact that cause the emergent system behaviour, and to enable the design of high-leverage policy to achieve the desired goal within the defined system boundary. The recycling models aim to highlight the delayed consequences or side effects that need to be considered at an earlier vehicle life cycle stage.

7.3 Research Contributions

This section addresses the contribution of this research to the theory and practice in vehicle recycling systems. The investigation of the influence of joints on ELV recyclability has extended the knowledge in the vehicle industry. This knowledge is then used to explore feasible implementations that can be incorporated into the current practices or policies.

7.3.1 Influence of Joint Technologies on ELV Recyclability

This study provides empirical evidence of the joining choices and their effects on current ELV recycling practices through industrial experiments. There is a lack of study that investigates the correlation between different joining methods and their liberation behaviours through industrial shredding processes, as highlighted in Section 2.8. The case study data collected from this research provided the actual material efficiency of large-scale recycling processes that is not widely available. Moreover, the interconnections between known material and joint input data, and their corresponding liberation behaviours through the shredding process are characterised. The joint characteristics that have an impact on material recyclability can then be generalised for new emerging joining technologies.

It is often assumed that steel fasteners, such as machine screws, bolt screws, etc., can be easily retrieved through magnetic separator during recycling due to the joint material type. This assumption is also reflected through some of the ecodesign guidelines specific to joint selection (VDI 2243, 1993). Such perception is shown to be incorrect based on the observations from the case studies. The joint characteristics play a more critical role due to the nature of shredder-based recycling practices. The efficiency of material liberation is largely based on the shredding process, which is the first step carried out in the recycling facility. This step determines how well the joints with different material combinations are liberated, which then influences the separability of different material types through the multiple sorting processes. It is worth noting that the efficiency of material liberation may change if disassembly process is largely incorporated into the future vehicle recycling systems. In such circumstances, the characteristics of joints that influence the ease of ELV recycling (inclusive of dismantling process) will differ.

7.3.2 Sustainable ELV Recycling through Current Practices

The potential to integrate the influence of joints into the standard LCA was explored through exergy losses. This method was introduced in past research to account for the consumption of natural resources used to improve the material quality. In this research, the integration of this method was further explored to associate the effects of joints on the presence of impurities and material losses in different output streams. The use of ELCA to address the environmental impacts associated with joint types is practical since it can be easily adapted to the commonly used vehicle LCA.

The findings from the case studies were then used to interpret the complex recycling systems to provide insights into the relationships between vehicle design and recycling phases. An SD approach using the system archetypes makes it easier to represent the changing behavioural patterns on the vehicle life cycle analysis as a consequence of the varying material recycling efficiencies due to unliberated joints. The dynamic vehicle recycling models showed that the pattern behaviours of two distinctive vehicle recycling systems, influenced by different vehicle policies, are both driven by the prevalence of common multi-material joining processes. Stricter ELV policies only prolong the delay in material degradation and valuable material losses due to unliberated joints. Despite the adoption of more rigorous recycling processes in current industrial practices, the fundamental ELV waste problem is not solved in the long term due to the inefficient liberation of preferred joining techniques used to cater for the complex multi-material designs.

7.4 Research Limitations

There are several limitations associated to this study. In this section, the limitations from the aspects of result applicability and the defined system boundary are discussed. The addressed limitations can then be used as a potential extension to the current work of this research.

7.4.1 Applicability of Research Findings

The use of case study experiments to generalise the main findings may be biased due to the lack of control on the experimental conditions. It is important to acknowledge that the industrial case studies are not used to provide representative samples, but rather to generalise the observations from multiple case studies (see Section 3.3). This study serves as the first step to validate the influence of joining choices on ELV recyclability that is not currently available in literature. The use of analytical techniques, such as pattern-matching and cross-case synthesis, validate the generalised findings based on the case studies carried out under different conditions. There is potential to carry out case studies in countries with different ELV policies, such as Japan, to further investigate the interaction between policy and joint types hindering full material separation during ELV recycling. In Japan, the implementation of ELV policies emphasise on the shared responsibility principle that clearly proportionates the recycling costs among government, recyclers, and consumers. By collecting multiple case study evidence that are carried out under different conditions, the reliability of the research findings on joint effects can be further supported.

This study only considered the challenges of recycling new vehicle designs through the commonly used shredder-based recycling processes from the joining methods perspective. The characteristics of joints that have an impact on the material recycling efficiency may vary based on the development in recycling technologies, such as the adoption of non-destructive material disassembly. Although the challenges associated with material separation errors are outside the scope of this study, they are still critical in determining the ELV recyclability for complex vehicle designs. In Section 7.5, the alternative recycling and treatment technologies for ELV are discussed in light of their capabilities to cater for the increasing lightweight multi-material concepts in future vehicle manufacturing.

7.4.2 Scope and Boundaries of Dynamic Vehicle Recycling Models

From a sustainable perspective, the optimisation of a complex system involves three main pillars: environmental, economic and social (legislation). However, the presented dynamic vehicle recycling models emphasised on the environmental aspect of unliberated joints, and to some extent of the relevant legislative boundaries. Most of the variables that drive the economics of vehicle recycling systems are treated as exogenous or excluded to ensure a full understanding of the associated environmental impacts due to the influence of joining techniques used. The narrow scope and boundaries of the dynamic vehicle recycling models can then be expanded to include the changing parameters associated with the economic and legislative perspectives with the aim of developing high-leverage policy interventions. Despite the scope limitations, it is arguable that the industrial case study data collected based on different vehicle recycling systems are implicitly influenced by the economic and legislative factors (see Section 6.3.1). In this study, two distinctive ELV legislative systems based in Australia and Europe are closely examined; one representing the strong profit-driven recycling market and the other, the influence of strict legislation on the ELV recycling industry. The key findings from this study can therefore be generalised for various vehicle recycling systems largely adopted in different countries with similar driving factors.

The case studies carried out in this work are bound by the vehicle and fuel type. Although the conceptualised recycling models are limited to the petrol-based passenger vehicles, the interpreted joint effects are still applicable to different vehicle types, alternative fuel vehicles, or vehicles with more advanced powertrain technologies where multi-material vehicle designs are continuously adopted.

7.5 Alternative ELV Recycling and Treatment Options

The recycling stages that can be improved to enhance material scrap quality, and to further recover valuable materials lost in ASR can be broadly divided into pre-shredder disassembly processes and post-shredder technologies. Pre-shredder disassembly processes can be further categorised into non-destructive, semi-destructive and destructive operations (Salvendy, 2001; Seliger et al., 2002; Vongbunyong and Chen, 2015). Post-shredder technologies include advanced sorting processes to further separate different material types (Froelich et al., 2007a; Vermeulen et al., 2011), and thermal treatment processes to convert waste into energy and recover valuable materials through the removal of organic impurities (Galvagno et al., 2001; Nourreddine, 2007; Taylor et al., 2013).

7.5.1 Pre-Shredder Disassembly Processes

The use of disassembly processes to improve material reuse and recycling can further minimise ELV waste disposal in accordance with Lansink's ladder (Lansink, 1980; Wolsink, 2010). Although this recycling technique can maximise the potential of material and part reuse or high quality material recovery during EoL products, it is not largely used in the current recycling practices. Often, disassembly processes are limited to the removal of hazardous components and precious materials or parts due to the high recycling costs (Ferrão and Amaral, 2006b; Tian and Chen, 2014).

Non-destructive disassembly process involves either manual or automated dismantling of materials and components without causing damage (Kara et al., 2006; Tolio et al., 2017). In most cases, the disassembled connectors or fasteners, such as threaded steel fasteners, can also be reused or recycled. Despite the high efficiency in separating different material types, full material or component dismantling is not economically viable due to high labour or operational costs (Wegener et al., 2015). This is particularly the case with the increasing trend of multi-material vehicle designs. The variety in vehicle designs will create more complexity to manually remove different parts, or automating the disassembly procedures (Tolio et al., 2017). Moreover, the conditions of the EoL products, particularly the state of the connections between materials or parts, will strongly influence the ease of disassembling. Corroded steel fasteners, for example, will require extra effort and highly flexible tools or equipment during the disassembly process.

To increase the efficiency of disassembly operations, semi-destructive technique is used. This approach targets the removal of connections or joints through automated disassembly tools or equipment (Vongbunyong et al., 2013). It is generally considered more cost-effective compared to non-destructive disassembly (Vongbunyong and Chen, 2015) due to the shorter time in separating different material types or parts. Additionally, this technique can overcome some of the issues related to the state of joints or connections that are difficult to be removed non-destructively. Much research has been carried out to optimise the disassembly time of EoL products (Cong et al., 2017; Feldmann et al., 1999; Vongbunyong et al., 2013); however, the highly complex vehicle designs with different joining techniques have increased the number of challenges. New innovative disassembly operations will play a critical role to fully optimise the value of material recovery (Cong et al., 2017; Wang et al., 2017).

Destructive disassembly approach is the most commonly used dismantling technique in the current recycling industry. This method is associated with partial or complete removal of obstructing components to reach inner parts or materials using destructive tools such as hammer, laser cutter, water jet cutter, and others (Jovane et al., 1993; Vongbunyong and Chen, 2015). Umeda et al. (2015) have proposed the integration of split lines into product design to assist in extracting targeted components at the EoL phase. These techniques are used to recover specific part or valuable materials that are difficult to reach, while remain cost-effective. The destructive disassembly procedures are often product-specific. Thus, it is more difficult to cater for all types of variations and uncertainties (Vongbunyong and Chen, 2015), particularly for highly complex vehicle designs. In contrast, the shredder-based recycling approach is applicable to a wide range of variations and complexity for different EoL products with predefined operation time. This approach is more favourable from the ELV recyclers' perspective due to its low operation time and high throughput.

Disassembly embedded designs, such as the use of active fasteners, are introduced to overcome the challenges associated with efficient removal of fasteners for highly complex product designs, and high operational costs (Duflou et al., 2008; Peeters et al., 2017; Peeters et al., 2015). Active fasteners are produced using smart materials that can be triggered to release the materials being joined (Tolio et al., 2017), and ensure material recycling with high purity during the EoL phase. These fasteners use the principle of shape memory alloy or shape memory polymer that is highly flexible when triggered by external conditions, such as temperature and pressure (Liu et al., 2010). This concept provides the convenience to disassemble and recycle products at a shorter operation time through modular disassembly processes that are lacking through the conventional disassembly approaches (Duflou et al., 2008; Duflou et al., 2006; Willems et al., 2005). There are many studies conducted to investigate the application of active disassembly fasteners for smaller products (Carrell et al., 2009; Nakamura and Yamasue, 2010; Peeters et al., 2015); however, the practicability of using such concept to assist in vehicle disassembly during EoL phase is unclear when high safety performance is required during its use life (Ziout, 2013). Furthermore, it is difficult to predict the joint behaviours, degradation, and failure modes of active fasteners used in vehicle due to the relatively long life span under varying surrounding conditions (Ziout, 2013).

7.5.2 Post-Shredder Technologies

Effective scrap sorting processes are critical to mitigate impurities and material losses due to material separation errors. Based on the case study observations, impurities and valuable material losses are still present in the different output streams despite the use of more rigorous recycling approaches. More advanced material sorting technologies need to be integrated into the current recycling practices to improve the quality of material recycling. Some of the suggestions to improve the quality of recycled materials from the recycling process perspective are as shown in Table 7-1.

Table 7-1: Overview of advanced post-shredder technologies.

Separation Techniques	**Description**	**Source**
Gravity separation (Wet or dry shaking tables)	Gravity concentration is used in the fraction of fine particles to separate: • light metals (e.g. Al) from heavier metals (e.g. Cu and wires) • light plastics from heavier plastics	(Dobrovszky and Ronkay, 2014; Gent et al., 2015; Jordão et al., 2016; Taherzadeh and Richards, 2015)
Laser induced breakdown spectroscopy	Short laser pulse is emitted on the particles' surface to separate the different types of alloys for Al (cast and wrought), Mg, Cu, SS, and others	(Cui and Roven, 2010; Gaustad et al., 2012; Kashiwakura and Wagatsuma, 2015; Koyanaka and Kobayashi, 2010)
Combined electromagnetic tensor spectroscopy and vision image analysis	Electromagnetic and spectroscopic principles are used to separate different heavy metals such as Cu, bronze, and brass alloy	(Margarido et al., 2014; Nogueira et al., 2015)
Combined chemical treatment and colour sorting	Chemical treatment is used for surface cleaning to allow the different grades of scrap (e.g. Al alloys) to be sorted through surface colour	(Nogueira et al., 2015)
Kinetic gravity separation	The different settling velocities of materials with various shapes and densities are used to separate fine wires and smaller NF particles that cannot be removed through eddy current separators due to low separation force	(Rem, 2009; Van Kooy et al., 2004)
Nail roll separation	Nails are attached to the cylindrical roll in a regular chequered pattern to separate wires	(Fabrizi et al., 2003)

Table 7-1 (Continued)

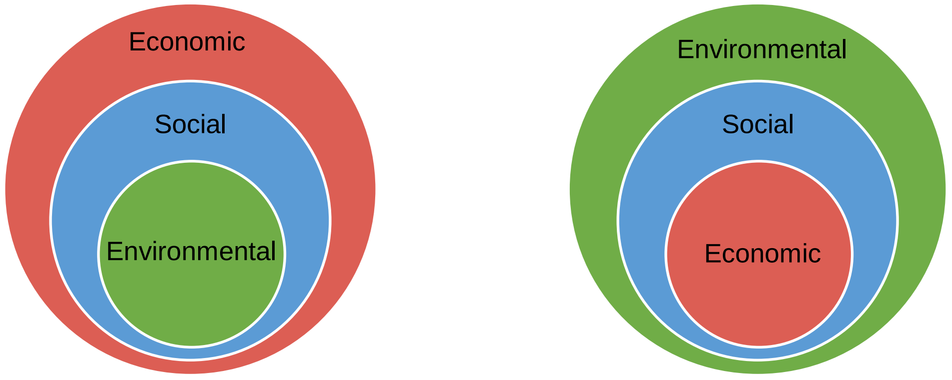
Separation Techniques	Description	Source
Thermo-mechanical sorting	Temperature difference due to the transition from one state to another is used to sort materials such as glass (brittle state to plastic-like state)	(Gent et al., 2015; Vermeulen et al., 2011)
Acoustic-visual sensor-based sorting	Impact acoustic emissions and visual sensors are used to separate the different types of black or dark-dyed plastics	(Huang et al., 2017)

Thermal treatment processes for ASR, such as incineration, gasification, and pyrolysis, are commonly used to reduce the amount and volume of ELV waste for disposal (Galvagno et al., 2001; Nourreddine, 2007; Srogi, 2008). Incineration converts ELV waste into ash through the combustion of organic substances present in ASR. In contrast, gasification is the process of converting organic substances of ELV waste to energy with a controlled amount of oxygen or steam supply at high temperature without combustion. Pyrolysis is similar to gasification, except that the process converts organic substances to energy at elevated temperature without the presence of oxygen. These thermal processes provide less environmental burden when compared to direct landfilling since waste is converted to energy. Past research has shown the potentials of pyrolysis and gasification in obtaining higher energy recovery values, and these methods are preferred to incineration that generates combustion residues, such as slag and fly ash (Srogi, 2008; Taylor et al., 2013). Furthermore, the use of Proler Syngas (gasification) process can further recover glass and metallic fractions in ASR (Galvagno et al., 2001; Sengupta, 1995).

The feasibility of the recommendations for alternative ELV material separation and treatment processes can be influenced by other factors, such as the economic aspect and legislative boundaries. Recycling of high purity materials can be affected by the additional recycling costs, the profit margin of end products, or the generated mass or volume of high quality scrap fractions. In addition, a governmental role can also be of importance through the implementation of policy targeting material degradation issues in current recycling activities. The incorporation of thermal treatment processes, on the other hand, is effective in reducing the amount and volume of ELV waste entering landfills while converting waste to energy; however, these methods are incapable of closing the material loop. At present, the recycling and recovery targets for ELV are not optimised for the potential of closed-loop material recycling.

7.6 Towards True Sustainability in Global Vehicle Industry

Conflicting areas of sustainability is unavoidable in the complex vehicle industry. This has led to the disparity between the three pillars of sustainability. Ideally, the sustainable vehicle recycling systems should operate based on the earth's carrying capacity, bound by the safe operating space for humanity, as shown in Figure 7-1(b). This ideal sustainability concept shows how both economic and social perspectives of the vehicle recycling activities are constrained by environmental limits, such as non-renewable resources consumption. In reality, the current vehicle recycling systems are profit-driven, dominating the social and environmental aspects, as can be seen in Figure 7-1(a). This situation is observed through the current ELV recycling practices adopted in different countries, inclusive of those with strict policy implementation.



(a) The current economic-driven vehicle recycling systems (Cato, 2009).

(b) The ideal sustainable vehicle recycling systems for a safe operating space of humanity (Rockström, 2015).

Figure 7-1: The paradigm of current and ideal sustainable vehicle recycling systems based on the three pillars of sustainability.

The ELV recycling systems are strongly driven by the economic values of the vehicle industry in different countries. Australia, U.S. and Canada are examples of countries operating solely based on the market mechanism where no direct legislations are regulated (Sakai et al., 2014). These countries rely mostly on the use of cost-effective shredder-based recycling processes to retrieve the high amount of steel scrap from ELV. The profit-driven recycling market faces increasing challenges due to the constant fluctuation in metal scrap price; the changing material composition and complexity in vehicle designs; and the rise of recycling costs due to the growing amount of ASR entering landfills. In such circumstances, there is a need to implement effective vehicle regulations to sustain the economic values of ELV to be recycled continuously.

It can be argued that ELV legislations play a more critical role in countries with strict policy implementation; however, the fundamental drivers of the efficiency of recycling processes and the adoption of more advanced recycling and treatment technologies are still strongly influenced by the economic factors. Countries and regions such as Japan, Korea, and Europe have strict legislation policies that set the recycling and recovery targets (Sakai et al., 2014). This has led to the advancement of recycling and waste treatment technologies to further retrieve valuable materials, and converting waste into energy to minimise the amount of ASR entering landfills. The practicability of integrating more advanced recycling and treatment options is constrained by the realisable profit (price of high quality scrap, ASR treatment costs, landfill cost, labour cost, etc.). The strict ELV policies play a major role in moderating the recycling costs through high landfill levy and recycling penalties. Moreover, the vehicle manufacturers, importers, and consumers are also responsible to share the burden of ELV recycling costs (Sakai et al., 2014).

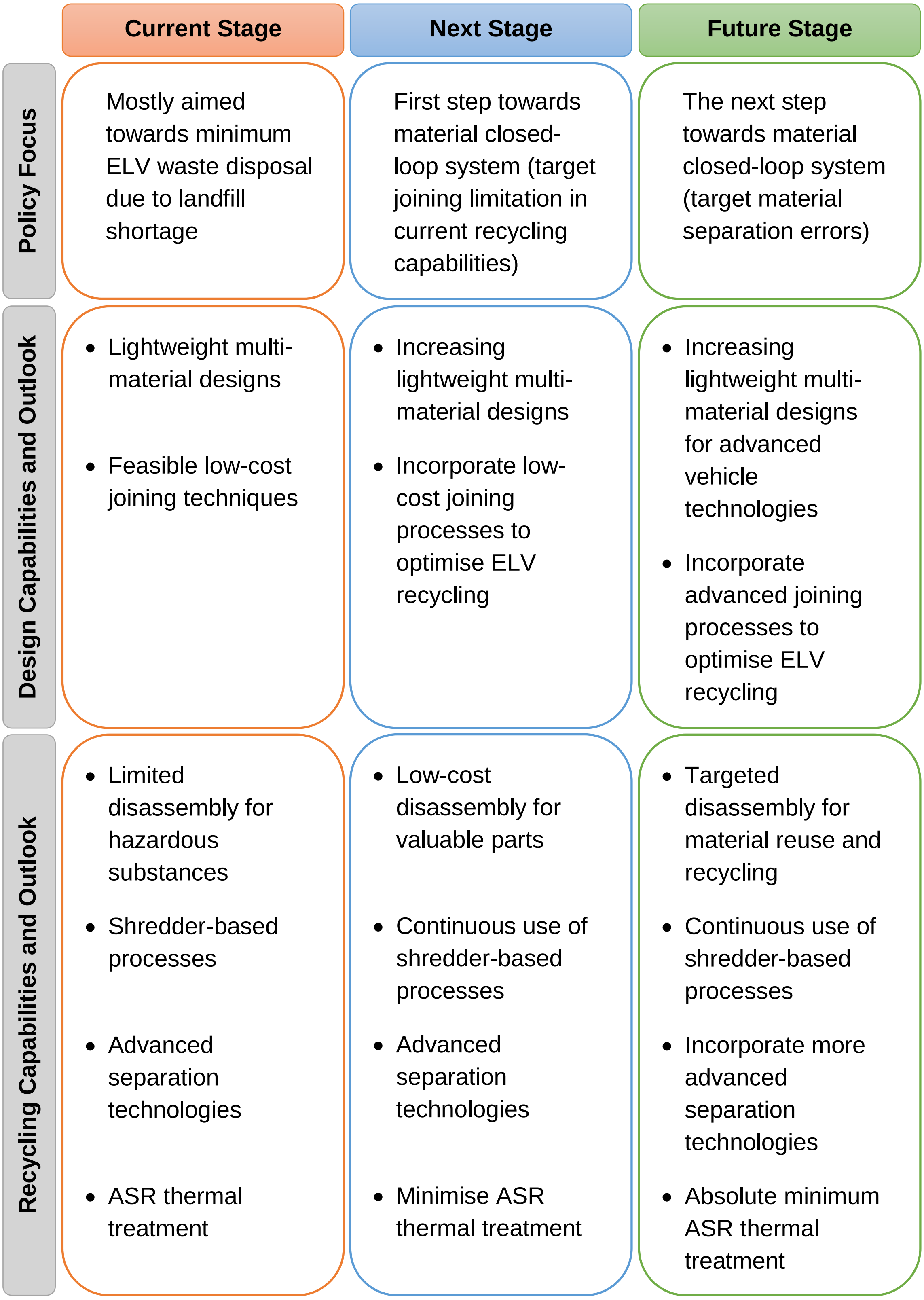
Acknowledging the fact that the vehicle recycling systems are strongly driven by economics, shredder-based recycling processes will still be largely incorporated into the ELV recycling systems. The shredding processes ease the handling of relatively large EoL products with low labour cost and high throughput. This process will continue to be an integral part of the vehicle recycling systems regardless of the implementation of different ELV policies. Therefore, the implications of joining techniques on the ELV recyclability as discussed in this work are highly relevant to the industrial recycling practices. Despite the promising research and development for pre-shredder disassembly processes, the integration into the current recycling practices remain uncertain. This is due to the high initial cost for tools and equipment; low throughput efficiency; and longer operation time compared to shredding process. Another emerging technology is the disassembly embedded design approach using active fasteners to cater for reverse assembly. This concept focuses on the extended producer responsibility where vehicle manufacturers assist through the vehicle design phase to facilitate material disassembly and separation at the EoL stage. Although this approach is favourable from the sustainability perspective, there are still challenges to overcome before a large-scale application, such as the applicability on highly complex vehicle designs; trade-off between the mass of valuable materials recycled and the initial manufacturing costs (particularly joining processes); and the lack of incentive for vehicle manufacturers to invest more time and expertise into the vehicle design phase to incorporate new fastener material types.

7.7 Place of This Work

A number of works have investigated the choice of material types and optimised multi-material designs to achieve vehicle mass reduction (see Section 2.4 and Section 2.11). These trends will continue to rise alongside the advancement in vehicle powertrain and alternative fuel technologies. Although these prior works have looked into the environmental impacts from a life cycle perspective, there is a lack of interaction between the changing complexity in vehicle designs and the ELV recyclability during the EoL phase. One of the major contributing factors to this gap is the increasing trend of joining processes used for multi-material combinations. The choice of joining methods has a great influence on the material recycling efficiency due to the shredder-based recycling processes largely used in industrial practices, as highlighted in Section 2.8 of the literature review. This work has filled the knowledge gap by addressing the sustainability issues in vehicle recycling from the following aspects:

- Case studies were conducted in industrial recycling facilities to address the influence of joints through current recycling practices (Chapter 4 and Chapter 5).
- The use of ELCA method to interpret the closed-loop recycling system more accurately by quantifying the influence of joining processes as an extension to the current environmental impact assessment of vehicle (Chapter 5).
- The integration of SD approach to observe the complex behavioural patterns of different vehicle recycling systems to allow a more pragmatic and holistic approach towards true vehicle sustainability from a joining techniques perspective (Chapter 6).

The stages of work and knowledge progression based on the proliferation of multi-material vehicle designs, and the feasibility of industrial recycling practices are shown in Figure 7-2. Intervention in current vehicle recycling systems can only be achieved progressively due to the time delays in complex dynamical system involving various stakeholders. The current stage represents the existing vehicle design and recycling capabilities constrained by the ELV policies commonly adopted in different countries. This is followed by the next stage, where this work is placed. The work of this thesis has extended the knowledge on effective joining choices to assist in liberation efficiency through current shredder-based recycling practices. More advanced recycling technologies to further improve material separation errors are then targeted in the future stage. The future stage aims to maximise closed-loop material recycling towards true vehicle sustainability while considering the economic feasibility.



	Current Stage	**Next Stage**	**Future Stage**
Policy Focus	Mostly aimed towards minimum ELV waste disposal due to landfill shortage	First step towards material closed-loop system (target joining limitation in current recycling capabilities)	The next step towards material closed-loop system (target material separation errors)
Design Capabilities and Outlook	• Lightweight multi-material designs • Feasible low-cost joining techniques	• Increasing lightweight multi-material designs • Incorporate low-cost joining processes to optimise ELV recycling	• Increasing lightweight multi-material designs for advanced vehicle technologies • Incorporate advanced joining processes to optimise ELV recycling
Recycling Capabilities and Outlook	• Limited disassembly for hazardous substances • Shredder-based processes • Advanced separation technologies • ASR thermal treatment	• Low-cost disassembly for valuable parts • Continuous use of shredder-based processes • Advanced separation technologies • Minimise ASR thermal treatment	• Targeted disassembly for material reuse and recycling • Continuous use of shredder-based processes • Incorporate more advanced separation technologies • Absolute minimum ASR thermal treatment

Figure 7-2: The proposed stages of intervention towards true sustainability in vehicle recycling within the economic constraints.

Chapter 8

Conclusion and Outlook

8.1 Introduction

This chapter concludes the research findings in line with the aims of this study. The key findings observed from case studies, and the critical insights obtained from the vehicle recycling systems' behaviours under different conditions are discussed. This is followed by the potential future work to further expand the knowledge on the interaction between joining techniques and vehicle recyclability. The future research directions are also explored.

8.2 Key Findings

The main findings of this work, as demonstrated in the previous chapters, are concluded in accordance with the research aims stated in Chapter 1. The main conclusions obtained from the two case studies are presented respectively, followed by the final remarks based on both case studies.

Aim 1: Assess the influence of joining choices for lightweight materials and their effects on vehicle recyclability through current recycling practices.

The Australian case study has captured data in an industrial trial measuring the recycling efficiency for various joining techniques observed on different car door models. Observations from the car door shredding trials showed that steel screws and bolts are increasingly used to combine different material types and are less likely to be perfectly liberated during the shredding process. The characteristics of joints that lead to impurities and valuable material losses, such as joint strength, joint material type, joint size, fastener diameter and length, joint location, and joint protrusion level, can influence the material liberation in the current sorting practices and thus, lead to ELV waste minimisation. Additionally, the liberation of joints is also affected by the density and thickness of materials being joined. Correlation analysis was then performed between the joint input data and the unliberated joints in different output streams. The results further supported the influence of mechanical screws and bolts through high correlation values, 0.9635 and 0.9994, for the NF and ASR output streams respectively.

The influence of machine screws on the resulting impurity levels in the valuable output streams is further evidenced through the Al recycling case study carried out in a leading European recycling facility located in Belgium. Despite the use of more advanced recycling processes, mechanical fasteners, such as machine screws, socket screws, bolt screws and rivets, cause impurities in the different Al output fractions. This is particularly the case for Al with high steel fractions where at least 69% of the total Fe impurities are contributed by unliberated joints. It is shown that the shredding of particles to smaller particle sizes can potentially decrease the Fe impurities due to unliberated joints by at least 33%; however, finer particles lead to higher material losses that affect the recycler's proft margin.

The empirical evaluation of the samples collected from both case studies showed that the characteristics of different joining techniques play a significant role in determining the material liberation level through current shredding process despite the use of different recycling approaches. The suggested preferences to improve the material recyclability in current shredder-based recycling processes from a joining techniques perspective are summarised as follows.

Joining part:

- Minimise joint strength, joint size, and area of bond contact without compromising the reliability during use phase.
- Encourage the use of joints with low temperature resistance, such as adhesive bonding.
- Minimise the use of fasteners with small diameter and size.
- Minimise the use of joints that degrade due to moisture (corroded joints) and encourage the use of joints that degrade due to heat to ease liberation without compromising the reliability during use phase.
- Place joints at easily accessible location to assist in joint liberation.
- Encourage the use of joints with similar or compatible material type.
- Encourage the use of protruded joints to assist in joint liberation.
- Encourage the use of fasteners with smoother surface to ease joint liberation.

Material part:

- Encourage the use of joints with large differences in material densities (e.g. metal-plastic combination) to ease material breakage.
- Encourage the use of joints with unequal thickness to ease material liberation.

Aim 2: Determine a method to quantify the impact of joints during the recycling phase towards a closed-loop ELV recycling system.

By measuring the influence of joints quantitatively, this work has looked at the potential of improving the quality of recycled ELV materials to be reused in a closed-loop vehicle manufacturing system, and minimise the amount of valuable material losses in ASR. Prior works have proposed generic ecodesign guidelines to assist in designing for disassembly and recycling; however, none of these works have provided a method to quantify to what extent the different joining choices are affecting the life cycle environmental impacts of vehicle.

The potential of measuring the additional environmental burden due to joint effects was investigated using the ELCA approach. Firstly, the feasibility to account for material quality loss through industrial practices was explored in the Australian car door case study. The varying amount of Cu impurities (tramp element) present in the Fe output streams for different vehicle door designs was used to calculate the respective amount of pig iron required for dilution to be reused as cold rolled sheet. Based on the analysis of the ELCA results, the climate change impact has increased by at least 68% due to the production of pig iron.

Based on the Al recycling case study in Belgium, the dilution and quality losses associated with the quality of different Al scrap fractions were investigated from a joining context. The respective mass fraction of unliberated joints causing Fe impurities was quantified based on the Al samples collected. ELCA approach was then used to assess the environmental impacts of diluting the varying amount of Fe impurities present in the different Al scrap fractions to achieve wrought Al 6061 commonly used in automotive applications. Al scrap fractions with high steel content required a higher amount of primary Al for dilution to achieve the desired Al quality. Consequently, the total environmental impact of recycling Al scrap fractions with high steel content have increased by at least 28 times in comparison to the recycling of Al scrap fractions with lower steel content (higher purity Al scrap). Unliberated joints are the major contributor to the environmental impact share of dilution losses, which account for about 70%.

This work shows the feasibility of quantifying the environmental impact due to joints using ELCA method to assist in optimising a closed-loop material recycling. The commonly used LCA method to assess the environmental impacts of vehicle is incapable of capturing the material degradation issues emerging from the complex vehicle designs. By taking the first step to quantify the influence of joints through LCA, the gap between changing vehicle designs and current recycling practices can be measured more accurately.

Aim 3: Demonstrate the interaction between multi-material vehicle designs and ELV recyclability through dynamical changes in vehicle life cycle environmental impacts over time from a joining techniques perspective.

An SD approach in LCA was explored to account for the dynamics of joining choices used for new vehicle designs and their delayed impact on the vehicle recycling phase. The system behaviours observed from the case studies were interpreted from the “lenses” of two widely known system archetypes: “Fixes that Fail” and “Shifting the Burden”. These methods map the understanding of the complex systems to the basic structures with anticipated behavioural patterns. Observations from historical trends, case study data, and the implementation of stricter emission and recycling targets were used to identify the most appropriate behaviour patterns to represent the different vehicle recycling systems. The implications of different joining choices through various recycling approaches were described from a life cycle perspective.

“Fixes that Fail” scenario is representative of the Australian recycling system due to the lack of strict recycling policy and low landfill levy that widens the gap between vehicle design and recycling phases. The vehicle industry is driven by the consumers’ demand to continuously produce vehicles with high fuel efficiency through changing vehicle designs. However, vehicle manufacturers have no responsibility for the delayed impact of joining techniques used for multi-material designs on the ELV recycling phase. With a relatively low landfill cost and no strict ELV regulatory policy, there is a lack of motivation among vehicle manufacturers to incorporate extended producer responsibility strategies to promote closed-loop recycling through effective choice of joining techniques. The delayed consequences of low quality material recycling due to joining choices at earlier design phase become an increasing burden to the recyclers due to the profit-driven recycling industry.

The “Fixes that Fail” archetype can be extended to “Shifting the Burden” when there is awareness of the effect of low material recycling efficiency from ELV through the implementation of strict recycling targets and high landfill levy. Therefore, the European vehicle recycling system can be more closely resembled through the “Shifting the Burden” archetype. The environmental burden associated with the vehicle use phase is progressively shifted to the recycling phase through a time delay due to the life cycle impact of joining choices for multi-material designs. One of the contributing factors to the “shift” is the use of standard LCA among vehicle manufacturers to identify potential opportunities for environmental improvement. Past vehicle LCA results have identified vehicle use phase as the major contributor to the environmental impact. This has led to the focus on reducing vehicle CO_2 emissions to abide by the strict vehicle emission targets. However, the increasing complexity of recycling new vehicle designs and their associated joining techniques is not well accounted for in current LCA. Often, a relatively high material recycling efficiency for different recyclable materials is assumed, which is not reflective of the efficiency of current shredder-based recycling practices. The commonly used ELV recycling processes are unable to separate the different material combinations due to the presence of unliberated joints. Moreover, the additional environmental burden to recycle high quality material to be reused in a closed-loop system is not well addressed despite the implementation of strict ELV recycling targets. The current ELV policies are designed to reduce the amount of ELV waste but lack consideration for material degradation issues due to unliberated joints. One of the potential solutions to overcome this problem is to focus on policies that incorporate closed-loop system, such as imposing strict impurity levels for different output streams to improve the material recycling efficiencies. Such policy can create awareness not only to design for better ELV recycling, but also to reduce the demand for natural resources by sustaining the reusability of secondary materials in a continuous closed-loop system.

This work shows that the liberation of common joining techniques used for different material combinations is critical to achieve a closed-loop material cycle despite the adoption of more rigorous recycling approaches. The dynamic models for different vehicle recycling systems illustrated the continued existence of environmental burden due to unliberated joints through exergy losses during recycling. It is shown that the implementation of strict ELV policies only prolongs the delay in material degradation issues and thus, the underlying ELV waste problem is not solved in the long term. This is particularly concerning with the proliferation of multi-material vehicle designs in the vehicle industry.

8.3 Future Work

This section describes the potential work that can be extended from this study, as highlighted in Section 7.4. The outlook of the research directions to further improve the ELV material recycling and recovery efficiencies are then discussed in light of the current industrial practices.

8.3.1 Further Implications of This Study

The qualitative vehicle recycling models in this research can be used as a reference to simulate the quantitative models. As shown in Chapter 6, the data collected from different case studies can be computed into mathematical expressions to interconnect different variables, and to simulate the dynamical changes based on the complex relationships between parameters. More rigorous testing can then be carried out for the simulated vehicle recycling models to test the robustness of the model under varying conditions, and to identify their sensitivity to various parameter changes. The extended SD recycling models can provide more rigid policy interventions that effectively address the joint effects on vehicle recyclability. Alternatively, different strategies and policy options can be simulated to assess the likely behavioural outcomes, and to identify uncertainties that may arise due to the action plan.

There is potential to broaden the system boundaries of the SD models to explore other dynamical effects from the economic and legislative perspectives. This research focuses on the environmental aspect from a joining techniques perspective, which can then be expanded to provide a more holistic sustainability approach addressing the triple bottom line—sustainability framework that includes the dynamics from the economic, social, and environmental aspects. The recycling models can also be adapted to suit the changing vehicle technologies, such as alternative fuel and new powertrain vehicles, that may be driven by different dynamics.

The results from this research (Chapter 4 and Chapter 5) can be further validated through more controlled experiments targeting the characteristics of joints that influence the material recyclability. Main findings from the case studies have provided some insights into the material liberation behaviours through industrial shredding processes. Such knowledge enables the simulation of the recycling scenarios in a lab-scale experiment to allow various joining techniques to be tested under different conditions (e.g. dissimilar material combinations or material thickness). Moreover, the specifications for the characteristics of joints affecting perfect material liberation, such as the optimum value of joint strength to ease material recycling, can be identified. The transfer of knowledge from industrial to lab-scale experiment provides the opportunity to test a wider range of joining techniques, and to investigate the likely material liberation behaviours for more advanced joining technologies through cost-effective experimental setup.

8.3.2 Directions for Future Research

This thesis identifies the range of joining techniques causing impurities and valuable material losses through the shredder-based recycling processes widely used in current recycling practices. However, the characteristics of joints that present challenges during material separation are likely to differ through the extensive use of different disassembly processes (see Section 7.5). Additionally, material separation errors due to structural designs (e.g. enclosure) and entanglement during shredding and sorting processes are also causing impurities and material losses in different output streams, as detailed in Chapter 4 and Chapter 5. When ecodesign specific to joint selection is significantly incorporated in new vehicle designs, the burden to achieve high material recycling efficiency will progressively shift to the effectiveness of recycling processes utilised. This is particularly the case for the increasing complexity in multi-material vehicle designs to produce lightweight vehicles, and this trend is projected to continue in the future of vehicle manufacturing. In such situation, the material recycling rate for ELV is strongly influenced by the efficiency of recycling technologies used to separate the different material types.

The two main areas of research extended from this work are the influence of various joining choices through extensive use of different disassembly processes (joining methods perspective); and the reduction of material separation errors through advanced sorting technologies (recycling process perspective), as highlighted in Section 7.7. This work has shown that imperfect material separation is largely caused by the inefficient liberation of the shredder-based recycling processes in releasing the joints with different material combinations. The influence of joining choices used in complex vehicle designs, particularly permanent weld and high-strength adhesive joints, will have different implications on the separability of various material types through rigorous disassembly process (Lu et al., 2014; Rotheiser, 2015). Thus, further investigation needs to be carried out to understand the implications of joining techniques on the adoption of different disassembly techniques into the current recycling processes. Additionally, impurities and material losses due to material separation errors are still present, and they are largely caused by the inefficiency of recycling processes. In such circumstances, the advancement of material sorting and waste treatment technologies has a larger effect on the overall material recycling rate.

References

Abe, Y., Kato, T., Mori, K., 2009. Self-piercing riveting of high tensile strength steel and aluminium alloy sheets using conventional rivet and die. J. Mater. Process. Technol. 209, 3914–3922. https://doi.org/10.1016/j.jmatprotec.2008.09.007

Abele, E., Anderl, R., Birkhofer, H., 2007. Environmentally-friendly product development. Springer Science & Business Media.

ABRI, n.d. Australian Battery Recycling Initiative [WWW Document]. URL http://www.batteryrecycling.org.au/home (accessed 8.16.16).

Ahmed, N. (Ed.), 2005. New developments in advanced welding. Elsevier.

Albin, S., 1997. Building a system dynamics model part 1: Conceptualization. Road Maps: A Guide to Learning System Dynamics. MIT System Dynamics in Education Project.

ALIVE [WWW Document], n.d. URL http://www.project-alive.eu/index.php?content=home&a=menu&b=item1 (accessed 12.30.16).

Alonso, E., Lee, T.M., Bjelkengren, C., Roth, R., Kirchain, R.E., 2012. Evaluating the Potential for Secondary Mass Savings in Vehicle Lightweighting. Environ. Sci. Technol. 46, 2893–2901. https://doi.org/10.1021/es202938m

Alonso, J.C., Dose, J., Fleischer, G., Geraghty, K., Greif, A., Rodrigo, J., Schmidt, W.-P., 2007. Electrical and electronic components in the automotive sector: Economic and environmental assessment. Int. J. Life Cycle Assess. 12, 328–335. https://doi.org/10.1065/lca2006.08.263

Amancio-Filho, S. t., dos Santos, J. f., 2009. Joining of polymers and polymer–metal hybrid structures: Recent developments and trends. Polym. Eng. Sci. 49, 1461–1476. https://doi.org/10.1002/pen.21424

American Automobile Manufacturers Association, Government Affairs Division, American Automobile Manufacturers Association, Economic and International Affairs Dept, American Automotive Manufacturers Association, 1994. AAMA Motor Vehicle Facts and Figures. Government Affairs Division of the American Automobile Manufacturers Association.

Amini, S.H., Remmerswaal, J.A.M., Castro, M.B., Reuter, M.A., 2007. Quantifying the quality loss and resource efficiency of recycling by means of exergy analysis. J. Clean. Prod. 15, 907–913. https://doi.org/10.1016/j.jclepro.2006.01.010

Andersen, F.M., Larsen, H.V., Skovgaard, M., 2008. Projection of end-of-life vehicles: Development of a projection model and estimates of ELVs for 2005-2030. European Topic Centre on Waste and Resources.

Andersson, K., Eide, M.H., Lundqvist, U., Mattsson, B., 1998. The feasibility of including sustainability in LCA for product development. J. Clean. Prod. 6, 289–298. https://doi.org/10.1016/S0959-6526(98)00028-6

Andersson, M., Söderman, M.L., Sandén, B.A., 2017a. Lessons from a century of innovating car recycling value chains. Environ. Innov. Soc. Transit. https://doi.org/10.1016/j.eist.2017.03.001

Andersson, M., Söderman, M.L., Sandén, B.A., 2017b. Are scarce metals in cars functionally recycled? Waste Manag., Special Thematic Issue: Urban Mining and Circular Economy 60, 407–416. https://doi.org/10.1016/j.wasman.2016.06.031

Anfara Jr, V.A., Brown, K.M., Mangione, T.L., 2002. Qualitative analysis on stage: Making the research process more public. Educ. Res. 31, 28–38. https://doi.org/10.3102/0013189X031007028

Argument, L., Lettice, F., Bhamra, T., 1998. Environmentally conscious design: matching industry requirements with academic research. Des. Stud. 19, 63–80. https://doi.org/10.1016/S0142-694X(97)00017-3

Armah, F.A., Yawson, D.O., Pappoe, A.A., 2010. A systems dynamics approach to explore traffic congestion and air pollution link in the city of Accra, Ghana. Sustainability 2, 252–265.

Ashby, M.F., 2012. Materials and the environment: eco-informed material choice. Elsevier.

Ashori, A., 2008. Wood–plastic composites as promising green-composites for automotive industries! Explor. Horiz. Biotechnol. Glob. Venture 99, 4661–4667. https://doi.org/10.1016/j.biortech.2007.09.043

Australian Bureau of Statistics, ABS, 2013. Average Age of Registered Vehicles (No. 9309.0), Motor Vehicle Census, Australia.

Avalle, M., Peroni, L., Peroni, M., Scattina, A., 2010. Bi-Material Joining for Car Body Structures: Experimental and Numerical Analysis. J. Adhes. 86, 539–560. https://doi.org/10.1080/00218464.2010.484308

Badino, V., Baldo, G.L., Legarth, J., 1997. LCA approach to the automotive glass recycling. J. Environ. Sci. CHINA-Engl. Ed.- 9, 208–214.

BAIDAO, 2007. Silicon metal 2202 [WWW Document]. URL http://siliconmetal.net/siliconmetal2202.htm (accessed 6.8.17).

Bakavos, D., Prangnell, P.B., 2010. Mechanisms of joint and microstructure formation in high power ultrasonic spot welding 6111 aluminium automotive sheet. Mater. Sci. Eng. A 527, 6320–6334. https://doi.org/10.1016/j.msea.2010.06.038

Balle, F., Wagner, G., Eifler, D., 2007. Ultrasonic spot welding of aluminum sheet/carbon fiber reinforced polymer – joints. Mater. Werkst. 38, 934–938. https://doi.org/10.1002/mawe.200700212

Barnes, T.A., Pashby, I.., 2000a. Joining techniques for aluminium spaceframes used in automobiles: Part II — adhesive bonding and mechanical fasteners. J. Mater. Process. Technol. 99, 72–79. https://doi.org/10.1016/S0924-0136(99)00361-1

Barnes, T.A., Pashby, I.R., 2000b. Joining techniques for aluminium spaceframes used in automobiles: Part I — solid and liquid phase welding. J. Mater. Process. Technol. 99, 62–71. https://doi.org/10.1016/S0924-0136(99)00367-2

Bay, N., 2011. Cold Welding, in: Welding, Fundamentals and Processes. ASM International.

Belboom, S., Lewis, G., Bareel, P.F., Léonard, A., 2016. Life cycle assessment of hybrid vehicles recycling: Comparison of three business lines of dismantling. Waste Manag. 50, 184–193. https://doi.org/10.1016/j.wasman.2016.02.007

Bellmann, K., Khare, A., 2000. Economic issues in recycling end-of-life vehicles. Technovation 20, 677–690. https://doi.org/10.1016/S0166-4972(00)00012-2

Belov, N.A., Aksenov, A.A., Eskin, D.G., 2002. Iron in aluminium alloys: impurity and alloying element. CRC Press.

Benoît, C., Norris, G.A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., Prakash, S., Ugaya, C., Beck, T., 2010. The guidelines for social life cycle assessment of products: just in time! Int. J. Life Cycle Assess. 15, 156–163. https://doi.org/10.1007/s11367-009-0147-8

Bethel, J., DiGaetano, R., Peppler, M., Sterrett, E., Dillman, S., 1993. Sampling Guidance for Scrap Metal Shredders-Field Manual.

Bielaczyc, P., Woodburn, J., Szczotka, A., 2014. An assessment of regulated emissions and CO2 emissions from a European light-duty CNG-fueled vehicle in the context of Euro 6 emissions regulations. Appl. Energy 117, 134–141. https://doi.org/10.1016/j.apenergy.2013.12.003

Bizzo, W.A., Figueiredo, R.A., de Andrade, V.F., 2014. Characterization of printed circuit boards for metal and energy recovery after milling and mechanical separation. Materials 7, 4555–4566. https://doi.org/10.3390/ma7064555

Bogue, R., 2007. Design for disassembly: a critical twenty-first century discipline. Assem. Autom. 27, 285–289. https://doi.org/10.1108/01445150710827069

Bonollo, F., Carturan, I., Capitò, G., Molina, R., 2013. Life cycle assessment in the automotive industry: comparison between aluminium and cast iron cylinder blocks. Metall. Sci. Tecnol. 24.

Boothroyd, G., Alting, L., 1992. Design for Assembly and Disassembly. CIRP Ann. 41, 625–636. https://doi.org/10.1016/S0007-8506(07)63249-1

Boothroyd, G., Dewhurst, P., Knight, W.A., 2010. Product Design for Manufacture and Assembly, Third Edition. CRC Press.

Brahmst, E., 2006. Copper in End-of-Life Vehicle Recycling. Manufacturing, Engineering & Technology Group Center for Automotive Research.

Bras, B., 1997. Incorporating environmental issues in product design and realization. Ind. Environ. 20, 7–13.

Bretz, R., n.d. SETAC LCA Workgroup: data availability and data quality. Data Qual. 3.

Briskham, P., Blundell, N., Han, L., Hewitt, R., Young, K., Boomer, D., 2006. Comparison of self-pierce riveting, resistance spot welding and spot friction joining for aluminium automotive sheet. SAE Int. 13.

Bureau of Infrastructure, Transport and Regional Economics (BITRE), 2014. New passenger vehicle fuel consumption trends, 1979 to 2013, Information Sheet 66. BITRE, Canberra.

Busse, S., Merklein, M., Roll, K., Ruther, M., Zürn, M., 2010. Development of a mechanical joining process for automotive body-in-white production. Int. J. Mater. Form. 3, 1059–1062. https://doi.org/10.1007/s12289-010-0953-3

Campbell, F.C. (Ed.), 2011. Joining: understanding the basics. ASM International.

Cao, X., Jahazi, M., Immarigeon, J.P., Wallace, W., 2006. A review of laser welding techniques for magnesium alloys. J. Mater. Process. Technol. 171, 188–204. https://doi.org/10.1016/j.jmatprotec.2005.06.068

Carboni, M., Beretta, S., Monno, M., 2006. Fatigue behaviour of tensile-shear loaded clinched joints. Eng. Fract. Mech., Advanced Fracture Mechanics for Life Safety Assessments 73, 178–190. https://doi.org/10.1016/j.engfracmech.2005.04.004

Carle, D., Blount, G., 1999. The suitability of aluminium as an alternative material for car bodies. Mater. Des. 20, 267–272. https://doi.org/10.1016/S0261-3069(99)00003-5

Carrell, J., Zhang, H.C., Tate, D., Li, H., 2009. Review and future of active disassembly. Int. J. Sustain. Eng. 2, 252–264. https://doi.org/10.1080/19397030903267431

Castro, M.B., Remmerswaal, J.A.M., Brezet, J.C., Van Schaik, A., Reuter, M.A., 2005. A simulation model of the comminution–liberation of recycling streams: Relationships between product design and the liberation of materials during recycling. Int. J. Miner. Process. 75, 255–281. https://doi.org/10.1016/j.minpro.2004.09.001

Castro, M.B.G., Remmerswaal, J.A.M., Brezet, J.C., Reuter, M.A., 2007. Exergy losses during recycling and the resource efficiency of product systems. Resour. Conserv. Recycl. 52, 219–233. https://doi.org/10.1016/j.resconrec.2007.01.014

Castro, M.B.G., Remmerswaal, J.A.M., Reuter, M.A., 2003. Life cycle impact assessment of the average passenger vehicle in the Netherlands. Int. J. Life Cycle Assess. 8, 297–304. https://doi.org/10.1007/BF02978922

Castro, M.B.G., Remmerswaal, J.A.M., Reuter, M.A., Boin, U.J.M., 2004. A thermodynamic approach to the compatibility of materials combinations for recycling. Resour. Conserv. Recycl. 43, 1–19. https://doi.org/10.1016/j.resconrec.2004.04.011

Cato, M.S., 2009. Green economics: An introduction to theory, policy and practice. Earthscan.

Center for Automotive Research, 2011. Lightweight Materials & Forming Report, Automotive Technology: Greener Products, Changing Skills.

Cerdan, C., Gazulla, C., Raugei, M., Martinez, E., Fullana-i-Palmer, P., 2009. Proposal for new quantitative eco-design indicators: a first case study. J. Clean. Prod. 17, 1638–1643. https://doi.org/10.1016/j.jclepro.2009.07.010

Chan, C.C., 2007. The state of the art of electric, hybrid, and fuel cell vehicles. Proc. IEEE 95, 704–718. https://doi.org/10.1109/JPROC.2007.892489

Changsirivathanathamrong, A., Moore, S., Linard, K., 2007. Integrating system dynamics with life cycle assessment: A framework for improved policy formulation and Analysis. Model. Simul. Soc. Aust. N. Z. MSSANZ.

Chao, Y.J., 2003. Failure mode of spot welds: interfacial versus pullout. Sci. Technol. Weld. Join. 8, 133–137. https://doi.org/10.1179/174329313X13789830157267

Cho, T.T., Meng, Y., Sugiyama, S., Yanagimoto, J., 2015. Separation technology of tramp elements in aluminium alloy scrap by semisolid processing. Int. J. Precis. Eng. Manuf. 16, 177–183. https://doi.org/10.1007/s12541-015-0023-3

Christensen, J., Bastien, C., Blundell, M., Gittens, A., Tomlin, O., 2011. Lightweight hybrid electrical vehicle structucal topology optimisation investigation focusing on crashworthiness. Int. J. Veh. Struct. Syst. 3, 113–122. http://dx.doi.org/10.4273/ijvss.3.2.06

Ciacci, L., Morselli, L., Passarini, F., Santini, A., Vassura, I., 2010. A comparison among different automotive shredder residue treatment processes. Int. J. Life Cycle Assess. 15, 896–906. https://doi.org/10.1007/s11367-010-0222-1

Clift, R., Frischknecht, R., Huppes, G., Weidema, B., Weidema, B., 1998. Report of the Working Group on Inventory Enhancement, SETAC-Europe, Toward a coherent approach to life cycle inventory analysis. SETAC-Europe, Brussels.

Climate Change Authority, 2014. Light vehicle emissions standards For Australia: research report.

Coelho, R.S., Kostka, A., dos Santos, J.F., Kaysser-Pyzalla, A., 2012. Friction-stir dissimilar welding of aluminium alloy to high strength steels: Mechanical properties and their relation to microstructure. Mater. Sci. Eng. A 556, 175–183. https://doi.org/10.1016/j.msea.2012.06.076

Coia, A., 2014. A star still on the rise in Brazil. Automot. Logist.

Cole, G.S., Sherman, A.M., 1995. Light weight materials for automotive applications. Microstruct. Charact. Lightweight Struct. Mater. Transp. 35, 3–9. https://doi.org/10.1016/1044-5803(95)00063-1

Collinge, W.O., Landis, A.E., Jones, A.K., Schaefer, L.A., Bilec, M.M., 2013. Dynamic life cycle assessment: framework and application to an institutional building. Int. J. Life Cycle Assess. 18, 538–552. https://doi.org/10.1007/s11367-012-0528-2

Cong, L., Zhao, F., Sutherland, J.W., 2017. Integration of dismantling operations into a value recovery plan for circular economy. J. Clean. Prod. 149, 378–386. https://doi.org/10.1016/j.jclepro.2017.02.115

Cooman, B.C.D., Chin, K., Kim, J., 2011. High Manganese Advanced High Strength TWIP Steels for Automotive Applications. pp. 101–128.

Corben, D.A., 1994. Integrating archetypes and generic models into a framework for model conceptualisation, in: Proceedings of the 1994 International System Dynamics Conference. System Dynamics Society, Stirling, UK.

Cornelissen, R.L., 1997. Thermodynamics and sustainable development: the use of exergy analysis and the reduction of irreversibility. Universiteit Twente.

Cossu, R., Lai, T., 2015. Automotive shredder residue (ASR) management: An overview. Waste Manag., Urban Mining 45, 143–151. https://doi.org/10.1016/j.wasman.2015.07.042

Cui, J., Forssberg, E., 2003. Mechanical recycling of waste electric and electronic equipment: a review. J. Hazard. Mater. 99, 243–263. https://doi.org/10.1016/S0304-3894(03)00061-X

Cui, J., Roven, H.J., 2010. Recycling of automotive aluminum. Trans. Nonferrous Met. Soc. China 20, 2057–2063. https://doi.org/10.1016/S1003-6326(09)60417-9

Cui, X., Wang, S., Hu, S.J., 2008. A method for optimal design of automotive body assembly using multi-material construction. Mater. Des. 29, 381–387. https://doi.org/10.1016/j.matdes.2007.01.024

Cui, X., Zhang, H., Wang, S., Zhang, L., Ko, J., 2011. Design of lightweight multi-material automotive bodies using new material performance indices of thin-walled beams for the material selection with crashworthiness consideration. Mater. Des. 32, 815–821. https://doi.org/10.1016/j.matdes.2010.07.018

Cullen, J.M., Allwood, J.M., 2013. Mapping the global flow of aluminum: From liquid aluminum to end-use goods. Environ. Sci. Technol. 47, 3057–3064. https://doi.org/10.1021/es304256s

Dalmijn, W.L., Jong, T.P.R.D., 2007. The development of vehicle recycling in Europe: Sorting, shredding, and separation. JOM 59, 52–56. https://doi.org/10.1007/s11837-007-0141-1

Danilecki, K., Mrozik, M., Smurawski, P., 2017. Changes in the environmental profile of a popular passenger car over the last 30 years–Results of a simplified LCA study. J. Clean. Prod. 141, 208–218. https://doi.org/10.1016/j.jclepro.2016.09.050

Das, S., 2011. Life cycle assessment of carbon fiber-reinforced polymer composites. Int. J. Life Cycle Assess. 16, 268–282. https://doi.org/10.1007/s11367-011-0264-z

Das, S., 2001. The cost of automotive polymer composites: a review and assessment of DOE's lightweight materials composites research. Oak Ridge National Laboratory Oak Ridge, TN.

Das, S., 2000. The life-cycle impacts of aluminum body-in-white automotive material. JOM 52, 41–44. https://doi.org/10.1007/s11837-000-0173-2

Davies, G., 2012. Materials for Automobile Bodies. Butterworth-Heinemann.

Davis, J.R., 1998. Metals handbook. ASM International.

Davis, S.C., Diegel, S.W., Boundy, R.G., 2015. Transportation Energy Data Book: Edition 34. Oak Ridge National Laboratory.

Dawes, C., 1992. Laser welding: a practical guide. Woodhead Publishing.

Dawkins, E., Allan, P., 2010. Landfill ban investigation. Hyder Consulting, Department of Sustainability, Environment, Water, Population and Communities, Melbourne.

De Silva, N., Jawahir, I.S., Dillon Jr., O., Russell, M., 2009. A new comprehensive methodology for the evaluation of product sustainability at the design and development stage of consumer electronic products. Int. J. Sustain. Manuf. 1, 251–264. https://doi.org/10.1504/IJSM.2009.023973

Department of Environment and Heritage, 2002. Environmental Impact of End-of-Life Vehicles: An Information Paper. Australia.

Department of the Environment and Energy, Australia, n.d. Product Stewardship for Oil (PSO) Program [WWW Document]. URL https://www.environment.gov.au/protection/used-oil-recycling/product-stewardship-oil-program (accessed 8.16.16a).

Department of the Environment and Energy, Australia, n.d. Product stewardship for end of life tyres [WWW Document]. URL https://www.environment.gov.au/protection/national-waste-policy/tyres (accessed 8.16.16b).

Department of the Environment, Australia, 2009. National Waste Policy: Less Waste, More Resources [WWW Document]. Natl. Waste Policy Fact Sheet. URL http://www.environment.gov.au/system/files/pages/94aa70c5-6681-44c6-8d83-77606d1d6afe/files/fs-national-waste-policy.pdf (accessed 4.6.16).

Dhingra, R., Das, S., 2014. Life cycle energy and environmental evaluation of downsized vs. lightweight material automotive engines. J. Clean. Prod., Special Volume: Making Progress Towards More Sustainable Societies through Lean and Green Initiatives 85, 347–358. https://doi.org/10.1016/j.jclepro.2014.08.107

Dilthey, U., Stein, L., 2006. Multimaterial car body design: challenge for welding and joining. Sci. Technol. Weld. Join. 11, 135–142. https://doi.org/10.1179/174329306X85967

Dobrovszky, K., Ronkay, F., 2014. Alternative polymer separation technology by centrifugal force in a melted state. Waste Manag. 34, 2104–2112. https://doi.org/10.1016/j.wasman.2014.05.006

Dos Santos Pegoretti, T., Mathieux, F., Evrard, D., Brissaud, D., De França Arruda, J.R., 2014. Use of recycled natural fibres in industrial products: A comparative LCA case study on acoustic components in the Brazilian automotive sector. Resour. Conserv. Recycl. 84, 1–14. https://doi.org/10.1016/j.resconrec.2013.12.010

Dowie, T., Simon, M., 1995. Guidelines for designing for disassembly and recycling. Presented at the R’95 Congress, Geneva, Switzerland, p. 10.

Dowling, A.M., MacDonald, R.H., Richardson, G.P., 1995. Simulation of Systems Archetypes, in: Proceedings of the 1995 International System Dynamics Conference. Tokyo, Japan, pp. 454–463.

Duflou, J.R., Seliger, G., Kara, S., Umeda, Y., Ometto, A., Willems, B., 2008. Efficiency and feasibility of product disassembly: A case-based study. CIRP Ann. - Manuf. Technol. 57, 583–600. https://doi.org/10.1016/j.cirp.2008.09.009

Duflou, J.R., Willems, B., Dewulf, W., 2006. Towards self-disassembling products design solutions for economically feasible large-scale disassembly. Innov. Life Cycle Eng. Sustain. Dev. 87–110.

E. U. Directive, 2000. 53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles. Off. J. Eur. Union Ser. 34–42.

Ebnesajjad, S., Landrock, A.H., 2014. Adhesives technology handbook, 3rd ed. William Andrew.

Edwards, C., Bhamra, T., Rahimifard, S., 2006. A design framework for end-of-life vehicle recovery, in: Proceedings of the 13th CIRP International Conference on Life Cycle Engineering. Leuven, Belgium, pp. 360–365.

Ehrenberger, S., Friedrich, H.E., 2013. Life-Cycle Assessment of the Recycling of Magnesium Vehicle Components. JOM 65, 1303–1309. https://doi.org/10.1007/s11837-013-0703-3

Eisenhardt, K.M., 1989. Building theories from case study research. Acad. Manage. Rev. 14, 532–550. https://doi.org/10.2307/258557

Ekvall, T., Assefa, G., Björklund, A., Eriksson, O., Finnveden, G., 2007. What life-cycle assessment does and does not do in assessments of waste management. Waste Manag. 27, 989–996. https://doi.org/10.1016/j.wasman.2007.02.015

Elmer, J.W., Kautz, D.D., 1993. Fundamentals of friction welding, in: Welding, Brazing and Soldering. ASM International.

ENLIGHT [WWW Document], n.d. URL http://www.project-enlight.eu/index.php?content=home&a=menu&b=item1 (accessed 12.30.16).

European Commission, 2016a. End of life vehicles [WWW Document]. Environment. URL http://ec.europa.eu/environment/waste/elv/ (accessed 12.24.16).

European Commission, 2016b. E-Light Report Summary. European Commission.

European Commission, 2014. Regulation (EU) No 333/2014 of the European Parliament and of the Council of 11 March 2014. Off. J. Eur. Union L 333.

European Commission, 2009. Regulation (EC) No 443/2009 of the European Parliament and of the Council of 23 April 2009. Off. J. Eur. Union L 140.

European Commission, 2006. Sustainable Surface Transport: Research Technological Development and Integration 492.

European Commission, Joint Research Centre, Institute for Environment and Sustainability, 2010. ILCD Handbook - General guide for Life Cycle Assessment- Detailed guidance.

European Environment Agency, 2013. Monitoring CO2 emissions from new passenger cars in the EU: summary of data for 2012. European Environment Agency.

EVolution [WWW Document], n.d. URL http://evolutionproject.eu/ (accessed 12.30.16).

Fabrizi, L., De Jong, T.P.R., Bevilacqua, P., 2003. Wire separation from automotive shredder residue. Phys. Sep. Sci. Eng. 12, 145–165. https://doi.org/10.1080/14786470310001608428

Febelauto [WWW Document], n.d. URL http://www.febelauto.be/en/ (accessed 8.17.16).

Feldmann, K., Trautner, S., Meedt, O., 1999. Innovative disassembly strategies based on flexible partial destructive tools. Annu. Rev. Control 23, 159–164. https://doi.org/10.1016/S1367-5788(99)90079-2

Ferrão, P., Amaral, J., 2006a. Assessing the economics of auto recycling activities in relation to European Union Directive on end of life vehicles. Technol. Forecast. Soc. Change, Technological Change and the Environment 73, 277–289. https://doi.org/10.1016/j.techfore.2004.03.010

Ferrão, P., Amaral, J., 2006b. Design for recycling in the automobile industry: new approaches and new tools. J. Eng. Des. 17, 447–462. https://doi.org/10.1080/09544820600648039

Finkbeiner, M., Schau, E.M., Lehmann, A., Traverso, M., 2010. Towards life cycle sustainability assessment. Sustainability 2, 3309–3322. https://doi.org/10.3390/su2103309

Finnveden, G., 2000. On the limitations of life cycle assessment and environmental systems analysis tools in general. Int. J. Life Cycle Assess. 5, 229–238. https://doi.org/10.1007/BF02979365

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Fouquet, R., 2010. The slow search for solutions: Lessons from historical energy transitions by sector and service. Energy Policy, Energy Efficiency Policies and Strategies with regular papers. 38, 6586–6596. https://doi.org/10.1016/j.enpol.2010.06.029

Friedrich, H., Schumann, S., 2001. Research for a “new age of magnesium” in the automotive industry. Contain. Keynote Pap. Present. Proc. THERMEC2000 Int. Conf. Process. Manuf. Adv. Mater. 117, 276–281. https://doi.org/10.1016/S0924-0136(01)00780-4

Froelich, D., Haoues, N., Leroy, Y., Renard, H., 2007a. Development of a new methodology to integrate ELV treatment limits into requirements for metal automotive part design. Miner. Eng., Selected papers from Material, Minerals & Metal Ecology ’06, Cape Town, South Africa, November 2006 20, 891–901. https://doi.org/10.1016/j.mineng.2007.04.019

Froelich, D., Maris, E., Haoues, N., Chemineau, L., Renard, H., Abraham, F., Lassartesses, R., 2007b. State of the art of plastic sorting and recycling: Feedback to vehicle design. Miner. Eng., Selected papers from Material, Minerals & Metal Ecology ’06, Cape Town, South Africa, November 2006 20, 902–912. https://doi.org/10.1016/j.mineng.2007.04.020

Fu, M., Mallick, P.K., 2003. Fatigue of self-piercing riveted joints in aluminum alloy 6111. Int. J. Fatigue 25, 183–189. https://doi.org/10.1016/S0142-1123(02)00115-9

Fuchs, E.R.H., Field, F.R., Roth, R., Kirchain, R.E., 2008. Strategic materials selection in the automobile body: Economic opportunities for polymer composite design. Compos. Sci. Technol. 68, 1989–2002. https://doi.org/10.1016/j.compscitech.2008.01.015

Galvagno, S., Fortuna, F., Cornacchia, G., Casu, S., Coppola, T., Sharma, V.K., 2001. Pyrolysis process for treatment of automobile shredder residue: preliminary experimental results. Energy Convers. Manag. 42, 573–586. https://doi.org/10.1016/S0196-8904(00)00089-3

Gaustad, G., Olivetti, E., Kirchain, R., 2012. Improving aluminum recycling: A survey of sorting and impurity removal technologies. Resour. Conserv. Recycl. 58, 79–87. https://doi.org/10.1016/j.resconrec.2011.10.010

Gent, M.R., Menéndez, M., Muñiz, H., Torno, S., 2015. Recycling of a fine, heavy fluff automobile shredder residue by density and differential fragmentation. Waste Manag. 43, 421–433. https://doi.org/10.1016/j.wasman.2015.06.010

Gerard, K., 2014. 13 High Performance Plastics Used in the Automotive Industry [WWW Document]. URL http://info.craftechind.com/blog/bid/391683/13-High-Performance-Plastics-Used-in-the-Automotive-Industry (accessed 10.24.16).

Gerrard, J., Kandlikar, M., 2007. Is European end-of-life vehicle legislation living up to expectations? Assessing the impact of the ELV Directive on ‘green’ innovation and vehicle recovery. J. Clean. Prod. 15, 17–27. https://doi.org/10.1016/j.jclepro.2005.06.004

Gesing, A., 2004. Assuring the continued recycling of light metals in end-of-life vehicles: A global perspective. JOM 56, 18–27. https://doi.org/10.1007/s11837-004-0176-5

Geyer, R., 2008. Parametric Assessment of Climate Change Impacts of Automotive Material Substitution. Environ. Sci. Technol. 42, 6973–6979. https://doi.org/10.1021/es800314w

Ghazilla, R.A.R., Taha, Z., Yusoff, S., Rashid, S.H.A., Sakundarini, N., 2014. Development of decision support system for fastener selection in product recovery oriented design. Int. J. Adv. Manuf. Technol. 70, 1403–1413. https://doi.org/10.1007/s00170-013-5373-3

Girubha, R.J., Vinodh, S., 2012. Application of fuzzy VIKOR and environmental impact analysis for material selection of an automotive component. Mater. Des. 37, 478–486. https://doi.org/10.1016/j.matdes.2012.01.022

Goede, M., Stehlin, M., Rafflenbeul, L., Kopp, G., Beeh, E., 2009. Super Light Car—lightweight construction thanks to a multi-material design and function integration. Eur. Transp. Res. Rev. 1, 5–10. https://doi.org/10.1007/s12544-008-0001-2

Goede, M., Stehlin, M., Rafflenbeul, L., Kopp, G., Beeh, E., 2008. Super Light Car—lightweight construction thanks to a multi-material design and function integration. Eur. Transp. Res. Rev. 1, 5–10. https://doi.org/10.1007/s12544-008-0001-2

Gould, J.E., 2012. Joining aluminum sheet in the automotive industry—A 30 year history. Weld J 91, 23–34.

Graham, D.J., Glaister, S., 2002. The demand for automobile fuel: a survey of elasticities. J. Transp. Econ. Policy 36, 1–25.

Granata, G., Moscardini, E., Furlani, G., Pagnanelli, F., Toro, L., 2011. Automobile shredded residue valorisation by hydrometallurgical metal recovery. J. Hazard. Mater. 185, 44–48. https://doi.org/10.1016/j.jhazmat.2010.08.107

Groche, P., Wohletz, S., Brenneis, M., Pabst, C., Resch, F., 2014. Joining by forming—a review on joint mechanisms, applications and future trends. J. Mater. Process. Technol. 214, 1972–1994. https://doi.org/10.1016/j.jmatprotec.2013.12.022

Grote, K.H., Antonsson, E.K. (Eds.), 2009. Springer handbook of mechanical engineering. Springer Science & Business Media.

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life cycle assessment: past, present, and future. Environ. Sci. Technol. 45, 90–96. https://doi.org/10.1021/es101316v

Habenicht, G., 2008. Applied Adhesive Bonding: A Practical Guide for Flawless Results. John Wiley & Sons.

Hagon, T., 2013. Top selling cars from 1982, 1992, 2002 and 2012 [WWW Document]. Drive. URL http://www.drive.com.au/motor-news/top-selling-cars-from-1982-1992-2002-and-2012-20130508-2j8ye.html (accessed 2.1.16).

Hakamada, M., Furuta, T., Chino, Y., Chen, Y., Kusuda, H., Mabuchi, M., 2007. Life cycle inventory study on magnesium alloy substitution in vehicles. Energy 32, 1352–1360. https://doi.org/10.1016/j.energy.2006.10.020

Halabi, E.E., Doolan, M., 2013. Operational Challenges in the Automotive Recycling Business: A System Dynamics Perspective, in: Nee, A.Y.C., Song, B., Ong, S.-K. (Eds.), Re-Engineering Manufacturing for Sustainability. Springer Singapore, pp. 353–357.

Hao, H., Geng, Y., Sarkis, J., 2016. Carbon footprint of global passenger cars: scenarios through 2050. Energy 101, 121–131. https://doi.org/10.1016/j.energy.2016.01.089

Happian-Smith, J. (Ed.), 2001. An introduction to modern vehicle design. Elsevier.

Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H., 2013. Comparative environmental life cycle assessment of conventional and electric vehicles. J. Ind. Ecol. 17, 53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x

He, L., Wang, M., Chen, W., Conzelmann, G., 2014. Incorporating social impact on new product adoption in choice modeling: A case study in green vehicles. Transp. Res. Part Transp. Environ. 32, 421–434. https://doi.org/10.1016/j.trd.2014.08.007

He, X., 2010. Recent development in finite element analysis of clinched joints. Int. J. Adv. Manuf. Technol. 48, 607–612. https://doi.org/10.1007/s00170-009-2306-2

He, X., Pearson, I., Young, K., 2008. Self-pierce riveting for sheet materials: State of the art. J. Mater. Process. Technol. 199, 27–36. https://doi.org/10.1016/j.jmatprotec.2007.10.071

Heijungs, R., Huppes, G., Guinée, J.B., 2010. Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. Polym. Degrad. Stab., Special Issue: MoDeSt 2008 95, 422–428. https://doi.org/10.1016/j.polymdegradstab.2009.11.010

Hellgren, J., 2007. Life cycle cost analysis of a car, a city bus and an intercity bus powertrain for year 2005 and 2020. Energy Policy 35, 39–49. https://doi.org/10.1016/j.enpol.2005.10.004

Helmers, E., Dietz, J., Hartard, S., 2017. Electric car life cycle assessment based on real-world mileage and the electric conversion scenario. Int. J. Life Cycle Assess. 22, 15–30. https://doi.org/10.1007/s11367-015-0934-3

Hernandez, M., Messagie, M., De Gennaro, M., Van Mierlo, J., 2017. Resource depletion in an electric vehicle powertrain using different LCA impact methods. Resour. Conserv. Recycl. 120, 119–130. https://doi.org/10.1016/j.resconrec.2016.11.005

Hiraki, T., Takeda, O., Nakajima, K., Matsubae, K., Nakamura, S., Nagasaka, T., 2011. Thermodynamic criteria for the removal of impurities from end-of-life magnesium alloys by evaporation and flux treatment. Sci. Technol. Adv. Mater. 12, 035003. https://doi.org/10.1088/1468-6996/12/3/035003

Hirsch, J., 2014. Recent development in aluminium for automotive applications. Trans. Nonferrous Met. Soc. China 24, 1995–2002. https://doi.org/10.1016/S1003-6326(14)63305-7

Hirsch, J., 2011. Aluminium in Innovative Light-Weight Car Design. Mater. Trans. 52, 818–824. https://doi.org/10.2320/matertrans.L-MZ201132

Huang, J., Tian, C., Ren, J., Bian, Z., 2017. Study on impact acoustic—Visual sensor-based sorting of ELV plastic materials. Sensors 17, 1325. https://doi.org/10.3390/s17061325

Huang, Z., Sugiyama, S., Yanagimoto, J., 2013. Hybrid joining process for carbon fiber reinforced thermosetting plastic and metallic thin sheets by chemical bonding and plastic deformation. J. Mater. Process. Technol. 213, 1864–1874. https://doi.org/10.1016/j.jmatprotec.2013.04.015

Huijbregts, M., Verones, F., Azevedo, L.B., Chaudhary, A., Cosme, N., Fantke, P., Goedkoop, M., Hauschild, M.Z., Laurent, A., Mutel, C.L., Pfister, S., Ponsioen, T., Steinmann, Z., Zelm, R. van, Vieira, M., Hellweg, S., n.d. LC-Impact Version 0.1.

Inghels, D., Dullaert, W., Raa, B., Walther, G., 2016. Influence of composition, amount and life span of passenger cars on end-of-life vehicles waste in Belgium: A system dynamics approach. Transp. Res. Part Policy Pract. 91, 80–104. https://doi.org/10.1016/j.tra.2016.06.005

International Energy Agency, 2016. Key CO2 Emissions Trends - Excerpt from CO2 Emissions from Fuel Combustion.

ISO, 2006. ISO 14040: Environmental management - Life cycle assessment - Principles of framework.

Jambor, A., Beyer, M., 1997. New cars — new materials. Mater. Des. 18, 203–209. https://doi.org/10.1016/S0261-3069(97)00049-6

Jang, G.-W., Yoon, M.-S., Park, J.H., 2010. Lightweight flatbed trailer design by using topology and thickness optimization. Struct. Multidiscip. Optim. 41, 295–307. https://doi.org/10.1007/s00158-009-0409-x

Janota, M., Neumann, H., 2008. Share of Spot Welding and Other Joining Methods in Automotive Production. Weld. World 52, 12–16. https://doi.org/10.1007/BF03266625

Jasiński, D., Meredith, J., Kirwan, K., 2016. A comprehensive framework for automotive sustainability assessment. J. Clean. Prod. 135, 1034–1044. https://doi.org/10.1016/j.jclepro.2016.07.027

Jawahir, I.S., Dillon, O.W., Rouch, K.E., Joshi, K.J., Venkatachalam, A., Jaafar, I.H., 2006. Total life-cycle considerations in product design for sustainability: A framework for comprehensive evaluation, in: Proceedings of the 10th International Research/Expert Conference. Barcelona, Spain, pp. 1–10.

Jeswani, H.K., Azapagic, A., Schepelmann, P., Ritthoff, M., 2010. Options for broadening and deepening the LCA approaches. J. Clean. Prod. 18, 120–127. https://doi.org/10.1016/j.jclepro.2009.09.023

Jha, N.K., 2015. Green design and manufacturing for sustainability. CRC Press.

Johnson, R.B., Onwuegbuzie, A.J., 2004. Mixed methods research: A research paradigm whose time has come. Educ. Res. 33, 14–26. https://doi.org/10.3102/0013189X033007014

Joost, W., 2015. Energy, Materials, and Vehicle Weight Reduction. US Department of Energy, Washington, DC.

Jordão, H., Sousa, A.J., Carvalho, M.T., 2016. Optimization of wet shaking table process using response surface methodology applied to the separation of copper and aluminum from the fine fraction of shredder ELVs. Waste Manag. 48, 366–373. https://doi.org/10.1016/j.wasman.2015.10.006

Jørgensen, A., Le Bocq, A., Nazarkina, L., Hauschild, M., 2008. Methodologies for social life cycle assessment. Int. J. Life Cycle Assess. 13, 96. https://doi.org/10.1065/lca2007.11.367

Jovane, F., Alting, L., Armillotta, A., Eversheim, W., Feldmann, K., Seliger, G., Roth, N., 1993. A key issue in product life cycle: Disassembly. CIRP Ann. - Manuf. Technol. 42, 651–658. https://doi.org/10.1016/S0007-8506(07)62530-X

Juehling, E., Torney, M., Herrmann, C., Droeder, K., 2010. Integration of automotive service and technology strategies. CIRP J. Manuf. Sci. Technol. 3, 98–106. https://doi.org/10.1016/j.cirpj.2010.02.002

Kah, P., Suoranta, R., Martikainen, J., Magnus, C., 2014. Techniques for joining dissimilar materials: metals and polymers. Rev Adv Mater Sci 36, 152–164.

Kalpakjian, S., Schmid, S., 2013. Manufacturing Engineering & Technology, 7 edition. ed. Prentice Hall, Upper Saddle River, NJ.

Kanari, N., Pineau, J.-L., Shallari, S., 2003. End-of-life vehicle recycling in the european union. JOM 55, 15–19. https://doi.org/10.1007/s11837-003-0098-7

Kara, S., Pornprasitpol, P., Kaebernick, H., 2006. Selective disassembly sequencing: A methodology for the disassembly of end-of-life products. CIRP Ann. - Manuf. Technol. 55, 37–40. https://doi.org/10.1016/S0007-8506(07)60361-8

Kaščák, Ľ., Spišák, E., 2013. Mechanical joining methods in car body construction. Transf. Inovácií 28.

Kashiwakura, S., Wagatsuma, K., 2015. Rapid Sorting of Stainless Steels by Open-air Laser-induced Breakdown Spectroscopy with Detecting Chromium, Nickel, and Molybdenum. ISIJ Int. 55, 2391–2396. https://doi.org/10.2355/isijinternational.ISIJINT-2015-316

Keeler, S., Kimchi, M. (Eds.), 2014. Advanced High-strength Steels Application Guidelines Version 5.0. WordAutoSteel.

Khodier, A., Williams, K., Dallison, N., 2017. Challenges around automotive shredder residue production and disposal. Waste Manag. https://doi.org/10.1016/j.wasman.2017.05.008

Kim, D.H., Anderson, V., 1998. Systems archetype basics. Walth. Mass Pegasus Commun. Inc.

Kim, D.H., Lannon, C., 1997. Applying systems archetypes. Waltham: Pegasus Communications.

Kim, H.-J., McMillan, C., Keoleian, G.A., Skerlos, S.J., 2010. Greenhouse Gas Emissions Payback for Lightweighted Vehicles Using Aluminum and High-Strength Steel. J. Ind. Ecol. 14, 929–946. https://doi.org/10.1111/j.1530-9290.2010.00283.x

Kim, K.H., Joung, H.T., Nam, H., Seo, Y.C., Hong, J.H., Yoo, T.W., Lim, B.S., Park, J.H., 2004. Management status of end-of-life vehicles and characteristics of automobile shredder residues in Korea. Waste Manag. 24, 533–540. https://doi.org/10.1016/j.wasman.2004.02.012

Kleiner, M., Chatti, S., Klaus, A., 2006. Metal forming techniques for lightweight construction. J. Mater. Process. Technol., Proceedings of the 11th International Conference on Metal Forming 2006 177, 2–7. https://doi.org/10.1016/j.jmatprotec.2006.04.085

Kleiner, M., Geiger, M., Klaus, A., 2003. Manufacturing of Lightweight Components by Metal Forming. CIRP Ann. 52, 521–542. https://doi.org/10.1016/S0007-8506(07)60202-9

Kloepffer, W., 2008. Life cycle sustainability assessment of products. Int. J. Life Cycle Assess. 13, 89–95. https://doi.org/10.1065/lca2008.02.376

Klöpffer, W., 2006. The Role of SETAC in the Development of LCA. Int. J. Life Cycle Assess. 11, 116–122. https://doi.org/10.1065/lca2006.04.019

Klöpffer, W., 2003. Life-Cycle based methods for sustainable product development. Int. J. Life Cycle Assess. 8, 157–159. https://doi.org/10.1007/BF02978462

Knoeri, C., Wäger, P.A., Stamp, A., Althaus, H.J., Weil, M., 2013. Towards a dynamic assessment of raw materials criticality: Linking agent-based demand—With material flow supply modelling approaches. Sci. Total Environ. 461, 808–812. https://doi.org/10.1016/j.scitotenv.2013.02.001

Koffler, C., 2014. Life cycle assessment of automotive lightweighting through polymers under US boundary conditions. Int. J. Life Cycle Assess. 19, 538–545. https://doi.org/10.1007/s11367-013-0652-7

Koffler, C., Rohde-Brandenburger, K., 2010. On the calculation of fuel savings through lightweight design in automotive life cycle assessments. Int. J. Life Cycle Assess. 15, 128–135. https://doi.org/10.1007/s11367-009-0127-z

Koltsov, A., Bailly, N., Cretteur, L., 2010. Wetting and laser brazing of Zn-coated steel products by Cu–Si filler metal. J. Mater. Sci. 45, 2118–2125. https://doi.org/10.1007/s10853-009-3949-y

Koplin, J., Seuring, S., Mesterharm, M., 2007. Incorporating sustainability into supply management in the automotive industry – the case of the Volkswagen AG. J. Clean. Prod., The Automobile Industry & Sustainability 15, 1053–1062. https://doi.org/10.1016/j.jclepro.2006.05.024

Kothari, C.R., 2004. Research methodology: Methods and techniques. New Age International.

Koyanaka, S., Kobayashi, K., 2010. Automatic sorting of lightweight metal scrap by sensing apparent density and three-dimensional shape. Resour. Conserv. Recycl. 54, 571–578. https://doi.org/10.1016/j.resconrec.2009.10.014

Kühlwein, J., 2016. Driving Resistances of Light-Duty Vehicles in Europe: Present Situation, Trends, and Scenarios for 2025 (White Paper). The International Council on Clean Transportation (ICCT).

Kulekci, M.K., 2008. Magnesium and its alloys applications in automotive industry. Int. J. Adv. Manuf. Technol. 39, 851–865. https://doi.org/10.1007/s00170-007-1279-2

Kumar, S., Yamaoka, T., 2007. System dynamics study of the Japanese automotive industry closed loop supply chain. J. Manuf. Technol. Manag. 18, 115–138. https://doi.org/10.1108/17410380710722854

Lansink, A.G.W.J., 1980. Vergaderjaar. Ned. Tweede Kamer Nr 21, 15–800.

Larsson, J.K., Hanicke, L., 1999. Multi-material Approach with Integrated Joining Technologies in the New Volvo S80. SAE Tech. Pap.

Levasseur, A., Lesage, P., Margni, M., Deschênes, L., Samson, R., 2010. Considering time in LCA: dynamic LCA and its application to global warming impact assessments. Environ. Sci. Technol. 44, 3169–3174. https://doi.org/10.1021/es9030003

Litman, T., Burwell, D., 2006. Issues in sustainable transportation. Int. J. Glob. Environ. Issues 6, 331–347. https://doi.org/10.1504/IJGENVI.2006.010889

Liu, G., Müller, D.B., 2012. Addressing sustainability in the aluminum industry: a critical review of life cycle assessments. J. Clean. Prod. 35, 108–117. https://doi.org/10.1016/j.jclepro.2012.05.030

Liu, Z.F., Zhao, L.X., Li, X.Y., Zhang, H.C., Cheng, H.B., 2010. Research on multi-step active disassembly method of products based on ADSM. Trans Tech Publ.

Lotus Engineering Inc., 2012. Evaluating the Structure and Crashworthiness of a 2020 Model-Year, Mass-Reduced Crossover Vehicle Using FEA Modeling.

Lu, T., Gupta, A., Jayal, A.D., Badurdeen, F., Feng, S.C., Jr, O.W.D., Jawahir, I.S., 2011. A Framework of Product and Process Metrics for Sustainable Manufacturing, in: Advances in Sustainable Manufacturing. Springer, Berlin, Heidelberg, pp. 333–338. https://doi.org/10.1007/978-3-642-20183-7_48

Lu, Y., Broughton, J., Winfield, P., 2014. A review of innovations in disbonding techniques for repair and recycling of automotive vehicles. Int. J. Adhes. Adhes. 50, 119–127. https://doi.org/10.1016/j.ijadhadh.2014.01.021

Luo, A.A., 2002. Magnesium: Current and potential automotive applications. JOM 54, 42–48. https://doi.org/10.1007/BF02701073

Lupton, D.C., 1983. Selection of an adhesive for bonding FRP automotive panels. Int. J. Adhes. Adhes. 3, 155–158. https://doi.org/10.1016/0143-7496(83)90121-5

Lutsey, N.P., 2010. Review of technical literature and trends related to automobile mass-reduction technology. Inst. Transp. Stud.

Luttropp, C., Karlsson, R., 2001. The conflict of contradictory environmental targets, in: Proceedings EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, 2001. pp. 43–48. https://doi.org/10.1109/.2001.992312

Luttropp, C., Lagerstedt, J., 2006. EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. J. Clean. Prod., EcoDesign: What’s happening? 14, 1396–1408. https://doi.org/10.1016/j.jclepro.2005.11.022

MacLean, H.L., Lave, L.B., 2003. Evaluating automobile fuel/propulsion system technologies. Prog. Energy Combust. Sci. 29, 1–69. https://doi.org/10.1016/S0360-1285(02)00032-1

MacLean, H.L., Lave, L.B., Lankey, R., Joshi, S., 2000. A life-cycle comparison of alternative automobile fuels. J. Air Waste Manag. Assoc. 50, 1769–1779. https://doi.org/10.1080/10473289.2000.10464209

Maggi, S., Murgia, M., 2008. Introduction to the metallurgic characteristics of advanced high-strength steels for automobile applications. Weld. Int. 22, 610–618. https://doi.org/10.1080/09507110802413001

Maliapen, M., 2007. Modeling with System Archetypes. Handbook of Computational Intelligence in Manufacturing and production magnagement, Ed, Idea Group Inc (IGI), USAp.

Malone, L.J., Dolter, T., 2008. Basic concepts of chemistry. John Wiley & Sons.

Margarido, F., Santos, R.N., Durão, F., Guimarães, C., Nogueira, C.A., Oliveira, P.C., Pedrosa, F., Gonçalves, A.M., 2014. Separation of non-ferrous fractions of shredded end-of-life vehicles for valorising its alloys, in: MMME’14-International Conference on Mining, Material and Metallurgical Engineering. pp. 77-1-77–4.

Martchek, K., 2006. Modelling more sustainable aluminium. Int. J. Life Cycle Assess. 11, 34–37. https://doi.org/10.1065/lca2006.01.231

Martinsen, K., Hu, S.J., Carlson, B.E., 2015. Joining of dissimilar materials. CIRP Ann. - Manuf. Technol. 64, 679–699. https://doi.org/10.1016/j.cirp.2015.05.006

Matsuyama, K., 2007. Trend of Automobile Vehicles and the Joining Technologies. Weld. World 51, 50–60. https://doi.org/10.1007/BF03266560

Matthews, F.L., Kilty, P.F., Godwin, E.W., 1982. A review of the strength of joints in fibre-reinforced plastics. Part 2. Adhesively bonded joints. Composites 13, 29–37. https://doi.org/10.1016/0010-4361(82)90168-9

Mayyas, A.T., Qattawi, A., Mayyas, A.R., Omar, M.A., 2012. Life cycle assessment-based selection for a sustainable lightweight body-in-white design. Energy 39, 412–425. https://doi.org/10.1016/j.energy.2011.12.033

Mazzanti, M., Zoboli, R., 2006. Economic instruments and induced innovation: The European policies on end-of-life vehicles. Ecol. Econ. 58, 318–337. https://doi.org/10.1016/j.ecolecon.2005.06.008

McAuley, J.W., 2003. Global sustainability and key needs in future automotive design. Environ. Sci. Technol. 37, 5414–5416.

McNamara, N., 2009. Vehicle Recycling and Sustainability. International Specialised Skills Institute Inc, Melbourne, Australia.

Merklein, M., Geiger, M., 2002. New materials and production technologies for innovative lightweight constructions. J. Mater. Process. Technol. 125–126, 532–536. https://doi.org/10.1016/S0924-0136(02)00312-6

Meschut, G., Janzen, V., Olfermann, T., 2014. Innovative and Highly Productive Joining Technologies for Multi-Material Lightweight Car Body Structures. J. Mater. Eng. Perform. 23, 1515–1523. https://doi.org/10.1007/s11665-014-0962-3

Messagie, M., Boureima, F., Matheys, J., Sergeant, N., Turcksin, L., Macharis, C., Van Mierlo, J., 2010. Life cycle assessment of conventional and alternative small passenger vehicles in Belgium, in: 2010 IEEE Vehicle Power and Propulsion Conference. pp. 1–5. https://doi.org/10.1109/VPPC.2010.5729233

Michalos, G., Makris, S., Papakostas, N., Mourtzis, D., Chryssolouris, G., 2010. Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach. CIRP J. Manuf. Sci. Technol. 2, 81–91. https://doi.org/10.1016/j.cirpj.2009.12.001

Miller, L., Soulliere, K., Sawyer-Beaulieu, S., Tseng, S., Tam, E., 2014. Challenges and alternatives to plastics recycling in the automotive sector. Materials 7, 5883–5902. https://doi.org/10.3390/ma7085883

Miller, W.., Zhuang, L., Bottema, J., Wittebrood, A.., De Smet, P., Haszler, A., Vieregge, A., 2000. Recent development in aluminium alloys for the automotive industry. Mater. Sci. Eng. A 280, 37–49. https://doi.org/10.1016/S0921-5093(99)00653-X

Mills, A.J., Durepos, G., Wiebe, E. (Eds.), 2010. Encyclopedia of case study research: L-Z; Index. SAGE.

Min, J., Li, Y., Carlson, B.E., Hu, S.J., Li, J., Lin, J., 2015. A new single-sided blind riveting method for joining dissimilar materials. CIRP Ann. - Manuf. Technol. 64, 13–16. https://doi.org/10.1016/j.cirp.2015.04.047

Mock, P., 2016. 2020–2030 CO2 standards for new cars and light-commercial vehicles in the European Union. The International Council on Clean Transportation (ICCT).

Mordike, B.., Ebert, T., 2001. Magnesium: Properties — applications — potential. Mater. Sci. Eng. A 302, 37–45. https://doi.org/10.1016/S0921-5093(00)01351-4

Mori, K., Bay, N., Fratini, L., Micari, F., Tekkaya, A.E., 2013. Joining by plastic deformation. CIRP Ann. - Manuf. Technol. 62, 673–694. https://doi.org/10.1016/j.cirp.2013.05.004

Moro, A., Helmers, E., 2017. A new hybrid method for reducing the gap between WTW and LCA in the carbon footprint assessment of electric vehicles. Int. J. Life Cycle Assess. 22, 4–14. https://doi.org/10.1007/s11367-015-0954-z

Motavalli, J., 2012. For Lightweight Cars, a Race Among Steel, Aluminum and Carbon Fiber.

Moya-Sanz, E.M., Ivañez, I., Garcia-Castillo, S.K., 2017. Effect of the geometry in the strength of single-lap adhesive joints of composite laminates under uniaxial tensile load. Int. J. Adhes. Adhes. 72, 23–29. https://doi.org/10.1016/j.ijadhadh.2016.10.009

Muchová, L., Eder, P., 2010. End-of-waste criteria for aluminium and aluminium alloy scrap: technical proposals. Inst. Prospect. Technol. Stud. Publ. Off. Eur. Union Luxemb. 66.

Nakajima, K., Takeda, O., Miki, T., Matsubae, K., Nakamura, S., Nagasaka, T., 2010. Thermodynamic Analysis of Contamination by Alloying Elements in Aluminum Recycling. Environ. Sci. Technol. 44, 5594–5600. https://doi.org/10.1021/es9038769

Nakamura, S., Kondo, Y., Matsubae, K., Nakajima, K., Tasaki, T., Nagasaka, T., 2012. Quality-and dilution losses in the recycling of ferrous materials from end-of-life passenger cars: input-output analysis under explicit consideration of scrap quality. Environ. Sci. Technol. 46, 9266–9273. https://doi.org/10.1021/es3013529

Nakamura, S., Yamasue, E., 2010. Hybrid LCA of a Design for Disassembly Technology: Active Disassembling Fasteners of Hydrogen Storage Alloys for Home Appliances. Environ. Sci. Technol. 44, 4402–4408. https://doi.org/10.1021/es903340h

Nanaki, E.A., Koroneos, C.J., 2012. Comparative LCA of the use of biodiesel, diesel and gasoline for transportation. J. Clean. Prod. 20, 14–19. https://doi.org/10.1016/j.jclepro.2011.07.026

Nappi, C., 2013. The global aluminium industry 40 years from 1972. World Alum. 1–27.

Nemry, F., Leduc, G., Mongelli, I., Uihlein, A., 2008. Environmental Improvement of Passenger Cars (IMPRO-car). European Commission.

Neugebauer, R., 2003. Fraunhofer Institut 2003 Year Report. IWI, Chemnitz, Germany.

Newell, A.S., 1965. Hammer mills. US3482788A.

Nicolay, S., Teller, P., Renzoni, R., Fontaine, J.L., Germain, A., Lilien, J.L., Toissaint, Y., Jamoulle, A., Smitz, J., 2000. A simplified LCA for automotive sector–comparison of ICE (diesel and petrol), electric and hybrid vehicles. SETAC-Eur.

Nogueira, C.A., Pedrosa, F., Margarido, F., Santos, R.N., Durão, F., Guimarães, C., 2015. ELV recycling steps up a gear: development of improved sorting technologies for the non-ferrous fraction of auto-shredders. Waste Manag. World 16.

Norgate, T.E., Jahanshahi, S., Rankin, W.J., 2007. Assessing the environmental impact of metal production processes. J. Clean. Prod., From Cleaner Production to Sustainable Production and Consumption in Australia and New Zealand:

Achievements, Challenges, and Opportunities 15, 838–848. https://doi.org/10.1016/j.jclepro.2006.06.018

Nourreddine, M., 2007. Recycling of auto shredder residue. J. Hazard. Mater. 139, 481–490. https://doi.org/10.1016/j.jhazmat.2006.02.054

Offer, G.J., Howey, D., Contestabile, M., Clague, R., Brandon, N.P., 2010. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy Policy 38, 24–29. https://doi.org/10.1016/j.enpol.2009.08.040

Ogden, J.M., Williams, R.H., Larson, E.D., 2004. Societal lifecycle costs of cars with alternative fuels/engines. Energy Policy 32, 7–27. https://doi.org/10.1016/S0301-4215(02)00246-X

Omar, M.A., 2011. The Automotive Body Manufacturing Systems and Processes. John Wiley & Sons.

Palencia, J.C.G., Furubayashi, T., Nakata, T., 2014. Techno-economic assessment of lightweight and zero emission vehicles deployment in the passenger car fleet of developing countries. Appl. Energy 123, 129–142. https://doi.org/10.1016/j.apenergy.2014.02.059

Paraskevas, D., Kellens, K., Dewulf, W., Duflou, J.R., 2015. Environmental modelling of aluminium recycling: a Life Cycle Assessment tool for sustainable metal management. J. Clean. Prod., Decision-support models and tools for helping to make real progress to more sustainable societies 105, 357–370. https://doi.org/10.1016/j.jclepro.2014.09.102

Passarini, F., Ciacci, L., Santini, A., Vassura, I., Morselli, L., 2012. Auto shredder residue LCA: implications of ASR composition evolution. J. Clean. Prod. 23, 28–36. https://doi.org/10.1016/j.jclepro.2011.10.028

Peeters, J.R., Vanegas, P., Dewulf, W., Duflou, J.R., 2017. Economic and environmental evaluation of design for active disassembly. J. Clean. Prod. 140, Part 3, 1182–1193. https://doi.org/10.1016/j.jclepro.2016.10.043

Peeters, J.R., Vanegas, P., Van den Bossche, W., Devoldere, T., Dewulf, W., Duflou, J.R., 2015. Elastomer-based fastener development to facilitate rapid disassembly for consumer products. J. Clean. Prod. 94, 177–186. https://doi.org/10.1016/j.jclepro.2015.01.081

Pehnt, M., 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renew. Energy 31, 55–71. https://doi.org/10.1016/j.renene.2005.03.002

Peixinho, N., Jones, N., Pinho, A., 2005. Application of Dual-Phase and TRIP Steels on the Improvement of Crashworthy Structures. Mater. Sci. Forum 502, 181–188. https://doi.org/10.4028/www.scientific.net/MSF.502.181

Petrie, E.M., 2000. Handbook of adhesives and sealants. McGraw Hill Professional.

Pickin, C.G., Young, K., Tuersley, I., 2007. Joining of lightweight sandwich sheets to aluminium using self-pierce riveting. Mater. Des. 28, 2361–2365. https://doi.org/10.1016/j.matdes.2006.08.003

Pryshlakivsky, J., Searcy, C., 2017. Uncertainty analysis focusing on the variance of energy intensity of vehicle materials. J. Clean. Prod. 143, 1165–1182. https://doi.org/10.1016/j.jclepro.2016.12.004

Puri, P., Compston, P., Pantano, V., 2009. Life cycle assessment of Australian automotive door skins. Int. J. Life Cycle Assess. 14, 420–428. https://doi.org/10.1007/s11367-009-0103-7

Radaj, D., Zhang, S., 1992. Stress intensity factors for spot welds between plates of dissimilar materials. Eng. Fract. Mech. 42, 407–426.

Ramani, A., Kaushik, A., 2012. Design of a Light-Weight Mixed-Material Door Through Structural Optimization. Presented at the 2012 India Hyperworks Technology Conference, India, p. 7.

RBC Capital Markets, 2015. Metal Prospects: Aluminium Market Outlook - Fourth Quarter 2015.

RDC Environment, 2015. Confidentiële data Galloo 2014.

Redelbach, M., Klötzke, M., Horst E., F., 2012. Impact of lightweight design on energy consumption and cost effectiveness of alternative powertrain concepts. Presented at the European electric Vehicle Conference, Brüssel, Belgien.

Rem, P., 2009. WRAP MDD018/23 WEEE separation techniques - Kinetic Gravity Separator trial report. Delft University of Technology.

Renouf, M.A., Grant, T., Logie, J., Ridoutt, B., Ximenes, F., Bengtsson, J., Cowie, A., Lane, J., 2015. Best Practice Guide to Life Cycle Impact Assessment in Australia.

Reuter, M.A., Boin, U., Rem, P., Yang, Y., Fraunholcz, N., Schaik, A. van, 2004. The optimization of recycling: Integrating the resource, technological, and life cycles. JOM 56, 33–37. https://doi.org/10.1007/s11837-004-0178-3

Reynolds, D.B., 2014. World oil production trend: Comparing Hubbert multi-cycle curves. Ecol. Econ. 98, 62–71. https://doi.org/10.1016/j.ecolecon.2013.12.016

Ribeiro, C., Ferreira, J.V., Partidário, P., 2007. Life cycle assessment of a multi-material car component. Int. J. Life Cycle Assess. 12, 336–345. https://doi.org/10.1065/lca2006.12.304

Ribolla, A., Damoulis, G.L., Batalha, G.F., 2005. The use of Nd:YAG laser weld for large scale volume assembly of automotive body in white. J. Mater. Process. Technol., AMPT/AMME05 Part 2 164–165, 1120–1127. https://doi.org/10.1016/j.jmatprotec.2005.02.104

Richardson, G.P., 2011. Reflections on the foundations of system dynamics. Syst. Dyn. Rev. 27, 219–243. https://doi.org/10.1002/sdr.462

Robert Bosch GmbH, 2011. Automotive Handbook. Wiley.

Rockström, J., 2015. Bounding the planetary future: Why we need a great transition. Gt. Transit. Initiat. 9.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S.I., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., De Wit, C.A., Hughes, T., Van Der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. Planetary boundaries: Exploring the safe operating space for humanity. Ecol. Soc. 14. https://doi.org/10.5751/ES-03180-140232

Rodrigues, L.L., Gupta, K., Motlagh, F.G., 2012. Vehicle fuel consumption modelling: A system dynamics approach, in: Proceedings of the World Congress on Engineering. pp. 4–6.

Rosen, D.W., Bras, B., Hassenzahl, S.L., Newcomb, P.J., Yu, T., 1996. Towards computer-aided configuration design for the life cycle. J. Intell. Manuf. 7, 145–160. https://doi.org/10.1007/BF00177070

Rotheiser, J., 2015. Joining of plastics: handbook for designers and engineers. Carl Hanser Verlag GmbH Co KG.

Rowe, J., 2012. Advanced Materials in Automotive Engineering. Elsevier.

Ruffino, B., Fiore, S., Zanetti, M.C., 2014. Strategies for the enhancement of automobile shredder residues (ASRs) recycling: results and cost assessment. Waste Manag. 34, 148–155. https://doi.org/10.1016/j.wasman.2013.09.025

Saeed, K., 1998. Defining a problem or constructing a reference mode. Dep. Soc. Sci. Policy Stud. Worcest. Polytech. Inst.

Sakai, S., Yoshida, H., Hiratsuka, J., Vandecasteele, C., Kohlmeyer, R., Rotter, V.S., Passarini, F., Santini, A., Peeler, M., Li, J., Oh, G.-J., Chi, N.K., Bastian, L., Moore, S., Kajiwara, N., Takigami, H., Itai, T., Takahashi, S., Tanabe, S., Tomoda, K., Hirakawa, T., Hirai, Y., Asari, M., Yano, J., 2014. An international comparative study of end-of-life vehicle (ELV) recycling systems. J. Mater. Cycles Waste Manag. 16, 1–20. https://doi.org/10.1007/s10163-013-0173-2

Sakiyama, T., Murayama, G., Naito, Y., Saita, K., Oikawa, Y.M.H., Nose, T., 2013. Dissimilar metal joining technologies for steel sheet and aluminum alloy sheet in auto body. Nippon Steel Sumitomo Met. Corp Tokyo Nippon Steel Tech. Rep. 91–98.

Sakundarini, N., Taha, Z., Abdul-Rashid, S.H., Ghazila, R.A.R., 2013. Optimal multi-material selection for lightweight design of automotive body assembly incorporating recyclability. Mater. Des. 50, 846–857. https://doi.org/10.1016/j.matdes.2013.03.085

Salvendy, G., 2001. Handbook of industrial engineering: Technology and operations management. John Wiley & Sons.

Sandén, B.A., Karlström, M., 2007. Positive and negative feedback in consequential life-cycle assessment. J. Clean. Prod. 15, 1469–1481. https://doi.org/10.1016/j.jclepro.2006.03.005

Sander, K., Schilling, S., Zangl, S., Lohse, J., 2002. Rules on compliance with Article 7.2 of Directive 2000/53/EC. ÖKOPOL Inst. Ecol. Polit. GmbH Rep. Compil. Dir. Gen. Environ. Nucl. Saf. Civ. Prot. Comm. Eur. Communities Ger.

Santini, A., Morselli, L., Passarini, F., Vassura, I., Di Carlo, S., Bonino, F., 2011. End-of-Life Vehicles management: Italian material and energy recovery efficiency. Waste Manag. 31, 489–494. https://doi.org/10.1016/j.wasman.2010.09.015

Saur, K., Fava, J.A., Spatari, S., 2000. Life cycle engineering case study: automobile fender designs. Environ. Prog. 19, 72–82. https://doi.org/10.1002/ep.670190205

Savov, L., Volkova, E., Janke, D., 2003. Copper and tin in steel scrap recycling. RMZ - Mater. Geoenvironment 50, 627–641.

Schmidt, W.P., 2006. Life cycle tools within Ford of Europe’s Product Sustainability Index. Case study Ford S-MAX & Ford Galaxy. Int. J. Life Cycle Assess. 11, 315–322. https://doi.org/10.1065/lca2006.08.267

Schmidt, W.-P., Dahlqvist, E., Finkbeiner, M., Krinke, S., Lazzari, S., Oschmann, D., Pichon, S., Thiel, C., 2004. Life cycle assessment of lightweight and end-of-life scenarios for generic compact class passenger vehicles. Int. J. Life Cycle Assess. 9, 405–416. https://doi.org/10.1007/BF02979084

Schubert, E., Klassen, M., Zerner, I., Walz, C., Sepold, G., 2001. Light-weight structures produced by laser beam joining for future applications in automobile and aerospace industry. J. Mater. Process. Technol., Containing selected papers from the 7th International Conference Sheet Metal: SheMet’99 115, 2–8. https://doi.org/10.1016/S0924-0136(01)00756-7

Schultz, R.A., Abraham, A.K., 2013. Metallic Material Trends For North American Light Vehicles.pdf.

Seliger, G., Basdere, B., Keil, T., Rebafka, U., 2002. Innovative Processes and Tools for Disassembly. CIRP Ann. - Manuf. Technol. 51, 37–40. https://doi.org/10.1016/S0007-8506(07)61460-7

Senge, P.M., 2006. The Fifth Discipline: The Art and Practice of the Learning Organization. Random House.

Senge, P.M., 1990a. The Fifth Discipline. Doupleday Currence, New York.

Senge, P.M., 1990b. The Fifth Discipline. Doupleday Currence, New York.

Sengupta, A.K., 1995. Hazardous and Industrial Waste Proceedings, 27th Mid-Atlantic Conference. CRC Press.

Shaw, J., Singh, H., Farahani, A., 2010. Reinventing Automotive Steel.

Shea, S.B., 2013. 54.5 MPG and Beyond: Materials Lighten the Load for Fuel Economy [WWW Document]. Energy.gov. URL http://energy.gov/articles/545-mpg-and-beyond-materials-lighten-load-fuel-economy (accessed 8.27.13).

Shu, L.H., Flowers, W.C., 1999. Application of a design-for-remanufacture framework to the selection of product life-cycle fastening and joining methods. Robot. Comput.-Integr. Manuf. 15, 179–190. https://doi.org/10.1016/S0736-5845(98)00032-5

Shu, L.H., Flowers, W.C., 1996. Towards Life-cycle Fastening and Joining Cost Optimisation using Genetic Algorithms. Proc. 1996 ASME Des. Eng. Tech. Conf. Comput. Eng. Conf.

Singh, Y.K., Bajpai, R.B., 2007. Research Methodology: Techniques and Trends. APH Pub.

SINOGU, 2016. Silicon Metal 2202 3303 553 441 [WWW Document]. URL http://www.sinogu.com/archives/high-quality-silicon-metal-2202-3303-553-441.html (accessed 6.8.17).

Skszek, T.W., Conklin, J., Zaluzec, M., Wagner, D., 2015. Multi-material Lightweight Vehicles(MMLV) Project. Society of Automotive Engineers.

Smink, C.K., 2007. Vehicle recycling regulations: lessons from Denmark. J. Clean. Prod., The Automobile Industry & Sustainability 15, 1135–1146. https://doi.org/10.1016/j.jclepro.2006.05.028

Song, Y.S., Youn, J.R., Gutowski, T.G., 2009. Life cycle energy analysis of fiber-reinforced composites. Compos. Part Appl. Sci. Manuf. 40, 1257–1265. https://doi.org/10.1016/j.compositesa.2009.05.020

Soo, V.K., Compston, P., Doolan, M., 2016. Is the Australian Automotive Recycling Industry Heading towards a Global Circular Economy?–A Case Study on Vehicle Doors. Procedia CIRP 48, 10–15. https://doi.org/10.1016/j.procir.2016.03.099

Soo, V.K., Compston, P., Doolan, M., 2015. Interaction between New Car Design and Recycling Impact on Life Cycle Assessment. Procedia CIRP, The 22nd CIRP Conference on Life Cycle Engineering 29, 426–431. https://doi.org/10.1016/j.procir.2015.02.055

Soo, V.K., Peeters, J., Compston, P., Doolan, M., Duflou, J.R., 2017. Comparative Study of End-of-Life Vehicle Recycling in Australia and Belgium. Procedia CIRP 61, 269–274. https://doi.org/10.1016/j.procir.2016.11.222

Sperling, D., Gordon, D., 2009. Two Billion Cars: Driving Toward Sustainability. Oxford University Press.

Spielmann, M., Althaus, H.-J., 2007. Can a prolonged use of a passenger car reduce environmental burdens? Life Cycle analysis of Swiss passenger cars. J. Clean. Prod., The Automobile Industry & Sustainability 15, 1122–1134. https://doi.org/10.1016/j.jclepro.2006.07.022

Srogi, K., 2008. An overview of current processes for the thermochemical treatment of automobile shredder residue. Clean Technol. Environ. Policy 10, 235–244. https://doi.org/10.1007/s10098-007-0103-x

Staff, P.D.L., 2008. Handbook of plastics joining: a practical guide. Cambridge University Press.

Stasinopoulos, P., 2013. A System Dynamics approach to Life Cycle Assessment (Doctoral thesis). The Australian National University, Canberra, Australia.

Stasinopoulos, P., Compston, P., 2014. A dynamical life cycle inventory of steel, aluminium, and composite car bodies-in-white, in: Wellnitz, J., Subic, A., Trufin, R. (Eds.), Sustainable Automotive Technologies 2013, Lecture Notes in Mobility. Springer International Publishing, pp. 111–117. https://doi.org/10.1007/978-3-319-01884-3_11

Stasinopoulos, P., Compston, P., Jones, H.M., 2012a. Policy resistance to fuel efficient cars and the adoption of next-generation technologies, in: Proceedings of the 30th International Conference of the System Dynamics Society. St. Gallen, Switzerland.

Stasinopoulos, P., Compston, P., Newell, B., Jones, H.M., 2012b. A system dynamics approach in LCA to account for temporal effects—a consequential energy LCI of car body-in-whites. Int. J. Life Cycle Assess. 17, 199–207. https://doi.org/10.1007/s11367-011-0344-0

Sterman, J.D., 2010. Business Dynamics: System Thinking and Modeling for a Complex World. McGraw-Hill Education (India) Pvt Limited.

Sterman, J.D., 2002. All models are wrong: reflections on becoming a systems scientist. Syst. Dyn. Rev. 18, 501–531. https://doi.org/10.1002/sdr.261

Subic, A., Francesco, S., 2006. Design-oriented application of LCA to an automotive system, in: Achieving Business Benefits from Managing Life Cycle Impacts. Presented at the 5th Australian Conference on Life Cycle Assessment, Australian Life Cycle Assessment Society, Melbourne, Australia.

Subic, A., Schiavone, F., Leary, M., Manning, J., 2010. Comparative Life Cycle Assessment (LCA) of Passenger Seats and their Impact on Different Vehicle Models. Int. J. Veh. Des. 53, 89–109.

Sullivan, J.L., Williams, R.L., Yester, S., Cobas-Flores, E., Chubbs, S.T., Hentges, S.G., Pomper, S.D., 1998. Life Cycle Inventory of a Generic U.S. Family Sedan

Overview of Results USCAR AMP Project. SAE Tech. Pap. 982160 15. https://doi.org/10.4271/982160

Sun, X., Liu, J., Lu, B., Zhang, P., Zhao, M., 2017. Life cycle assessment-based selection of a sustainable lightweight automotive engine hood design. Int. J. Life Cycle Assess. 1–11. https://doi.org/10.1007/s11367-016-1254-y

Sutherland, J., Gunter, K., Allen, D., Bauer, D., Bras, B., Gutowski, T., Murphy, C., Piwonka, T., Sheng, P., Thurston, D., Wolff, E., 2004. A global perspective on the environmental challenges facing the automotive industry: state-of-the-art and directions for the future. Int. J. Veh. Des. 34, 86–110.

Swarr, T.E., Hunkeler, D., Klöpffer, W., Pesonen, H.L., Ciroth, A., Brent, A.C., Pagan, R., 2011. Environmental life-cycle costing: a code of practice. Int. J. Life Cycle Assess. 16, 389–391. https://doi.org/10.1007/s11367-011-0287-5

Szeteiová, K., 2010. Automotive Materials—Plastics in Automotive Markets Today. Institute of Production Technologies, Machine Technologies and Materials, Faculty of Material Science and Technology, Slovak University of Technology Bratislava.

Taherzadeh, M.J., Richards, T., 2015. Resource recovery to approach zero municipal waste. CRC Press.

Taub, A., 2012. Advanced Automotive Materials: The New DNA of Personal Mobility.

Taub, A.I., Krajewski, P.E., Luo, A.A., Owens, J.N., 2007. The evolution of technology for materials processing over the last 50 years: The automotive example. JOM 59, 48–57. https://doi.org/10.1007/s11837-007-0022-7

Taylor, R., Ray, R., Chapman, C., 2013. Advanced thermal treatment of auto shredder residue and refuse derived fuel. Fuel 106, 401–409. https://doi.org/10.1016/j.fuel.2012.11.071

Tellis, W.M., 1997. Application of a case study methodology. Qual. Rep. 3, 1–19.

Tharumarajah, A., Koltun, P., 2007. Is there an environmental advantage of using magnesium components for light-weighting cars? J. Clean. Prod., The Automobile Industry & Sustainability 15, 1007–1013. https://doi.org/10.1016/j.jclepro.2006.05.022

The Aluminium Association, 2013. The Environmental Footprint of Semi-finished Aluminium Products in North America, A life cycle assessment report.

The Aluminium Association, Inc., 2011. The Changing Make Up of Automobiles.

The Parliament of the Commonwealth of Australia, 2011. Product Stewardship Act 2011, C2011A00076.

Tian, J., Chen, M., 2014. Sustainable design for automotive products: Dismantling and recycling of end-of-life vehicles. Waste Manag. 34, 458–467. https://doi.org/10.1016/j.wasman.2013.11.005

Todd, J.A., Curran, M.A., Weitz, K., Sharma, A., Vigon, B., Norris, G., Eagan, P., Owens, W., Veroutis, A., 1999. Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America Streamlined LCA Workgroup.

Tolio, T., Bernard, A., Colledani, M., Kara, S., Seliger, G., Duflou, J., Battaia, O., Takata, S., 2017. Design, management and control of demanufacturing and remanufacturing systems. CIRP Ann. - Manuf. Technol. 66, 585–609. https://doi.org/10.1016/j.cirp.2017.05.001

Trimble, J., 2014. Boundary Concepts in System Dynamics, in: Proceedings of the 32nd International Conference of the System Dynamics Society. System Dynamics Society, Delft, Netherlands.

Trochim, W.M.K., 1989. Outcome pattern matching and program theory. Eval. Program Plann., Special Issue: The Theory-Driven Perspective 12, 355–366. https://doi.org/10.1016/0149-7189(89)90052-9

Troy, M., 2012. Kickstarting the widespread adoption of automotive carbon fiber composites.

Truman, K., n.d. Road Congestion [WWW Document]. URL http://www.systems-thinking.org/theWay/sff/ffx02.htm (accessed 5.16.18).

Tsujino, J., Ueoka, T., Hasegawa, K., Fujita, Y., Shiraki, T., Okada, T., Tamura, T., 1996. New methods of ultrasonic welding of metal and plastic materials. Ultrasonics, Proceedings of Ultrasonics International 1995 34, 177–185. https://doi.org/10.1016/0041-624X(96)81780-X

Udo, de H., H.A., Bensahel, J.F., Clift, R., Fuessler, C.R., Griesshammer, R., Jensen, A.A., 1994. Guidelines for the application of life cycle assessment in the EU ecolabelling programme (No. DG-XI-A-2). European Commission, Belgium.

Udo, de H., Heijungs, R., Suh, S., Huppes, G., 2004. Three Strategies to Overcome the Limitations of Life-Cycle Assessment. J. Ind. Ecol. 8, 19–32. https://doi.org/10.1162/1088198042442351

Ungureanu, C.A., Das, S., Jawahir, I.S., 2007. Life-cycle cost analysis: aluminum versus steel in passenger cars. TMS Miner. Met. Mater. Soc. 11–24.

U.S Department of Energy, 2013. Use of Lightweight Materials is on the Rise [WWW Document]. Veh. Technol. Off. URL https://www1.eere.energy.gov/vehiclesandfuels/facts/2013_fotw786.html (accessed 2.24.14).

US Department of Energy, 2013. Workshop Report: Light-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials. Vehicles Technologies Office.

USAMP, 2011. United States Automotive Materials Partnership LLC (USAMP). United States Automotive Materials Partnership LLC.

Uzun, H., Dalle Donne, C., Argagnotto, A., Ghidini, T., Gambaro, C., 2005. Friction stir welding of dissimilar Al 6013-T4 to X5CrNi18-10 stainless steel. Mater. Des. 26, 41–46. https://doi.org/10.1016/j.matdes.2004.04.002

Van Acker, K., Verpoest, I., De Moor, J., Duflou, J.-R., Dewulf, W., 2009. Lightweight materials for the automotive: environmental impact analysis of the use of composites. Rev. Métallurgie 106, 541–546. https://doi.org/10.1051/metal/2009086

Van Kooy, L., Mooij, M., Rem, P., 2004. Kinetic gravity separation. Phys. Sep. Sci. Eng. 13, 25–32.

Van Schaik, A., 2004. Theory of recycling systems–applied to car recycling. Doctoral thesis, Delft Technical University, The Netherlands.

Van Schaik, A., Reuter, M.A., 2007. The use of fuzzy rule models to link automotive design to recycling rate calculation. Miner. Eng., Selected papers from Material, Minerals & Metal Ecology ’06, Cape Town, South Africa, November 2006 20, 875–890. https://doi.org/10.1016/j.mineng.2007.03.016

Van Schaik, A., Reuter, M.A., 2004. The time-varying factors influencing the recycling rate of products. Resour. Conserv. Recycl. 40, 301–328. https://doi.org/10.1016/S0921-3449(03)00074-0

VDI 2243, 2002. Recyclingorientierte Produktentwicklung (Recycling-oriented product development). Germany.

VDI 2243, 1993. Konstruieren Recyclinggerechter Technischer Produkte (Designing Technical Products for ease of Recycling). Germany.

Vermeulen, I., Van Caneghem, J., Block, C., Baeyens, J., Vandecasteele, C., 2011. Automotive shredder residue (ASR): Reviewing its production from end-of-life vehicles (ELVs) and its recycling, energy or chemicals’ valorisation. J. Hazard. Mater. 190, 8–27. https://doi.org/10.1016/j.jhazmat.2011.02.088

Volkswagen Group, 2009. Innovative Developments for Lightweight Vehicle Structures. Wolfsburg, Germany, p. 304.

Vongbunyong, S., Chen, W.H., 2015. Disassembly automation: Automated systems with cognitive abilities. Springer.

Vongbunyong, S., Kara, S., Pagnucco, M., 2013. Application of cognitive robotics in disassembly of products. CIRP Ann. - Manuf. Technol. 62, 31–34. https://doi.org/10.1016/j.cirp.2013.03.037

Wallentowitz, H., Wohlecker, R., Henn, R., 2006. Communication module–mass reduction. Final Rep.

Wang, H., Peng, Q., Zhang, J., Gu, P., 2017. Selective Disassembly Planning for the End-of-life Product. Procedia CIRP, Complex Systems Engineering and Development Proceedings of the 27th CIRP Design Conference Cranfield

University, UK 10th – 12th May 2017 60, 512–517. https://doi.org/10.1016/j.procir.2017.02.003

Warnecke, H.J., Bäßler, R., 1988. Design for Assembly — Part of the Design Process. CIRP Ann. 37, 1–4. https://doi.org/10.1016/S0007-8506(07)61572-8

Wegener, K., Chen, W.H., Dietrich, F., Dröder, K., Kara, S., 2015. Robot assisted disassembly for the recycling of electric vehicle batteries. Procedia CIRP, The 22nd CIRP Conference on Life Cycle Engineering 29, 716–721. https://doi.org/10.1016/j.procir.2015.02.051

Wiel, J.W. van der, Besouw, M. van, Huijbers, S., 2012. Future of Automotive Design & Materials.

Wieringa, R.J., 2014. What Is Design Science?, in: Design Science Methodology for Information Systems and Software Engineering. Springer, pp. 3–11.

Willems, B., Dewulf, W., Duflou, J., 2005. Design for active disassembly (DfAD): an outline for future research, in: Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment, 2005. Presented at the Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment, 2005., pp. 129–134. https://doi.org/10.1109/ISEE.2005.1437007

William, B., 2002. The system archetypes. System.

Witik, R.A., Payet, J., Michaud, V., Ludwig, C., Månson, J.-A.E., 2011. Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. Compos. Part Appl. Sci. Manuf. 42, 1694–1709. https://doi.org/10.1016/j.compositesa.2011.07.024

Wolsink, M., 2010. Contested environmental policy infrastructure: Socio-political acceptance of renewable energy, water, and waste facilities. Environ. Impact Assess. Rev., Conflict Mediation and Social Impact Assessment 30, 302–311. https://doi.org/10.1016/j.eiar.2010.01.001

Wolstenholme, E.F., 2003. Towards the definition and use of a core set of archetypal structures in system dynamics. Syst. Dyn. Rev. 19, 7–26. https://doi.org/10.1002/sdr.259

Worrell, E., Reuter, M., 2014. Handbook of Recycling: State-of-the-art for Practitioners, Analysts, and Scientists. Newnes.

Wright Corporate Strategy, 2010. Review of the Application of Landfill Standards. Wright Corp. Strategy Pty Ltd. March 2010 Prep. Dep. Environ. Herit. Arts.

Wypych, G., 2001. Handbook of solvents. ChemTec Publishing.

Yin, R.K., 2011. Applications of case study research. SAGE.

Yin, R.K., 2007. Case study research: Design and methods, 4th ed. SAGE, Los Angeles and London.

Zamagni, A., 2012. Life cycle sustainability assessment. Int. J. Life Cycle Assess. 17, 373–376. https://doi.org/10.1007/s11367-012-0389-8

Zhang, F., Yang, X., Wang, H.-P., Zhang, X., Xia, Y., Zhou, Q., 2013. Durability of adhesively-bonded single lap–shear joints in accelerated hygrothermal exposure for automotive applications. Int. J. Adhes. Adhes. 44, 130–137. https://doi.org/10.1016/j.ijadhadh.2013.02.009

Zhang, S., Forssberg, E., 1997. Mechanical separation-oriented characterization of electronic scrap. Resour. Conserv. Recycl. 21, 247–269. https://doi.org/10.1016/S0921-3449(97)00039-6

Zhang, Z., Yang, X., Zhang, J., Zhou, G., Xu, X., Zou, B., 2011. Effect of welding parameters on microstructure and mechanical properties of friction stir spot welded 5052 aluminum alloy. Mater. Des. 32, 4461–4470. https://doi.org/10.1016/j.matdes.2011.03.058

Zhu, Q., Sarkis, J., Lai, K., 2007. Green supply chain management: pressures, practices and performance within the Chinese automobile industry. J. Clean. Prod., The Automobile Industry & Sustainability 15, 1041–1052. https://doi.org/10.1016/j.jclepro.2006.05.021

Ziout, A., 2013. Innovative Design for Active Disassembly and Sustainable Product Recovery (Doctoral thesis). University of Windsor.

Zoepf, S.M., 2011. Automotive features : mass impact and deployment characterization (Thesis). Massachusetts Institute of Technology.

Appendices

Appendix A Exergy Analysis for Belgian Case Study

A.1 Al with high steel content fraction (40-120mm)

Table A-1: Dilution and quality losses calculation for Al with high steel content fraction (40-120mm) with average Fe, Si, and Cu percentage values.

	Alloy/mix		**Mass (kg)**	**Chemical composition (wt.%)**			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Dilution loss	Al scrap	Al with high steel	44.76	82.07	11.32	0.40	0.27
	Primary Al	Dilution agent	950.80	99.60	0.20	0.10	
	Al scrap + Primary Al	Diluted alloy	995.56	98.81	0.70	0.11	0.01
Quality loss	Primary Si (2202)	Alloying element	3.06	0.20	0.20	99.50	
	Primary Cu	Alloying element	1.38				99.99
	Secondary AA6061	Produced alloy	1000.00	98.37	0.70	0.42	0.15

Table A-2: Dilution and quality losses calculation for Al with high steel content fraction (40-120mm) with minimum Fe, Si, and Cu percentage values.

	Alloy/mix		**Mass (kg)**	**Chemical composition (wt.%)**			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Dilution loss	Al scrap	Al with high steel	51.04	82.07	9.95	0.00	0.00
	Primary Al	Dilution agent	944.40	99.60	0.20	0.10	
	Al scrap + Primary Al	Diluted alloy	995.44	98.70	0.7	0.09	0
Quality loss	Primary Si (2202)	Alloying element	3.06	0.2	0.2	99.50	0
	Primary Cu	Alloying element	1.50				99.99
	Secondary AA6061	Produced alloy	1000.00	98.25	0.70	0.40	0.15

Table A-3: Dilution and quality losses calculation for Al with high steel content fraction (40-120mm) with maximum Fe, Si, and Cu percentage values.

	Alloy/mix		Mass (kg)	Chemical composition (wt.%)			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Dilution loss	Al scrap	Al with high steel	39.88	82.07	12.69	0.94	0.56
	Primary Al	Dilution agent	956.16	99.60	0.20	0.10	
	Al scrap + Primary Al	Diluted alloy	996.05	98.90	0.70	0.13	0.02
Quality loss	Primary Si (2202)	Alloying element	2.68	0.20	0.20	99.50	
	Primary Cu	Alloying element	1.28				99.99
	Secondary AA6061	Produced alloy	1000.00	98.51	0.70	0.40	0.15

A.2 Al with high steel content fraction (12-40mm)

Table A-4: Dilution and quality losses calculation for Al with high steel content fraction (12-40mm) with average Fe, Si, and Cu percentage values.

	Alloy/mix		Mass (kg)	Chemical composition (wt.%)			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Dilution loss	Al scrap	Al with high steel	51.80	80.75	9.82	1.56	1.38
	Primary Al	Dilution agent	945.15	99.60	0.20	0.10	
	Al scrap + Primary Al	Diluted alloy	996.96	98.62	0.70	0.18	0.07
Quality loss	Primary Si (2202)	Alloying element	2.26	0.20	0.20	99.50	
	Primary Cu	Alloying element	0.79				99.99
	Secondary AA6061	Produced alloy	1000.00	98.32	0.70	0.40	0.15

Table A-5: Dilution and quality losses calculation for Al with high steel content fraction (12-40mm) with minimum Fe, Si, and Cu percentage values.

	Alloy/mix		**Mass (kg)**	**Chemical composition (wt.%)**			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Dilution loss	Al scrap	Al with high steel	51.04	80.75	7.12	0.00	0.51
	Primary Al	Dilution agent	944.40	99.6	0.20	0.10	
	Al scrap + Primary Al	Diluted alloy	995.44	98.24	0.70	0.09	0.04
Quality loss	Primary Si (2202)	Alloying element	3.06	0.20	0.20	99.50	
	Primary Cu	Alloying element	1.50				99.99
	Secondary AA6061	Produced alloy	1000.00	97.82	0.70	0.40	0.15

Table A-6: Dilution and quality losses calculation for Al with high steel content fraction (12-40mm) with maximum Fe, Si, and Cu percentage values.

	Alloy/mix		**Mass (kg)**	**Chemical composition (wt.%)**			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Dilution loss	Al scrap	Al with high steel	40.45	80.75	12.53	3.51	2.24
	Primary Al	Dilution agent	957.33	99.60	0.20	0.10	
	Al scrap + Primary Al	Diluted alloy	997.78	98.84	0.70	0.24	0.09
Quality loss	Primary Si (2202)	Alloying element	1.63	0.20	0.20	99.50	
	Primary Cu	Alloying element	0.59				99.99
	Secondary AA6061	Produced alloy	1000.00	98.62	0.70	0.40	0.15

A.3 Al fraction (40-120mm)

Table A-7: Quality losses calculation for Al fraction (40-120mm) with average Fe, Si, and Cu percentage values.

	Alloy/mix		**Mass (kg)**	**Chemical composition (wt.%)**			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
Quality loss	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
	Al scrap	Al (40-120mm)	996.49	98.64	0.36	0.05	0.25
	Primary Si (2202)	Alloying element	3.51	0.20	0.20	99.50	
	Secondary AA6061	Produced alloy	1000.00	98.29	0.36	0.40	0.25

Table A-8: Quality losses calculation for Al fraction (40-120mm) with minimum Fe, Si, and Cu percentage values.

	Alloy/mix		**Mass (kg)**	**Chemical composition (wt.%)**			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
Quality loss	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
	Al scrap	Al (40-120mm)	995.04	98.64	0.03	0.00	0.06
	Primary Si (2202)	Alloying element	4.02	0.20	0.20	99.50	
	Primary Cu	Alloying element	0.94				99.99
	Secondary AA6061	Produced alloy	1000.00	98.15	0.03	0.40	0.15

Table A-9: Dilution and quality losses calculation for Al fraction (40-120mm) with maximum Fe, Si, and Cu percentage values.

	Alloy/mix		Mass (kg)	Chemical composition (wt.%)			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Dilution loss	Al scrap	Al (40-120mm)	992.20	98.64	0.68	0.11	0.46
	Primary Al	Dilution agent	0.83	99.60	0.20	0.10	
	Al scrap + Primary Al	Diluted alloy	993.03	98.64	0.68	0.11	0.46
Quality loss	Primary Si (2202)	Alloying element	6.97	0.20	0.20	99.50	
	Secondary AA6061	Produced alloy	1000.00	97.95	0.70	0.80	0.40

A.4 Al fraction (12-40mm)

Table A-10: Quality losses calculation for Al fraction (12-40mm) with average Fe, Si, and Cu percentage values.

	Alloy/mix		Mass (kg)	Chemical composition (wt.%)			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Quality loss	Al scrap	Al (12-40mm)	996.37	99.57	0.03	0.06	0.13
	Primary Si (2202)	Alloying element	3.42	0.20	0.20	99.50	
	Primary Cu	Alloying element	0.21				99.99
	Secondary AA6061	Produced alloy	1000.00	99.21	0.03	0.40	0.15

Table A-11: Quality losses calculation for Al fraction (12-40mm) with minimum Fe, Si, and Cu percentage values.

	Alloy/mix		**Mass (kg)**	**Chemical composition (wt.%)**			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Quality loss	Al scrap	Al (12-40mm)	994.77	99.56	0.00	0.03	0.00
	Primary Si (2202)	Alloying element	3.73	0.20	0.20	99.50	
	Primary Cu	Alloying element	1.50				99.99
	Secondary AA6061	Produced alloy	1000.00	99.04	0.00	0.40	0.15

Table A-12: Quality losses calculation for Al fraction (12-40mm) with maximum Fe, Si, and Cu percentage values.

	Alloy/mix		**Mass (kg)**	**Chemical composition (wt.%)**			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Quality loss	Al scrap	Al (12-40mm)	996.85	99.56	0.06	0.09	0.28
	Primary Si (2202)	Alloying element	3.15	0.20	0.20	99.50	
	Secondary AA6061	Produced alloy	1000.00	99.25	0.06	0.40	0.27

A.5 Al fraction (4-12mm)

Table A-13: Chemical composition for Al fraction (4-12mm) with average Fe, Si, and Cu percentage values.

Alloy/mix		**Mass (kg)**	**Chemical composition (wt.%)**			
Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Al scrap	Al (4-12mm)	1000.00	98.11	0.14	0.41	0.26
Secondary AA6061	Produced alloy	1000.00	98.11	0.14	0.41	0.26

Table A-14: Quality losses calculation for Al fraction (4-12mm) with minimum Fe, Si, and Cu percentage values.

	Alloy/mix		**Mass (kg)**	**Chemical composition (wt.%)**			
	Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
	Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Quality loss	Al scrap	Al (4-12mm)	998.61	98.11	0.07	0.27	0.14
	Primary Si (2202)	Alloying element	1.27	0.20	0.20	99.50	
	Primary Cu	Alloying element	0.12				99.99
	Secondary AA6061	Produced alloy	1000.00	97.97	0.07	0.40	0.15

Table A-15: Chemical composition for Al fraction (4-12mm) with maximum Fe, Si, and Cu percentage values.

Alloy/mix		**Mass (kg)**	**Chemical composition (wt.%)**			
Material	**Description**		**Al**	**Fe**	**Si**	**Cu**
Al 6061	Target alloy		95.85-98.56	0-0.70	0.4-0.8	0.15-0.4
Al scrap	Al (4-12mm)	1000.00	98.11	0.20	0.54	0.38
Secondary AA6061	Produced alloy	1000.00	98.11	0.20	0.54	0.38

Appendix B Midpoint Impact Contribution for Belgian Case Study

Table B-1: Environmental impact contribution of different midpoint impact categories based on ILCD recommendations v1.09.

Midpoint Impact Categories	Environmental Impact (person equivalent per tonne)				
	Al with high steel content fraction (12-40mm)	**Al with high steel content fraction (40-120mm)**	**Al fraction (4-12mm)**	**Al fraction (12-40mm)**	**Al fraction (40-120mm)**
Acidification	1.01E+00	1.01E+00	2.50E-02	2.69E-02	2.69E-02
Climate change, include biogenic carbon	9.39E-01	9.46E-01	6.83E-02	7.02E-02	7.02E-02
Ecotoxicity freshwater	7.69E-02	7.85E-02	7.43E-03	8.40E-03	8.07E-03
Eutrophication freshwater	9.23E-03	9.25E-03	7.07E-03	7.09E-03	7.09E-03
Eutrophication marine	3.89E-01	3.92E-01	2.02E-02	2.11E-02	2.11E-02
Eutrophication terrestrial	4.04E-01	4.08E-01	1.94E-02	2.03E-02	2.03E-02
Human toxicity, cancer effects	5.07E-01	5.12E-01	2.16E-02	2.61E-02	2.59E-02
Human toxicity, non-cancer effects	8.82E-01	8.95E-01	3.38E-02	4.13E-02	3.96E-02
Ionizing radiation	1.17E+00	1.17E+00	8.72E-02	8.88E-02	8.89E-02
Ozone depletion	5.22E-06	5.32E-06	1.55E-05	1.60E-05	1.60E-05
Particulate matter/Respiratory inorganics	7.19E-01	7.25E-01	1.28E-02	1.46E-02	1.43E-02
Photochemical ozone formation	6.33E-01	6.38E-01	2.93E-02	3.12E-02	3.12E-02
Resource depletion water	2.01E+00	2.03E+00	1.84E-01	1.86E-01	1.86E-01
Resource depletion, mineral, fossils and renewables	1.58E+00	1.81E+00	7.98E-03	8.43E-02	8.10E-03
Total	1.03E+01	1.06E+01	5.25E-01	6.27E-01	5.48E-01

Appendix C Material Recyclability Rating

Table C-1: Material recyclability rating based on joint characteristics for dissimilar metals bonding.

Principle of connection / Characteristics of connection			Dissimilar Metals																
			Welding			Adhesive bonding			Mechanical fastening										
									Screwing		Riveting								
			Fusion weld	Solid-state weld	Brazing	Chemically cured	Physically cured (melt/evaporate)	Pressure sensitive	Screws & bolts	Pin & collar	Solid/ tubular	Self-piercing	Blind rivet	Stitching/ stapling	Spring & snap-in	Crimping	Seaming	Shrink & press fits	Shape-memory alloy
Joint part	Joint strength	Static strength	1	1	1	2	2	3	1	1	1	1	2	2	2	2	2	1	2
		Fatigue strength	1	1	1	1	2	3	1	1	1	1	2	2	2	2	2	1	2
	Area of bond contact (strength)	Large area	1	1	1	1	2	3	1	1	1	1	2	2	2	2	2	1	2
		Small area	2	2	2	2	2	3	2	2	2	2	3	3	3	1	1	2	3
	Temperature resistance	High temperature	1	1	1	3	3	3	1	1	1	1	2	2	2	1	2	1	2
		Low temperature	1	1	1	2	3	3	1	1	1	1	2	2	2	2	2	1	2
	Joint location	Accessible	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
		Non-accessible	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Joint material type	Same type (metal)	2[a]	NA	2	NA	NA	NA	2	2	2	2	2	2	2	NA	NA	2	2
		Different type (metal)	1[a]	NA	1	NA	NA	NA	1	1	1	1	1	1	1	NA	NA	1	1
	Degradation over time	Moisture effect	2	2	2	3	3	3	2	2	2	2	2	2	2	2	2	2	2
		Heat effect	1	1	1	3	3	3	1	1	1	1	1	2	2	2	2	1	2
	Joint diameter	Large diameter	NA	NA	NA	NA	NA	NA	2	2	2	2	3	NA	NA	NA	NA	2	NA
		Small diameter	NA	NA	NA	NA	NA	NA	1	1	1	1	2	NA	NA	NA	NA	1	NA
	Joint size	Large joint	NA	NA	NA	NA	NA	NA	2	2	2	2	3	3	NA	NA	NA	2	NA
		Small joint	NA	NA	NA	NA	NA	NA	1	1	1	1	2	2	NA	NA	NA	1	NA
	Geometry unevenness at joining area	Protrusion	NA	NA	NA	NA	NA	NA	2	2	2	2	2	2	3	3	NA	2	NA
		No protrusion	NA	NA	NA	NA	NA	NA	1	1	1	1	2	1	2	2	NA	1	NA
Material part	Material density	Same density	1	1	1	2	2	3	1	1	1	1	2	2	2	2	1	1	2
		Different density	2	2	2	3	3	3	2	2	2	2	3	3	3	2	2	2	2
	Material thickness	Equal thickness	1	1	1	2	2	3	1	1	1	1	2	2	2	2	2	1	2
		Unequal thickness	2	2	2	3	3	3	2	2	2	2	3	3	3	2	3	2	2
AVERAGE SCORE:			**1.36**	**1.36**	**1.38**	**2.14**	**2.36**	**2.79**	**1.41**	**1.41**	**1.41**	**1.41**	**2.14**	**2.05**	**2.11**	**1.88**	**1.86**	**1.41**	**1.94**

Note: 3=good recyclability, 2=average recyclability, 1=poor recyclability *a: Applicable only for consumable welds* *NA: Not Applicable*

Table C-2: Material recyclability rating based on joint characteristics for similar metals bonding.

Principle of connection			Similar Metals																
			Welding			Adhesive bonding			Mechanical fastening										
									Screwing		Riveting								
Characteristics of connection			Fusion weld	Solid-state weld	Brazing	Chemically cured	Physically cured (melt/evaporate)	Pressure sensitive	Screws & bolts	Pin & collar	Solid/ tubular	Self-piercing	Blind rivet	Stitching/ stapling	Spring & snap-in	Crimping	Seaming	Shrink & press fits	Shape-memory alloy
Joint part	Joint strength	Static strength	1	1	1	2	2	3	1	1	1	1	2	2	2	2	2	1	2
		Fatigue strength	1	1	1	1	2	3	1	1	1	1	2	2	2	2	2	1	2
	Area of bond contact (strength)	Large area	1	1	1	1	2	3	1	1	1	1	2	2	2	2	2	1	2
		Small area	2	2	2	2	2	3	2	2	2	2	3	3	3	1	1	2	3
	Temperature resistance	High temperature	1	1	1	3	3	3	1	1	1	1	2	2	2	1	2	1	2
		Low temperature	1	1	1	2	3	3	1	1	1	1	2	2	2	2	2	1	2
	Joint location	Accessible	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
		Non-accessible	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Joint material type	Same type (metal)	3	NA	2	NA	NA	NA	3	3	3	3	3	3	3	NA	NA	3	3
		Different type (metal)	2[a]	NA	2	NA	NA	NA	2	2	2	2	2	2	2	NA	NA	2	2
	Degradation over time	Moisture effect	2	2	2	3	3	3	2	2	2	2	2	2	2	2	2	2	2
		Heat effect	1	1	1	3	3	3	1	1	1	1	1	2	2	2	2	1	2
	Joint diameter	Large diameter	NA	NA	NA	NA	NA	NA	2	2	2	2	3	NA	NA	NA	NA	2	NA
		Small diameter	NA	NA	NA	NA	NA	NA	1	1	1	1	2	NA	NA	NA	NA	1	NA
	Joint size	Large joint	NA	NA	NA	NA	NA	NA	2	2	2	2	3	3	NA	NA	NA	2	NA
		Small joint	NA	NA	NA	NA	NA	NA	1	1	1	1	2	2	NA	NA	NA	1	NA
	Geometry unevenness at joining area	Protrusion	NA	NA	NA	NA	NA	NA	2	2	2	2	2	2	3	3	NA	2	NA
		No protrusion	NA	NA	NA	NA	NA	NA	1	1	1	1	2	1	2	2	NA	1	NA
Material part	Material density	Same density	1	1	1	2	2	3	1	1	1	1	2	2	2	2	1	1	2
		Different density	2	2	2	3	3	3	2	2	2	2	3	3	3	2	2	2	2
	Material thickness	Equal thickness	1	1	1	2	2	3	1	1	1	1	2	2	2	2	2	1	2
		Unequal thickness	2	2	2	3	3	3	2	2	2	2	3	3	3	2	3	2	2
AVERAGE SCORE:			**1.47**	**1.36**	**1.44**	**2.14**	**2.36**	**2.79**	**1.50**	**1.50**	**1.50**	**1.50**	**2.18**	**2.15**	**2.22**	**1.88**	**1.86**	**1.50**	**2.06**

Note: 3=good recyclability, 2=average recyclability, 1=poor recyclability *a: Applicable only for consumable welds* *NA: Not Applicable*

Table C-3: Material recyclability rating based on joint characteristics for metals to non-metals bonding.

Principle of connection			Metals to Non-metals																
			Welding			Adhesive bonding			Mechanical fastening										
									Screwing		Riveting								
Characteristics of connection			Fusion weld^b	Solid-state weld	Brazing	Chemically cured	Physically cured (melt/evaporate)	Pressure sensitive	Screws & bolts	Pin & collar	Solid/ tubular	Self-piercing	Screw rivet (Plastic)	Stitching/ stapling	Spring & snap-in	Crimping	Seaming	Shrink & press fits	Shape-memory alloy
Joint part	Joint strength	Static strength	1	1	NA	2	2	3	1	1	1	1	3	2	2	2	2	1	2
		Fatigue strength	1	1	NA	1	2	3	1	1	1	1	2	2	2	2	2	1	2
	Area of bond contact (strength)	Large area	1	1	NA	1	2	3	1	1	1	1	2	2	2	2	2	1	2
		Small area	2	2	NA	2	2	3	2	2	2	2	3	3	3	1	3	2	3
	Temperature resistance	High temperature	2	1	NA	3	3	3	1	1	1	1	2	2	2	2	2	1	2
		Low temperature	1	1	NA	2	3	3	1	1	1	1	2	2	2	2	2	1	2
	Joint location	Accessible	2	2	NA	2	2	2	2	2	2	2	2	2	2	2	2	2	2
		Non-accessible	1	1	NA	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Joint material type	Metal (different)	NA	NA	NA	NA	NA	NA	2	2	2	2	NA	2	2	NA	NA	2	2
		Non-metal	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	2	NA	NA	2	NA
	Degradation over time	Moisture effect	2	2	NA	3	3	3	2	2	2	2	2	2	2	2	2	2	2
		Heat effect	2	2	NA	3	3	3	1	1	1	1	2	2	2	2	2	1	2
	Joint diameter	Large diameter	NA	NA	NA	NA	NA	NA	2	2	2	2	2	NA	NA	NA	NA	2	NA
		Small diameter	NA	NA	NA	NA	NA	NA	1	1	1	1	1	NA	NA	NA	NA	1	NA
	Joint size	Large joint	NA	NA	NA	NA	NA	NA	2	2	2	2	2	3	NA	NA	NA	3	NA
		Small joint	NA	NA	NA	NA	NA	NA	1	1	1	1	1	2	NA	NA	NA	2	NA
	Geometry unevenness at joining area	Protrusion	NA	NA	NA	NA	NA	NA	3	3	3	3	2	3	3	2	NA	3	NA
		No protrusion	NA	NA	NA	NA	NA	NA	2	2	2	2	1	2	2	2	NA	2	NA
Material part	Material density	Same density	1	1	NA	2	2	3	1	1	1	1	3	2	2	2	2	1	2
		Different density	2	2	NA	3	3	3	2	2	2	2	2	3	3	2	2	2	2
	Material thickness	Equal thickness	1	1	NA	2	2	3	2	2	2	2	3	3	3	2	2	2	2
		Unequal thickness	2	2	NA	2	2	3	1	1	1	1	2	2	2	2	2	1	2
AVERAGE SCORE:			**1.50**	**1.43**	**-**	**2.07**	**2.29**	**2.79**	**1.52**	**1.52**	**1.52**	**1.52**	**1.95**	**2.21**	**2.17**	**1.88**	**2.00**	**1.64**	**2.00**

Note: 3=good recyclability, 2=average recyclability, 1=poor recyclability *b: Applicable only for laser welding* *NA: Not Applicable*

Table C-4: Material recyclability rating based on joint characteristics for dissimilar non-metals bonding.

Principle of connection / Characteristics of connection			Dissimilar Non-metals																
			Welding			Adhesive bonding			Mechanical fastening										
									Screwing		Riveting								
			Fusion weld^b	Solid-state weld	Brazing	Chemically cured	Physically cured (melt/evaporate)	Pressure sensitive	Screws & bolts	Pin & collar	Solid/ tubular	Self-piercing	Screw rivet (Plastic)	Stitching/ stapling	Spring & snap-in	Crimping	Seaming	Shrink & press fits	Shape-memory alloy
Joint part	Joint strength	Static strength	1	1	NA	2	2	3	1	1	1	1	3	2	2	2	2	1	NA
		Fatigue strength	1	1	NA	1	2	3	1	1	1	1	2	2	2	2	2	1	NA
	Area of bond contact (strength)	Large area	1	1	NA	1	2	3	1	1	1	1	2	2	2	2	2	1	NA
		Small area	2	2	NA	2	2	3	2	2	2	2	3	3	3	1	3	2	NA
	Temperature resistance	High temperature	3	3	NA	3	3	3	1	1	1	1	2	2	2	2	2	1	NA
		Low temperature	1	1	NA	2	3	3	1	1	1	1	2	2	2	2	2	1	NA
	Joint location	Accessible	2	2	NA	2	2	2	2	2	2	2	2	2	2	2	2	2	NA
		Non-accessible	1	1	NA	1	1	1	1	1	1	1	1	1	1	1	1	1	NA
	Joint material type	Metal	NA	NA	NA	NA	NA	NA	2	2	2	2	NA	2	2	NA	NA	2	NA
		Non-metal	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3	NA	3	NA	NA	3	NA
	Degradation over time	Moisture effect	3	3	NA	3	3	3	2	2	2	2	2	2	2	3	3	3	NA
		Heat effect	3	3	NA	3	3	3	1	1	1	1	2	2	2	3	3	3	NA
	Joint diameter	Large diameter	NA	NA	NA	NA	NA	NA	2	2	2	2	2	NA	NA	NA	NA	2	NA
		Small diameter	NA	NA	NA	NA	NA	NA	1	1	1	1	1	NA	NA	NA	NA	1	NA
	Joint size	Large joint	NA	NA	NA	NA	NA	NA	2	2	2	2	2	3	NA	NA	NA	3	NA
		Small joint	NA	NA	NA	NA	NA	NA	1	1	1	1	1	2	NA	NA	NA	2	NA
	Geometry unevenness at joining area	Protrusion	NA	NA	NA	NA	NA	NA	2	2	2	2	2	3	3	2	NA	3	NA
		No protrusion	NA	NA	NA	NA	NA	NA	1	1	1	1	2	2	2	2	NA	2	NA
Material part	Material density	Same density	1	1	NA	2	2	3	1	1	1	1	2	2	2	2	2	1	NA
		Different density	2	2	NA	2	3	3	2	2	2	2	3	3	3	2	2	2	NA
	Material thickness	Equal thickness	2	2	NA	2	2	3	2	2	2	2	2	2	2	2	2	2	NA
		Unequal thickness	1	1	NA	2	2	3	2	2	2	2	2	3	3	2	2	2	NA
AVERAGE SCORE:			**1.71**	**1.71**	**-**	**2.00**	**2.29**	**2.79**	**1.48**	**1.48**	**1.48**	**1.48**	**2.05**	**2.21**	**2.22**	**2.00**	**2.14**	**1.86**	**-**

Note: 3=good recyclability, 2=average recyclability, 1=poor recyclability *b: Applicable only for laser welding* *NA: Not Applicable*