System Model for Sustainable End-of-Life Vehicle Treatment in the Australian Context

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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September 2016
Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Mehdi Hedayati
15 September 2016
To my mum who had no chance to go to school but she was and remains my greatest life’s teacher
ACKNOWLEDGMENTS

This PhD program was a great opportunity for me to engage with high calibre individuals at RMIT University, in particular, the invaluable guidance and advice given by my supervisors, Professor Aleksandar Subic, Professor John Andrews and Dr Bahman Shabani. Professor Subic guided me from the commencing of the research in 2007 until his departure from RMIT University in 2015.

Thanks also extended to AutoCRC for their financial contribution to this research and to the industry representatives whom I consulted throughout the research. I wish to thank Cate Clark, Suzanne Williams, Ali Gerami and Sam Gerami for their proofreading support. Finally, but most importantly, I wish to thank my wife Azar and my son Daniel for their love, patience, assistance, support and faith in me.
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EXECUTIVE SUMMARY

Around 30% of the total mass of a typical passenger end-of-life vehicle (ELV) is made of non-metallic materials such as plastics, textiles, rubbers, and others. These materials, after shredding in an automobile shredding plant, are currently sent to landfill in Australia in the form of a residue called automobile shredder residue (ASR). Some countries including Japan, South Korea, China, Taiwan, and member states of the European Union have legislation requiring energy and material reclamation from non-metallic materials of ELVs. In these countries, the energy and material of non-metallic materials of ELVs are mainly reclaimed through seven treatment practices (regarded in the research as the international best practice ELV reclamation options). These ELV reclamation options are:

1. Deep ELV dismantling for the collection and reuse of non-metallic parts
2. Remanufacturing of non-metallic auto-parts
3. Use of plastics from end-of-life vehicles as reducing agents in blast furnaces
4. Use of treated automobile shredder residue (ASR) as construction aggregate or other construction products
5. Thermal treatment of ASR and its co-incineration with other waste streams
6. Thermo-chemical treatment of ASR (pyrolysis and gasification)
7. Mechanical-physical separation of ASR to recover its materials

This research was set out to address the key research gaps associated with the sustainable treatment of non-metallic materials of ELVs in the Australian context. These research gaps, formulated as four research questions, are as follows:

1. Which of the international best practice ELV reclamation options are technically viable in Australia?
2. What are the most relevant indicators to assess the sustainability performance of the international best practice ELV reclamation options in the Australian context?
3. Which of the international best practice ELV reclamation options is the most sustainable ELV reclamation option for Australia?
4. What is the most sustainable business model to implement the selected most sustainable ELV reclamation option in Australia?
A sustainable ELV reclamation option is defined as ‘an option that is environmentally effective, economically affordable and socially acceptable’. A sustainable business model is defined as ‘a business model that contributes to a sustainable development of the company and society through creating value (materials or energy) from non-metallic materials of ELVs’.

As reflected in its key questions, the research is an attempt to expand the existing boundaries surrounding sustainable management of an industrial waste from a ‘technology’ level to a ‘system’ level. The first three questions are focused on the identification of waste treatment technology that is technically viable, environmentally effective, economically affordable and socially acceptable. The fourth question is focused on the behaviour (i.e. value creation) of a system.

There is some evidence indicating that the success of a waste reclamation strategy is not only dependent on how sustainable is the strategy at the technology-level but it is also dependent on how the strategy is sustainable at the system-level. A proposed waste reclamation strategy might work perfectly in isolation but it might not be able to sustain its operation when it interacts with other elements of its supply chain. A relevant example is the case of waste reclamation in the meat and poultry industry through the conversion of animal wastes to tallow and then the application of tallow as the feedstock for biodiesel production. A sudden increase in the price of tallow in the international market in 2007 forced many of the Australian biodiesel production plants to shut down. It was referred in the media at the time as a ‘Australian biodiesel producers in Melt Down’.

A literature review on the existing ELV reclamation studies indicated only a few studies have compared a set of ELV reclamation options based on the social, economic and environmental indicators. The majority of the studies have compared the environmental performance of a set of ELV reclamation options through the application of the Life Cycle Assessment (LCA) method. It was also found that no ELV reclamation study has yet developed a sustainable business model for ELV reclamation in a region.

A literature review on the existing decision-making support frameworks (DSFs) related to waste management indicated that the existing DSFs such as ‘waste management hierarchy’ are not applicable in the present research as their underpinning assessment tools are incapable to analyse the dynamic behaviour of systems (i.e. the sustainability performance of a business model for ELV reclamation in Australia). As such, the research identified the need for a customised DSF. A challenge associated with the development of a customised DSF was the selection of the
sustainability assessment tools for the proposed DSF from 32 available sustainability assessment tools.

The challenge was successfully addressed through the use of an existing framework called ‘Framework for Sustainability Assessment Tools’. The framework has categorised the available 32 sustainability assessment tools into three clusters. The analysis of the clusters concluded that the sustainability assessment tools located in the ‘Integrated Assessment Cluster’ are sustainable for the present research. A further analysis indicated that three of the eight sustainability assessment tools located in the ‘Integrated Assessment Cluster’ have the greater ability to effectively address the research questions. These tools were: (1) multi-criteria analysis (MCA), (2) conceptual modelling, and (3) system dynamics.

The customised DSF was applied in the research to help answer the four research questions. To address the first question, the research compared the international best practice ELV reclamation options against the four relevant technical indicators suggested in the literature namely (1) functionality, (2) existing experience-reliability, (3) adaptability to local conditions, and (4) flexibility. The MCA analysis of the ELV reclamation options was conducted based on the principles of a MCA technique called ‘Analytical Hierarchy Process (AHP)’.

According to the first principle of the AHP technique, the decision problem was decomposed into a hierarchy containing three levels namely: (1) goal, (2) assessment criteria (the technical indicators), and (3) alternatives (the ELV reclamation options). Based on the second principle of the AHP technique, the relative importance of the elements within each level of the hierarchy was evaluated with respect to the individual elements located in an upper level. The evaluation was conducted through the pairwise comparison approach.

Two sets of the pairwise comparisons were made. In the first set, the relative abilities of the ELV reclamation options to meet the requirements of the technical indicators were identified. This drove the “local” priorities or the performance ranking of the ELV reclamation options with respect to the technical indicators. In the second set, the relative importance of the individual technical indicators with respect to the assessment goal was identified. This drove the ‘weighting factors’ of the technical indicators.
Based on the third principle of the AHP technique, the results were synthesised through the multiplication of the ‘local priority’ of a specific ELV reclamation and the ‘weighting factor’ of the relevant technical indicator and then added together the multiplication results. The analysis produced the ‘global priorities’ of the ELV reclamation options. The calculated amounts of the ‘global priorities’ were used to develop the performance ranking of the ELV reclamation options with respect to the assessment goal.

The research considered the ELV reclamation options with the ‘global priorities’ between 0.5 to 1 as the technically viable ELV reclamation options in the Australian context and with the ‘global priorities’ less than 0.5 as the ELV reclamation options that are not currently technically viable in Australia. Three of the ELV reclamation options had the ‘global priorities’ between 0.5 to 1; and as such, were identified as the most technically viable ELV reclamation options in the Australian context. The technical viable ELV reclamation options were: (1) injection of ELV plastics as reducing agents in blast furnaces, (2) thermo-chemical treatment of automobile shredder residue (ASR), and (3) mechanical-physical separation of ASR.

To answer the second question, the research reviewed the literature and identified a list of the most frequently applied social, economic, and environmental indicators for the identification of optimal waste management strategy in the existing publications. The research screened the identified indicators based on the Australian conditions and then developed a set of Australian-specific sustainability indicators suitable for the assessment of the technically viable ELV reclamation options. These sustainability indicators were: (1) climate change mitigation, (2) water conservation, (3) job creation, (4) safety and public health, (5) capital conservation, (6) social satisfaction, (7) minerals conservation, (8) fossil fuel conservation, (9) landfill space conservation.

To answer the third question, the research compared the sustainability performance of the ELV reclamation options through two different sustainability assessment models, based on the principles of the AHP technique. The applied sustainability assessment models were an emerging model referred in the research as ‘multi-dimensionality’ and the established sustainability assessment model of ‘triple bottom line (TBL)’. In the multi-dimensionality model, as opposed to the TBL model, a sustainability assessment indicator can represent more than one dimension of sustainability (i.e. social, economic and environmental).
The multi-dimensionality model identified the ELV reclamation option of ‘thermo-chemical treatment of ASR’ and the TBL identified the ELV reclamation option of ‘injection of ELV plastics as reducing agents in blast furnaces’ as the most sustainable ELV reclamation option for Australia. A comprehensive sensitivity analysis was conducted in which the sensitivity of the assessment models with respect to the weighting factors of the sustainability indicators was assessed. The results indicated that the selected ELV reclamation option based on the TBL model, as opposed to the reclamation option based on the multi-dimensionality model, is highly sensitive to the applied weighting factors. Thus, there is little confidence on the selected ELV reclamation option based on the TBL model. The research identified that ELV reclamation option (i.e. thermo-chemical treatment of ASR) as the most sustainable ELV reclamation for Australia.

To address the fourth research question, a literature review was conducted to identify the existing business models relevant to the ELV reclamation option of ‘thermo-chemical treatment of ASR’. Three business models were identified namely: (1) the business model in which vehicle manufacturers build and operate ASR thermo-chemical treatment plants, (2) the business model in which waste management companies build and operate ASR thermo-chemical plants, and (3) the business model in which ELV shredding facilities build and operate ASR thermo-chemical plants.

To identify the most effective business model for Australia, the business models were compared, according to the principles of the AHP technique, against three relevant assessment indicators found in the literature namely (1) goal alignment, (2) self-reinforcement, and (3) robustness. The results indicated that the business model in which the proposed ASR thermo-chemical plants are established and operated by the ELV shredding facilities is the most effective business model for Australia.

The sustainability assessment of the identified business model was conducted through two sustainability assessment methods of the conceptual modelling and the system dynamics. The conceptual modelling method created an abstract of the business model in the form of a produced the causal loop diagram (CLD). The CLD represented the major interactions (feedback loops) between the proposed business model for ELV reclamation and the other business models within the Australian ELV recycling network.
One reinforcing feedback, the loop creates value (energy) for the business model, and four balancing feedback loops, the loops that reduce the value creation of the business model, were identified in the CLD. A comprehensive analysis of the feedback loops indicated that the reinforcing loop of the CLD is the most influential feedback loop and this would be unlikely to change in the future. This provided enough confidence to conclude that the business model is a sustainable business model as it can create value (energy) from non-metallic materials of ELVs.

The sustainability assessment of the business model through the system dynamics method was conducted through the analysis of the behaviour-over-time (BOT) pattern mode of the business model based on the model lifetime of 25 years. The annual electricity production of the ASR gasification plants across Australia was considered as the behaviour of the business model. The abstract developed by the conceptual modelling method was used as a basis to produce the stocks and flows diagram (SFD) of the business model. A computer simulation of the SFD based on the Australian-specific data identified the BOT pattern mode of the business model as an ‘Exponential Growth’ pattern mode. The identified BOT pattern mode was regarded as evidence that the business model is a sustainable business model as it creates value (energy) from non-metallic materials of ELV in a growing trend.

The BOT pattern mode of the business model was validated and verified through the recommended techniques in the literature. Three ‘what-if’ scenarios were developed based on the requirements of one of the validation techniques, the behaviour pattern test. The scenarios covered some extreme and undesirable conditions that the selected business model might encounter during its lifetime.

In the first scenario, ten years after the establishment of the business model, the fraction of the total ELVs generated in Australia that leave Australia as used cars suddenly increased from 4% to 18%. This would initially decrease the relative annual electricity production of the business (relative to the electricity production of the first year) by around 5% but three years later, the business model would create the same amount of electricity that would be produced in the first year. The business model then will have a growing electricity production trend. This scenario could happen for a number of reasons including the adoption of a ‘beyond-Europe’ product stewardship policy by some European car makers.
In the second scenario, ten years after the establishment of the business model, car dismantlers decide to suddenly increase the mass of the removed non-metallic materials from 4% to 12% of the total mass of an ELV. This would reduce the relative electricity production of the business model (relative to the electricity production of the first year) by around 30% but nine years later, the business model would create the same amount of electricity that would be produced in the first year. The business model then will have a growing electricity production trend. The scenario could happen for different reasons including further expansion of the plastic recycling facilities in Australia that would create a strong demand for ELV plastics in Australia.

In the third scenario, ten years after the establishment of the business model, the mass fraction of non-metallic materials of ELVs is reduced by 20% and kept constant during the remaining lifetime of the business model. This would reduce the relative electricity production of the business model (relative to the electricity production of the first year) by 5% but 13 years later, the business model would create the same amount of electricity that would be produced in the first year. A possible cause of the scenario would be the extensive application of lightweight metal alloys (e.g. magnesium-based alloys) as the substitutes for the fraction of the removed steel in cars.

While the ‘Exponential Growth’ pattern mode of the business model would be temporarily changed in the considered scenarios, the overall BOT pattern mode of the business model was consistent with the BOT pattern mode of ‘Exponential Growth’. This provided enough confidence to regard the investigated business model as the most sustainable business model for ELV reclamation in Australia.

The major policy implication of the research is on the Australian National Waste Policy, particularly its Product Stewardship Act 2011. Whilst vehicles have not yet been included in the Australian product stewardship schemes, the product stewardship scheme relating to vehicles could be proposed for Australia in the coming years. The failed experience of the ELV legislation in Malaysia — because of the public perception that little ELV management research was conducted prior to the introduction of the legislation — highlights the importance of the contextual research on ELV management. The present research, to some extent, reduces the risks of such public perception if any ELV legislation is proposed for Australia.

The advancements made in the research in relation to the emerging sustainability assessment model of multi-dimensionality are regarded the major research contributions of this research. The
conceptual structure of the multi-dimensionality model was developed in the relevant early research studies. The present research contributed to the development of that conceptual model through developing some important methodological aspects of the model including the allocation of the weighting factors of the sustainability indicators used in the model (i.e. best-case-scenario/worst-case-scenario analysis).

The research demonstrated the practical application of the multi-dimensionality model in a sustainability assessment analysis. The research compared the results based on the multi-dimensionality model and the results based on the established sustainability assessment model of the triple bottom line (TBL) model. The comparison concluded that the results based on the former model are less sensitive to the key modelling assumptions than the results based on the latter model. This could further promote the application of the multi-dimensionality model in the future research focused on the sustainability assessment of a set of options.

Another implication of this research is related to the sustainability assessment of a set of business models for the implementation of a selected waste treatment practice for a given region. Whilst the sustainability assessment of a set of waste treatment practices for a region has been the subject of many research studies, none of the research studies has yet developed a sustainable business model for the implementation of the selected waste treatment practice in that region. The system-based methodology developed in this research relating to the sustainability assessment of a set of business models could be applied in future waste management research studies.

The key recommendations of the research are as follows:

1. The commencement of a national debate and discussion about the sustainable management of ELVs in Australia is recommended. The information provided in this thesis may assist in forming this debate.
2. The first Australian large-scale thermo-chemical (gasification) waste treatment plants will be operated soon in Port Hedland. It is recommended that the lessons learnt from the plant are shared with the research community and the industry, in particular the Australian ELV recycling industry.
3. It is recommended that the both sustainability assessment models of TBL and multi-dimensionality are applied in the research studies focused on the sustainability assessment of
a set of waste treatment practices. The performance ranking of the waste treatment practices could be sensitive to the applied sustainability assessment model.

4. An effective dialogue is recommended between the automobile industry and the Australian ELV recycling industry with respect to the most likely scenarios for the future material composition of cars. If the automobile industry decides to predominantly use lightweight metal alloys as a substitute for the reduced fraction of steel in cars, the decision could significantly reduce the annual energy recovered by the selected ELV reclamaiton option for Australia (i.e. thermo-chemical treatment of ASR).
## TERMS AND DEFINITIONS

<table>
<thead>
<tr>
<th>Business model</th>
<th>A conceptual tool (or framework) to help understand how a business entity does business and how value can be proposed, created and delivered from a business.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resilience</td>
<td>The ability of a system to maintain high-level objectives (e.g. sustainability, rural livelihoods, ecosystem services) in the face of unknown changes or disturbance.</td>
</tr>
<tr>
<td>Sustainability</td>
<td>To make development sustainable—to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.</td>
</tr>
<tr>
<td>Sustainability assessment indicator</td>
<td>The indicators that allow focusing the efforts on specific areas of sustainability and to measure performance and improvements.</td>
</tr>
<tr>
<td>Sustainability assessment tool</td>
<td>A tool that can help decision-makers and policy-makers decide which actions they should or should not take.</td>
</tr>
<tr>
<td>Sustainable business model</td>
<td>A business mode that creates competitive advantage through superior customer value and contributes to a sustainable development of the company and society through creating value.</td>
</tr>
<tr>
<td>Sustainable ELV reclamation business model</td>
<td>A business model that creates competitive advantage through superior customer value and contributes to a sustainable development of the company and society through creating value (materials or energy) from non-metallic materials of the ELVs.</td>
</tr>
<tr>
<td>Sustainability science</td>
<td>A research area that combines work in the area of environmental science with work in economic, social and development studies to better understand the complex dynamic interactions between environmental, social and economic issues.</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>ASR</td>
<td>Automobile shredder residue</td>
</tr>
<tr>
<td>BOT</td>
<td>Behaviour over time</td>
</tr>
<tr>
<td>CFCs</td>
<td>Chlorofluorocarbons</td>
</tr>
<tr>
<td>CLD</td>
<td>Causal loops diagram</td>
</tr>
<tr>
<td>DSF</td>
<td>Decision support framework</td>
</tr>
<tr>
<td>ELV</td>
<td>End-of-life vehicle</td>
</tr>
<tr>
<td>HFCs</td>
<td>Hydrofluorocarbons</td>
</tr>
<tr>
<td>LCA</td>
<td>Life cycle assessment</td>
</tr>
<tr>
<td>MCA</td>
<td>Multi-criteria analysis</td>
</tr>
<tr>
<td>MCDA</td>
<td>Multi-criteria decision analysis</td>
</tr>
<tr>
<td>OEM</td>
<td>Original equipment manufacturer</td>
</tr>
<tr>
<td>SFD</td>
<td>Stocks and flows diagram</td>
</tr>
<tr>
<td>SR</td>
<td>Shredder residue</td>
</tr>
</tbody>
</table>
PUBLICATIONS FROM THIS RESEARCH PROGRAM

Conference Papers (presented):


Journal Paper:

1 Introduction

1.1 END-OF-LIFE VEHICLE GENERATION

The precise number of annual passenger end-of-life vehicles (ELVs) produced in Australia is
unknown because people can keep their non-drive vehicles unregistered (Sustainability Victoria,
2014). This creates uncertainty about the number of the annual ELVs generated in Australia as the
non-registered vehicles could have been permanently or temporarily unregistered. The annual
ELVs generated in Australia have been estimated between six to seven hundreds ELVs (Puri et
al., 2009, Halabi and Doolan, 2013). Table 1-1 provides the approximate annual number of ELVs
generated in the various Australian States and Territories based on an average vehicle attrition rate
of 4.7% (Sustainability Victoria, 2007).

<table>
<thead>
<tr>
<th>State or Territory</th>
<th>Registered vehicles</th>
<th>Number of ELVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>New South Wales</td>
<td>3,803,926</td>
<td>178,784</td>
</tr>
<tr>
<td>Victoria</td>
<td>3,373,564</td>
<td>158,557</td>
</tr>
<tr>
<td>Queensland</td>
<td>2,489,266</td>
<td>116,995</td>
</tr>
<tr>
<td>South Australia</td>
<td>1,000,132</td>
<td>47,006</td>
</tr>
<tr>
<td>Western Australia</td>
<td>1,432,969</td>
<td>67,349</td>
</tr>
<tr>
<td>Tasmania</td>
<td>303,622</td>
<td>14,270</td>
</tr>
<tr>
<td>Northern Territory</td>
<td>87,284</td>
<td>4,102</td>
</tr>
<tr>
<td>Australian Capital Territory</td>
<td>223,472</td>
<td>10,503</td>
</tr>
</tbody>
</table>

As indicated in Table 1-1, the differences between the number of the generated ELVs in the
different Australian States and Territories are significant. For instance, the combined ELVs
generated in Tasmania, Northern Territory, and the Australian Capital Territory (~ 29,000 units)
represent a third of the ELVs generated in New South Wales alone (178,784).

The annual number of the global ELVs in 2010 has been estimated around 40 million units (Table
1-2). There are remarkable differences between the numbers of ELVs generated in 2010 in the
various countries and regions (Table 1-2). As indicated in Table 1-2, in 2010, in a country-basis,
the approximate number of the ELVs generated in the United States (~12 millions) is equal to the combined number of the ELVs that are generated in European Union (~7.8 millions) and China (~3.5 millions). Among the countries listed in Table 1-2, Australia has a relatively low number of the generated ELVs per year.

<table>
<thead>
<tr>
<th>Country/state</th>
<th>Automobile ownership (units)</th>
<th>Deregistered automobiles (units/year)</th>
<th>Number of ELVs (units/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Union</td>
<td>271,319,000</td>
<td>14,077,000</td>
<td>7,823,211</td>
</tr>
<tr>
<td>(Germany)</td>
<td>(45,261,188)</td>
<td>(2,570,137)</td>
<td>(500,193)</td>
</tr>
<tr>
<td>(Italy)</td>
<td>(41,649,877)</td>
<td>(1,835,293)</td>
<td>(1,610,137)</td>
</tr>
<tr>
<td>(France)</td>
<td>(37,744,000)</td>
<td>(2,002,669)</td>
<td>(1,583,283)</td>
</tr>
<tr>
<td>(England)</td>
<td>(35,478,652)</td>
<td>(1,810,571)</td>
<td>(1,157,438)</td>
</tr>
<tr>
<td>(Spain)</td>
<td>(27,750,000)</td>
<td>(996,718)</td>
<td>(839,637)</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>41,224,913</td>
<td>300,000</td>
<td>Not available</td>
</tr>
<tr>
<td>USA</td>
<td>239,811,984</td>
<td>20,419,898</td>
<td>12,000,000</td>
</tr>
<tr>
<td>Canada</td>
<td>21,053,994</td>
<td>1,321,658</td>
<td>1,200,000</td>
</tr>
<tr>
<td>Brazil</td>
<td>32,100,000</td>
<td>1,058,064</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Japan</td>
<td>75,361,876</td>
<td>4,080,000</td>
<td>2,960,000</td>
</tr>
<tr>
<td>China</td>
<td>78,020,000</td>
<td>6,000,000</td>
<td>3,506,000</td>
</tr>
<tr>
<td>Korea</td>
<td>17,941,356</td>
<td>849,280</td>
<td>684,000</td>
</tr>
<tr>
<td>Australia*</td>
<td>15,352,487</td>
<td>600,311</td>
<td>500,000</td>
</tr>
<tr>
<td>Subtotal</td>
<td>792,185,610</td>
<td>57,921,599</td>
<td>29,673,211</td>
</tr>
<tr>
<td>Global total</td>
<td>1,016,763,420</td>
<td>15,805,275</td>
<td>40,176,051</td>
</tr>
</tbody>
</table>

* Values in () are not included in the subtotal
* For 2002

1.2 END-OF-LIFE VEHICLE TREATMENT PRACTICES

The processes involved in the treatment of ELVs are summarised in Figure 1-1. As shown in Figure 1-1, the treatment processes commence with the depollution stage, which removes working
fluids (e.g. engine oil) from an ELV. Following this, the ELV is passed onto the dismantling processes which remove any marketable parts. The compressed vehicle hulk is then transferred to a metal shredding facility which separates metallic materials and non-metallic materials of ELVs.

The residue generated through the shredding processes of ‘Aeraulic separator’ and ‘Eddy current separator’ in Figure 1-1 is called ASR (automobile shredder residues) or ‘fluff’. ASR is defined as a predominantly non-metallic material that remains after separating ferrous and nonferrous metal from shredder output (DTSC, 2014). ASR is typically disposed of in landfill sites in Australia and in most countries around the world (Viganò et al., 2010). A picture of typical ASR, taken during a site visit to a metal shredding facility in Melbourne, is shown in Figure 1-2.
ASR consists mainly of shredded foam, fabric, plastics, rubber, tyres, glass, wood, incidental sediment and debris and other such non-metallic components. The average composition of ASR is presented in Table 1-3 Average composition of ASR (Ciacci et al., 2010a).

<table>
<thead>
<tr>
<th>Material type</th>
<th>Average composition (% weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics</td>
<td>35-55</td>
</tr>
<tr>
<td>Rubber</td>
<td>10-20</td>
</tr>
<tr>
<td>Metals</td>
<td>6-13</td>
</tr>
<tr>
<td>Textiles</td>
<td>7-15</td>
</tr>
<tr>
<td>Fines (paint, glass, sand)</td>
<td>10-20</td>
</tr>
</tbody>
</table>

As indicated in Table 1-3, the non-metallic materials of plastics, rubber, and textiles collectively contribute 52-90 per cent of the total weight of an ASR sample. The average weight of non-metallic materials in vehicles is increasing. For example, as indicated in Table 1-4, the cars built in Germany during 1996 to 2000 had around 9% more non-metallic materials than the cars built in that country during 1981 to 1985 (GHK/Bios, 2006).
Table 1-4 Material compositions of newly built vehicles in Germany from 1980 to 2000 (GHK/Bios, 2006)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative mass per cent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferrous metal</td>
<td>83</td>
<td>67.5</td>
<td>62.4</td>
<td>57.5</td>
</tr>
<tr>
<td>Non-ferrous metal</td>
<td>4.3</td>
<td>6.1</td>
<td>8.0</td>
<td>10</td>
</tr>
<tr>
<td>Plastics</td>
<td>3.6</td>
<td>4.9</td>
<td>6.2</td>
<td>7.5</td>
</tr>
<tr>
<td>Textiles</td>
<td>4.0</td>
<td>5.1</td>
<td>6.2</td>
<td>7.3</td>
</tr>
<tr>
<td>Tyres/rubbers</td>
<td>3.8</td>
<td>3.8</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Glass</td>
<td>3.1</td>
<td>3.8</td>
<td>4.5</td>
<td>5.2</td>
</tr>
<tr>
<td>Liquids</td>
<td>2.9</td>
<td>2.8</td>
<td>2.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Other</td>
<td>5.3</td>
<td>6.0</td>
<td>6.1</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Metal shredding plants might process other end-of-life (EoL) products, particularly discarded household appliances such as refrigerators. Thus, the ASR generated in a shredding plant might be sourced from the non-metallic fraction of a broad range of products but the amount of ASR sourced from ELVs would be dominant (SIMS, 2013). For example, the weight portion of refrigerators and air conditioning in the total weight of shredded materials in the Australian metal shredding plants have been reported as low as 1% (Australian Government, 2014b). The non-metallic fractions of some EoL products are presented in Table 1-5.

Table 1-5 Average metallic fraction and non-metallic fraction of selected products
### Average weight fraction of material

<table>
<thead>
<tr>
<th>Product</th>
<th>Metallic fraction (%)</th>
<th>Non-metallic fraction (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger car</td>
<td>70</td>
<td>30</td>
<td>(Giannouli et al., 2007)</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>52</td>
<td>48</td>
<td>(Oguchi et al., 2011)</td>
</tr>
<tr>
<td>Washing machine</td>
<td>57</td>
<td>43</td>
<td>(Oguchi et al., 2011)</td>
</tr>
<tr>
<td>Air conditioner</td>
<td>73</td>
<td>27</td>
<td>(Oguchi et al., 2011)</td>
</tr>
<tr>
<td>Cathode ray tube television (CRT TV)</td>
<td>17</td>
<td>83</td>
<td>(Oguchi et al., 2011)</td>
</tr>
<tr>
<td>Liquid-crystal-display television (LCD TV)</td>
<td>48</td>
<td>52</td>
<td>(Oguchi et al., 2011)</td>
</tr>
<tr>
<td>Printer</td>
<td>39</td>
<td>61</td>
<td>(Oguchi et al., 2011)</td>
</tr>
<tr>
<td>Mobile phone</td>
<td>45</td>
<td>55</td>
<td>(Oguchi et al., 2011)</td>
</tr>
<tr>
<td>Toys</td>
<td>5</td>
<td>95</td>
<td>(Pérez-Belis et al., 2013)</td>
</tr>
</tbody>
</table>

It should be noted that, while the average non-metallic fraction of ELVs are less than those of some household appliances such as refrigerators and washing machines, the total weight of non-metallic material per unit of ELVs are much greater than those of the compared appliances. For example, based on the average weight of 1300 kg for an ELV (Sustainability Victoria, 2014, Australian Government, 2002) and the average non-metallic fraction of 30% for an ELV (Giannouli et al., 2007), the average weight of non-metallic material per one ELV is 390 kg. However, the typical domestic refrigerator will contain about 15 to 20 kg of plastics and other non-metallic materials (Australian Government, 2014b).

In the Australian metal shredding facilities, the striped ELVs from dismantlers join some ELVs which are supplied directly from the cars’ last owners. Figure 1-3 (taken during a site visit to a metal shredding facility in Melbourne in 2008) presents both ELV types (i.e. the ELVs from the cars’ last owners and the ELVs supplied by car dismantlers). The red ELV (in the figure) is a whole ELV and the ELV underneath the red ELV in the figure is a compressed ELV hulk. As indicated in Figure 1-3, in addition to ELVs, metal shredding facilities process other metal-contained end-of-life products.
1.3 INTERNATIONAL BEST PRACTICE END-OF-LIFE VEHICLE RECLAMATION OPTIONS

A number of treatment practices have been applied to date, in the international level, to recover non-metallic materials of ELVs. These treatment practices that are also referred in the present research as ‘ELV reclamation options’ are listed in Table 1-6. These options can be broadly divided into the ‘pre-shredding’ ELV reclamation options (e.g. Option 3) and the ‘post-shredding’ ELV reclamation options (e.g. Option 6).
Table 1-6 International best treatment practices for recovery of non-metallic materials of ELVs (or referred in the research as ‘best-practice ELV reclamation options’)

<table>
<thead>
<tr>
<th>Options</th>
<th>ELVs recovery options</th>
<th>References*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1</td>
<td>Deep ELV dismantling for the collection and reuse of non-metallic parts</td>
<td>(Kim et al., 2004, Vermeulen et al., 2011)</td>
</tr>
<tr>
<td>Option 2</td>
<td>Remanufacturing of non-metallic parts of ELVs</td>
<td>(Xiang and Ming, 2011, Gerrard and Kandlikar, 2007)</td>
</tr>
<tr>
<td>Option 3</td>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>(GHK/Bios, 2006)</td>
</tr>
<tr>
<td>Option 4</td>
<td>Use of treated ASR as construction aggregate or other construction products</td>
<td>(European Parliament, 2010)</td>
</tr>
<tr>
<td>Option 5</td>
<td>Thermal treatment of ASR and its co-incineration with other waste streams</td>
<td>(US EPA, 2010, Vermeulen et al., 2011)</td>
</tr>
<tr>
<td>Option 6</td>
<td>Thermo-chemical treatment of ASR (pyrolysis, and gasification)</td>
<td>(Jody et al., 2007, Viganò et al., 2010)</td>
</tr>
<tr>
<td>Option 7</td>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>(Jody et al., 2007, GHK/Bios, 2006)</td>
</tr>
</tbody>
</table>

* Further references are provided in Table 2-4.

There is also a number of emerging ELV treatment options (Table 1-7). These ELV reclamation options are in the research and development stage.

Table 1-7 Emerging ELV reclamation options

<table>
<thead>
<tr>
<th>Options</th>
<th>ELV recovery options</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1</td>
<td>ASR hydrolysis to light fuel oils</td>
<td>(Boughton and Horvath, 2006a)</td>
</tr>
<tr>
<td>Option 2</td>
<td>ASR recycling by coal tar based oil bath treatment</td>
<td>(Ichiro et al., 2002)</td>
</tr>
<tr>
<td>Option 3</td>
<td>ASR material and energy recovery by vacuum pyrolysis</td>
<td>(Roy and Chaala, 2001b)</td>
</tr>
<tr>
<td>Option 4</td>
<td>ASR material recovery by froth flotation with ozonation</td>
<td>(Reddy et al., 2007)</td>
</tr>
<tr>
<td>Option 5</td>
<td>ASR treatment to produce special granules suitable to be used as aggregates in cementitious or asphalt mixes</td>
<td>(Rossetti et al., 2006)</td>
</tr>
</tbody>
</table>
1.4 SUSTAINABILITY ISSUES OF THE CURRENT END-OF-LIFE VEHICLE TREATMENT IN AUSTRALIA

1.4.1 Definition of sustainability and its related terms

The standard definition of ‘sustainability’ is provided by the Brundtland Commission “to make development sustainable — to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). This only provides a general definition for sustainability without any reference to the goals that should be met by a particular sector of the economy. The different goals set by different sectors have led to the formation of a new science called ‘Sustainability Science’ (Ness et al., 2007). Kasemir et al. (2003) describe ‘Sustainability Science’ as a research area that combines work in the area of environmental science with work in economic, social and development studies to better understand the complex dynamic interactions between environmental, social and economic issues.

No standard definition for a ‘sustainable ELV reclamation option’ has been presented to date. However, for a waste management option to be sustainable, it needs to be environmentally effective, economically affordable and socially acceptable (Nilsson-Djerf, 2000). It can be argued that the definition of a ‘sustainable waste management option’ could be applied in this research for describing a ‘sustainable ELV reclamation option’. This is based on the current consideration of the non-metallic fraction of ELVs (e.g. ASR) as a waste in Australia.

The importance of including the environmental, social and economic aspects in the sustainability assessment studies and the way that these aspects should be linked together have been best described by Singh et al. (2012), (Singh et al., 2012):

“Although there are various international efforts on measuring sustainability, only a few of them have an integral approach taking into account environmental, economic and social aspects. In most cases the focus is on one of the three aspects. Although, it could be argued that they could serve supplementary to each other, sustainability is more than an aggregation of the important issues, it is also about their interlinkages and the dynamics developed in a system. This point will be missing if tried to use them supplementary and it is one of the most difficult parts to capture and reflect in measurements”.

Often a sustainability tool or method is required to better understand the complex dynamic interactions between environmental, social and economic issues (Ness et al., 2007). Devuyst et al.
define ‘sustainability assessment tool’ as “… a tool that can help decision-makers and policy-makers decide which actions they should or should not take in an attempt to make society more sustainable”. Sustainability assessment studies often use ‘sustainability assessment indicators’, the indicators that allow decision-makers to focus the efforts on specific areas of sustainability and to measure performance and improvements (Australian Government, 2015). The above descriptions for a ‘sustainability assessment tool’ and for a ‘sustainability assessment indicator’ are used in this research.

The new concept of ‘sustainable business models’ has emerged in recent years (Bohnsack et al., 2014, Bocken et al., 2014). A business model is described as a conceptual tool (or framework) to help understand how a business entity does business and how value can be proposed, created and delivered from a business (Bohnsack et al., 2014, Osterwalder et al., 2005). Lüdeke-Freund (2010) describes a sustainable business model as a business model that creates competitive advantage through superior customer value and contributes to a sustainable development of the company and society through creating value.

The description presented by Lüdeke-Freund (2010) for a ‘sustainable business model’ needs to be slightly changed to make it more specific to the proposed business entity that will reclaim non-metallic materials of ELVs in Australia. A revised form of that description that will be used in this research is: a sustainable business model is a business model that creates competitive advantage through superior customer value and contributes to a sustainable development of the company and society through creating value (materials or energy) from non-metallic materials of the ELVs that are generated in Australia.

1.4.2 Current Australian end-of-life vehicle treatment network

The current framework for the treatment of ELVs in Australia is shown in Figure 1-4. The upper section of the framework shows the different types of vehicles (imported second-hand vehicles, imported new vehicles) joining the locally made vehicles. The framework also shows the different treatment pathway for the mature ELVs (i.e. those vehicles that reach the end-of-life stage because the costs of their repairs exceeds the value of the vehicle) and for the pre-mature ELVs.
Figure 1-4 Australian ELV treatment network

It can be argued that the current Australian framework for the treatment of ELVs is not sustainable. As stated earlier, for a waste management system to be sustainable, it needs to be environmentally effective, socially acceptable and economically affordable (Nilsson-Djerf, 2000). The following sections explain why the current ELV treatment practices in Australia are not environmentally effective, socially acceptable, and economically affordable.

1.4.3 Environmental issues of the current end-of-life vehicle treatment network

The current ELV treatment practices in Australia are associated with significant resource losses. It is better understood if the total number of generated ELVs in the country is considered. In 2010, around 620,000 ELVs were generated in Australia (Halabi and Doolan, 2013), each weighting approximately 1300 kg (Australian Government, 2002). As around 30% of the mass of each ELV...
is sent to landfill in the form of ASR (Australian Government, 2002), the annual amount of the resources that are wasted from ELV treatment in Australia is around 240,000 tonnes or around 650 tonnes per day. Based on this figure and the indicative ASR composition shown in Table 1-3, the approximate annual material loss from the current Australian ELV treatment practices are provided in Table 1-8.

<table>
<thead>
<tr>
<th>Material</th>
<th>Annual loss (thousand tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics</td>
<td>84</td>
</tr>
<tr>
<td>Urethane foam</td>
<td>38.4</td>
</tr>
<tr>
<td>Fibre</td>
<td>31.2</td>
</tr>
<tr>
<td>Rubber</td>
<td>16.8</td>
</tr>
<tr>
<td>Wood</td>
<td>7.2</td>
</tr>
<tr>
<td>Paper</td>
<td>4.8</td>
</tr>
<tr>
<td>Ferrous metal</td>
<td>19.2</td>
</tr>
<tr>
<td>Glass</td>
<td>16.8</td>
</tr>
<tr>
<td>Wire harness</td>
<td>12</td>
</tr>
<tr>
<td>Non-ferrous metal</td>
<td>9.6</td>
</tr>
</tbody>
</table>

Furthermore, the annual consumption of plastics in Australia is around 1,533 thousand tonnes (PACIA, 2011). Based on this figure, if the total plastics material available in the generated ASR in Australia is recovered, it can replace around 5% of the total annual plastics consumption in the country.

Whilst ASR is regarded as a waste in Australia, it is regarded as a commodity in some countries. A research study in a Taiwan study (Tai and He, 2015) concluded that ASR is a commodity in Taiwan because of its characteristics of having low moisture content and high heat value. ASR is a heterogeneous product, comprising mainly non-metallic materials including plastics, rubbers, and textiles. These materials have high energy calorific values and their presence in ASR makes ASR a potential alternative fuel source. The study conducted by Tai and He (2015) (Tai and He, 2015) indicated that the ASR generated in Taiwan, on average, has 68.97–83.47% combustible content, 95% of which was polymers, foam, and fibre. Major combustible elements were identified as 60% carbon; 10% hydrogen and oxygen; and less than 4% nitrogen, sulphur, and chlorine. The
study measured the calorific value of ASR between 6581 to 7246 kcal/kg (~24 MJ/kg to 26 MJ/kg). An earlier research study (ECRIS, 1998) has also pointed out the commodity value of ASR and suggested the use of it, following some treatment, as a fuel. Based on the measurement conducted in that study (ECRIS, 1998), the calorific value of ASR was measured close to the calorific value of coal (~27 MJ/kg).

The current Australian practice for the management of ASR (i.e. landfill disposal) could damage the environment through the possible leak of some concerning elements such as heavy metals (Forton et al., 2006, Passarini et al., 2012, Vermeulen et al., 2011). While no study has been conducted to determine the level of concerning chemical elements in each of the Australian metal shredding plants, there is some evidence (Sustainability Victoria, 2014) suggesting that the ASR generated in Australia might contain some hazardous chemicals, such as heavy metals, polychlorinated biphenyls (PCBs), mineral oils, and hydrocarbons. Australian shredding plants accept ELVs directly from the cars’ last owners and shred the ELVs without completing proper removal of the working fluids (e.g. engine oils). The presence of the working fluids infects the generated ASR from that shredding batch. The leaking from the contaminated ASR can potentially cause serious environmental issues including pollution of the groundwater sources.

Another source of resource loss in the current Australian framework for the treatment of ELVs is the generation of the abandoned ELVs. Each year around 8% of the total ELVs are abandoned in the environment (Australian Government, 2002). Based on the 2010 generation rate of 620,000 ELVs, the abandoned figure in 2010 would be around 50,000 ELVs. The resource that would be recovered from the abandoned ELVs in 2010 would be around 45,500 tonnes of metallic material and 19,500 tonnes of non-metallic material.

1.4.4 Social issues of the current end-of-life vehicle treatment network

Several social issues are associated with the current treatment of ELVs in Australia. The first issue involves illegal abandonment of ELVs in nature (e.g. lakes, bushlands), mainly caused by the fact that the transport costs of the abandoned ELVs to a metal recycling plant exceed the price of ELVs. It is estimated that around 8% of the total ELVs generated in Australia are abandoned each year (Australian Government, 2002). The abandoned ELVs impose some health hazards to the community due to environmental pollution (e.g. contamination of water) and unpleasant visual impact of the abandoned ELVs on the side of roads, farms and bushland.
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The second social issue is the cross-board transfer of ASR to reduce its landfill costs. Generally, the total landfill cost is comprised of three main cost elements of landfill levy, gate fee and transport fee (DEWHA, 2009b). The indicative values of these cost items for New South Wales (NSW) are presented in Table 1-9.

<table>
<thead>
<tr>
<th>Cost element</th>
<th>Cost ($/tonne)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill levy</td>
<td>119.8</td>
<td>(EPA NSW, 2016)</td>
</tr>
<tr>
<td>Gate fee</td>
<td>154.2</td>
<td>(MCC, 2013)</td>
</tr>
<tr>
<td>Transport fee</td>
<td>90.0</td>
<td>(Sydney Morning Herald, 2013)</td>
</tr>
<tr>
<td>Total landfill cost</td>
<td>364.0</td>
<td>Estimated</td>
</tr>
</tbody>
</table>

In Australia, apart from Queensland, the landfill costs of ASR and any other waste types comprise two components: landfill gate fee (charged by the landfill operator) and waste levy (tax). The purpose of waste levy is to encourage waste avoidance and resource recovery (Australian Government, 2014b). In Queensland, the waste levy was repealed on 1 July 2012 through an amendment to the Waste Reduction and Recycling Regulation 2011 to provide for a nil levy rate on all waste. The landfill levies are of between $40 and $50 per tonne in South Australia and Victoria, and $100 to $120 per tonne in New South Wales. The levy of $12 per cubic metre in Western Australia equates to about $30 per tonne (Australian Government, 2014b).

The inconsistency between the landfill costs among the Australian States and Territories has led to the transport of ASR from the locations with high landfill costs to the locations with moderate and low landfill costs (Australian Government, 2014b). This is regarded as an example of ‘shifting the burden’ to others (Sydney Morning Herald, 2013). The issue of the cross-boarding transfer of the industrial waste including ASR is particularly significant between Queensland (QLD) and New South Wales (NSW) due to lower landfill fees (~ the gate fee around $15 per tonne) that apply in Queensland and the short transfer distances between these States. There is also evidence of ASR contributing to illegal dumping (Australian Government, 2014b).

The landfill levy in some Australian jurisdictions has a notable growing trend and this trend might continue in the future. For example, the landfill levy in Victoria increased 233 per cent in 2010-11, 47 per cent in 2011-12, 10 per cent in 2012-13, 10 per cent in 2013-14 and 10 per cent in 2014-15 (Municipal Association Victoria, 2015). The increasing landfill levy in some Australian
jurisdictions and the nil or very low landfill levy in some other jurisdictions intensify the issue of cross-board transfer of waste materials including ASR.

The third social issue is increased health risks associated with the handling and disposal of ASR, in particular the health risks caused by the heavy metals such as lead that are present in ASR. In 1999, the government of the Australian Capital Territory (ACT) closed one of the local landfill sites and ordered the health checks of the operators of the landfill site because of the concern about the lead contamination of ASR dumped in that landfill (Australian Government, 2002).

The other social issue associated with current ELV treatment practices is reflected through missing job opportunities which could be created if ELV waste (e.g. ASR) was recovered. Treatment of non-metallic materials from ELVs has the potential to create new jobs in the economy. For example, according to a report developed by Argonne National Laboratory (ANL, 2010) a thermal-based ASR recycling plant, with the capacity of treating 300 tonnes of ASR per day, can employ up to 50 people. The average weight of the daily ASR generation in Australia is around 650 tonnes per day (See Section 1.4.3).

1.4.5 Economic issues of the current end-of-life vehicle treatment network

Waste management and resource recovery in Australia is administered by the State and Local Governments whereby the Commonwealth Government addresses issues of national significance (WME, 2009). While there are obvious common trends between the Australian States, each jurisdiction has its own policy framework and legislations. In recent years, a number of States and Territories have adopted zero waste policies and strategies (WME, 2009). As part of these strategies, the costs of landfill disposal have increased significantly in some States to minimise the amount of waste generation (see Section 1.4.4) and also to create further incentives for businesses that recycle waste materials (WAWA, 2013a, EPAVIC, 2013).

As presented in Table 1-9, the indicative landfill disposal cost of ASR is around $350 per tonne\(^1\) in NSW, of which half of that is related to the gate fee (which is charged by the landfill owner).

\(^1\) The actual cost of ASR disposal could be less than the estimated indicative cost of $350 per tonne as some shredders might dispose ASR in landfills located in the nearby States, which have no or very low landfill levy and/or have a
Given the current outlook for the landfill levy, which has an increasing trend (EPAVIC, 2013), the issue of high costs of ASR landfill disposal is intensifying in most Australian jurisdictions. The increasing cost of ASR reduces the financial performance of the metal shredding companies. This also financially effects other elements within the ELV recycling system including car dismantlers through the reduced price paid to them for the ELV hulks from the shredding plants. If this happens, the car dismantlers might offer a lower price to the cars’ last owners to purchase ELVs. This will reduce the willingness of some ELV owners to bring ELVs to car recyclers. This might lead to the illegal abandonment of some ELVs; in particular, those that are generated in the remote areas where the cost of transporting an ELV to a car recycler is high. These types of causal relationship will be further detailed in Chapter 6, when the sustainable business model for the implementation of identified ELV reclamation option is discussed.

It should be noted that the cost analysis provided in the above sections is based on the current classification of ASR in Australia as an ‘inert industrial waste’ and not as a hazardous waste. Whilst in the USA, under Federal standards, ASR is not classified a hazardous waste, it is classified as a hazardous waste in its State of California (DTSC, 2014). Some metals present in the ASR generated in California exceed hazardous waste regulatory thresholds of that State (DTSC, 2014).

If ASR is classified in Australia as hazardous (or called Prescribed Industrial Waste or PIW), the costs associated with the landfill disposal of ASR will be significantly increased in some jurisdictions. For example, the waste levy for PIW in Victoria in 2016, for the PIW category B (wastes from manufacturing industries and contaminated soils), is $250 per tonne of PIW (EPA VIC, 2016). If it is assumed that the other costs associated with landfill disposal of ASR in Victoria (e.g. the gate fee) are similar to those reported in Table 1-9, the indicative total costs of ASR treatment (classified as PIW) would be around $494 per tonne of ASR. There are some evidence that the current disposal costs of ASR in Australia (classified as an inert waste) is high for the Australian metal shredding plants (OneSteel, 2013). The ASR disposal costs would be more challenging for the Australian metal shredding plants if ASR is classified as hazardous waste (PIW).
1.5 KNOWLEDGE GAPS REGARDING SUSTAINABLE END-OF-LIFE VEHICLE RECLAMATION IN AUSTRALIA

As discussed in Section 1.4, the current Australian ELV recycling network (Figure 1-4) is unsustainable mainly because of the current landfill disposal of non-metallic materials of ELVs and the resource lost through ELV abandonment. There is no concern about the sustainability performance of the network with respect to the treatment of metallic materials of ELV (e.g. steel) as there are well-established infrastructures in Australia for the recovery of the metallic fraction of ELVs (Australian Government, 2002, Sustainability Victoria, 2014).

The sustainability performance of the current Australian ELV recycling network (Figure 1-4) can be improved through the replacement of the ASR landfill disposal with one of the international best practice ELV reclamation options (Table 1-6). However, the selection of one of the international best practice ELV reclamation options for Australia is a challenging task. Little knowledge exists within the Australian ELV recycling industry with respect to the best practice ELV reclamation options and little is known about the technical viability of the international ELV reclamation options in the Australian context.

Even with the identification of the technically viable ELV reclamation options in the Australian context, there are some challenges to identify one of the technically viable ELV reclamation options as the most sustainable ELV reclamation option in the Australian context. The sustainability assessment of the technically viable ELV reclamation options requires the application of a set of Australian-based sustainability indicators that cover the social, economic and environmental aspects of ELV reclamation. There is a significant discrepancy in early research studies focused on the ELV reclamation options with respect to the applied assessment indicators (Jenseit et al., 2003, Boughton and Horvath, 2006a, GHK/Bios, 2006, Mergias et al., 2007b, Jeong et al., 2007, Ciacci et al., 2010a, Morselli et al., 2010, Santini et al., 2012, Vermeulen et al., 2012e, Vermeulen et al., 2012b). Most of the comparative ELV reclamation studies have compared the ELV reclamation options based on the environmental assessment indicators. Only one study (Mergias et al., 2007), has applied the assessment criteria that encompasses the economic, social, and environmental factors.

There is also little known about the identification of a sustainable business model to implement a sustainable ELV reclamation in Australia (see Section 1.4.1). The scope of all previously
conducted comparative ELV reclamation studies has been limited to the assessment of a set of the ELV reclamation options for a region. No ELV reclamation study has yet developed a sustainable business model for the implementation of a selected ELV reclamation option.

1.6 AIM AND OBJECTIVES

The aim of the present research is:

- to identify a sustainable ELV reclamation option for Australia from a list of the international best practice ELV reclamation options as well as the identification of a sustainable business model for the implementation of the identified sustainable ELV reclamation option.

The objectives of the research are to identify the following:

- the international best practice ELV reclamation options
- a set of indicators to assess the technical viability of the international best practice ELV reclamation options in the Australian context
- the best practice ELV reclamation options that are technically viable in Australia
- a set of the Australian-specific indicators to assess the sustainability performance of the technically viable ELV reclamation options
- the most sustainable ELV reclamation option for Australia
- the existing international business models for the implementation of the selected sustainable ELV reclamation option
- a set of indicators to compare the performance of the identified business models in the Australian context
- the most sustainable business model for ELV reclamation in the Australian context

1.7 RESEARCH QUESTIONS

1.7.1 Which of the international best practice end-of-life vehicle reclamation options are technically viable in Australia?

The adopted ELV reclamation options vary among the countries. Not all of the internationally practiced ELV reclamation options are expected to be technically viable in Australia. The conditions in Australia for the application of a given ELV reclamation could be different from the
conditions in the country where that specific ELV reclamation has been implemented. For instance, remanufacturing of the auto parts made from non-metallic materials would be technically a viable ELV reclamation option in China where there are enough used parts for the remanufacturing of a specific car brand and mark. However, such an ELV reclamation option might not be a technically viable ELV reclamation option for Australia where the amount of the used parts for a specific car brand and mark would be very limited.

The present research will identify which of the international best practice ELV reclamation options are the most technically viable ELV reclamation options in the Australian context.

1.7.2 What are the most relevant indicators to assess the sustainability performance of the international best practice ELV reclamation options in the Australian context?

There are several existing comparative studies in which a set of ELV reclamation options have been compared against a set of assessment indicators (Jenseit et al., 2003, Boughton and Horvath, 2006a, GHK/Bios, 2006, Mergias et al., 2007b, Jeong et al., 2007, Ciacci et al., 2010a, Morselli et al., 2010, Santini et al., 2012, Vermeulen et al., 2012e, Vermeulen et al., 2012b).

The indicators used in the existing ELV reclamation studies cannot be directly used in the present research to assess the sustainability performance of the technically viable best practice ELV reclamation options in the Australian context. The majority of the indicators used in the existing studies are related only to the environmental dimension of sustainability. As such, broader indicators should be identified in this research to cover all of the sustainability dimensions (i.e. social, economic and environmental). Furthermore, whilst some of the existing indicators in the previously conducted ELV reclamation options were important in those studies, the indicators might not be important in the present research that is based on the Australian context. For instance, the land occupied by different waste treatment options is an important assessment indicator in the countries where land is scarce (e.g. Japan); whereas, the land requirement of the different waste treatment options has not yet been identified as a decision factor in the waste management studies conducted in Australia.
1.7.3 Which of the international best practice end-of-life vehicle reclamation options is the most sustainable end-of-life vehicle reclamation option for Australia?

Different ELV reclamation options might perform differently against a set of sustainability indicators. Some of the reclamation options might perform very well against the indicators representing the social dimension of sustainability while performing poor against the indicators representing other dimensions of sustainability. This is a major challenge to identify any of the ELV reclamation options without a comprehensive assessment through which the ELV reclamation options are fairly assessed against a set of sustainability indicators. The results of such assessment would identify the most sustainable ELV reclamation option in the Australian context.

1.7.4 What is the most sustainable business model to implement the selected most sustainable end-of-life vehicle reclamation option in Australia?

There is some evidence indicating that the success of a waste reclamation strategy is not only dependent on how sustainable is the strategy at the technology-level but it is also dependent on how the strategy is sustainable at the system-level. A proposed waste reclamation strategy might work perfectly in isolation but it might not able to sustain its operation when it interacts with other elements of its supply chain. A relevant example is the case of waste reclamation in the meat and poultry industry through the conversion of animal wastes to tallow and then the application of tallow as the feedstock for biodiesel production. A sudden increase in the price of tallow (from $600 per tonne to over $900 per tonne just a few months in 2007) forced many of the Australian biodiesel production plants to shut down. It was referred in the media at the time as “Australian biodiesel producers in Melt Down” (RENDER, 2007).

The process of resource recovery (biodiesel) from animal wastes (tallow) initially could have been regarded as a socially acceptable, economically viable, and environmentally compatible process. However, the sustainable process failed to maintain its operation because of some unexpected interaction (or feedback) from some elements within its system (the suppliers of raw materials).

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2 Two of the closed biodiesel production plants were: Australian Biodiesel Group, Ltd., (ABG) and Australian Renewable Fuels, Ltd., (ARF).
The selected ELV reclamation option in the present study could encounter problems similar to the problems which occurred to the detailed biodiesel production plants (e.g. shortage of feedstock) or could encounter other problems. The development of a sustainable business model for the implementation of the selected ELV reclamation option would minimise the risks associated with the undesirable interactions between the ELV reclamation plants and other elements of the Australian ELV recycling systems.

1.8 SCOPE

As reflected in its research questions, this thesis is an attempt to expand the existing boundaries surrounding sustainable management of an industrial waste from a ‘technology’ level to a ‘system’ level. The first three research questions are focused on the identification of waste treatment technology that is technically viable, environmentally effective, economically affordable and socially acceptable, and the fourth question is focused on the behaviour (i.e. value creation) of a system.

The expected audiences of the present research are the Australian ELV recycling industry, the Australian waste management industry, and the research community. The geographical scope of the research is the Australian States and Territories and the temporal scope of the research is the sustainable treatment of the passenger ELVs generated in Australia from 2015 to 2040. This timeframe is regarded as a reasonable temporal scope as the key attributes of the present research such as the ELV materials composition could be completely different from those attributes that are considered in the present research in 2040 and beyond.

This research is one of the four PhD research projects that are included in a national research cluster focused on the ELV treatment and management in Australia (Halabi and Doolan, 2013, Stasinopoulos et al., 2012, Lee et al., 2012a). The scope of the present research is limited to the investigation on the sustainability performance of ELV reclamation practices and ELV reclamation business models. The other aspects of ELV treatment and management in Australia (e.g. the most effective ELV legislation in Australia) are investigated in three other research studies of the national ELV research cluster.

The research is limited to the assessment of the international best practice ELV reclamation options that were listed in Table 1-6. The emerging ELV reclamation options listed in Table 1-7
Table 1-7 are not considered in the present research as the information related to the social, economic and environmental aspects of the technologies are very limited.

Whilst the process of sustainability assessment of the international best practice ELV reclamation options in the Australian context could be combined with the process of technical assessment of the reclamation options, the research separates these two processes, conducting the technical assessment of the reclamation options before assessing the options against a set of social, economic, and environmental indicators. The rationale for this sequence is to use the technical assessment process as a screening technique, by which international ELV reclamation options unlikely to be adopted by the Australian car recycling industry are identified, and then excluded from the sustainability assessment process.

The value created by the proposed business model (energy or material) will be considered in the research as an index to analyse the sustainability performance of the model. The main attention will be given in the research to the identification of the ‘behaviour over time’ pattern mode of the business model rather than to the calculation of the precise amount of the energy or material that is created by the proposed business model.

1.9 PLANNED OUTCOMES

The planned outcomes of this research are:

- Identification of the key social, economic and environmental issues associated with the current treatment of non-metallic materials of ELV in Australia
- Identification of the international best practice ELV reclamation options and the identification of those reclamation options that are technically viable in Australia
- Formulation of a set of Australian-specific sustainability indicators to assess the sustainability performance of the technically viable ELV reclamation options
- Identification of the most sustainable ELV reclamation for Australia
- Development and validation of a sustainable business model for the implementation of the identified sustainable ELV reclamation option for Australia
1.10 RESEARCH METHODOLOGY

The present research is carried out through five major stages as shown in Figure 1-5. Following the interpretation of the results of one stage, the key conclusions inform the subsequent stages. The research commenced with a comprehensive literature review. This includes the review of the ELV treatment practices in other countries and the ELV legislation at the global level. The literature review is continued throughout the research to help identify the required information. The goal and scope of the research are defined in the second stage. Furthermore, the stage identifies the key questions that the present research will answer.

![Diagram of research methodology]

The third stage of the research is focused on the technical assessment of the international best practice ELV reclamation options in the Australian context. Prior to the technical assessment, the key technical indicators relevant to the ELV recycling industry will be identified through a

Figure 1-5 An overview of the major stages involved in the research
comprehensive literature review. The international best practice ELV reclamation options will be assessed against the identified technical indicators and the best performed ELV reclamation options will be regarded as the most technically viable ELV reclamation options in the Australian context.

The technically-viable ELV reclamation options are carried into the fourth stage of the research in which their sustainability performance is assessed against a set of Australian-specific sustainability indicators. The preference was to identify the sustainability indicators from the existing ELV reclamation options, with supplementation if necessary with additional indicators identified by reviewing of existing waste management studies. The best performed ELV reclamation option in this stage was regarded as the most sustainable ELV reclamation option for Australia.

The last stage of the research identifies a sustainable business model for the implementation of the sustainable ELV reclamation in Australia. A comprehensive literature review will identify the existing business models relevant to the selected ELV reclamation option. These business models are assessed against a set of indicators that are essential for a successful business model. The sustainability performance of the best performed business model are assessed in the stage. Given the definition of a sustainable business model (see Section 1.4.1), the assessed business model is regarded as a sustainable business model for ELV reclamation in Australia if the business model can create value (material or energy) from non-metallic materials of ELVs and can demonstrate its robustness against some severe and unexpected conditions imposed by other business models.

1.11 GUIDE TO THESIS

The thesis consists of seven chapters. Chapter 1 initially provides an overview of the current ELV generation and treatment in Australia and elsewhere complemented with some relevant statistical data. The chapter then defines some of the terms associated with sustainability and describes the relevance of the terms with the present research. This is followed by providing a comprehensive overview of the major social, economic and environmental issues associated with the current treatment of non-metallic materials of ELV in Australia. The chapter then outlines the key knowledge gaps surrounding the process of selecting a sustainable ELV reclamation option for Australia. The goal and objectives of the present research are clearly described in the chapter along with the description of the four questions that the research is intending to address. The chapter
concludes with defining the scope of the research and outlines the planned outcomes of the research.

Chapter 2 summarises the existing body of knowledge and current research status in relation to the research topic through extensive literature review. The literature review covers four main aspects: (i) current ELV recycling network in Australia, (ii) international ELV legislation and voluntary ELV reclamation programs, (iii) the early research studies relating to the assessment of ELV reclamation options, and (iv) prospects for improving ELV treatment practices in Australia.

A particular attention will be given in Chapter 2 to the review of the existing ELV research studies from the different aspects including: (i) investigated ELV reclamation options, (ii) comparative and non-comparative studies, (iii) sustainability dimensions included in the studies, (iv) assessment indicators, (v) assessment level, (vi) assessment tools, (vii) decision-making methods, (viii) obtained results, (ix) sustainability assessment models, and (x) characteristics of successful business models.

Chapter 2 then presents the existing decision-making support frameworks (DSFs) for the comparative assessment of a set of waste treatment practices for a given region. The chapter then discusses that the existing DSFs are not applicable in the present research, mainly because the applied sustainability tools in the existing DSFs are irrelevant to the present research. The chapter also provides a comprehensive overview of the international best practice ELV reclamation options. This provides a context for the technical assessment of the reclamation options in Chapter 4.

Chapter 3 identifies all the existing sustainability assessment tools. The abilities of the individual sustainability assessment tools will be matched against the goal and objectives of the present research and the chapter will identify the most relevant sustainability assessment tools for the research. The chapter concludes with describing the stages included in the proposed decision-making support framework.

Chapter 4 will identify the technical indicators relevant to the ELV recycling industry. The identified technical indicators then will be used to assess the technical performance of the international best practice ELV reclamation options in the Australian context. The chapter will
regard the best performed ELV reclamation options, based on the criteria that will be defined in the chapter, as the most technically viable ELV reclamation options in the Australian context.

Chapter 5 initially will identify a set of Australian-specific sustainability assessment indicators and then will use the indicators to assess the sustainability performance of the technically viable ELV reclamation options in the Australian context. The chapter uses both existing and emerging sustainability assessment models to assess the sustainability performance of the ELV reclamation options. The chapter then compares the results of the assessment models to select the results that provide the highest confidence.

Chapter 6 initially contains a literature review to identify the existing business models of the identified sustainable ELV reclamation option and to identify the essential characteristics of a successful business model. The chapter then uses the identified characteristics as the assessment indicators for the comparative assessment of the identified business models. The best performed business model is advanced to the sustainability assessment stage in which the sustainability assessment of the business model is conducted through the application of the different sustainability assessment tools.

The sustainable business model is expected to create value (energy and material) over time and it should maintain its performance even in some severe conditions where other business models impose some undesirable effects. The chapter selects the energy or material production of the business model as the behaviour of the business model and plots the energy or material production over the assessment period. The developed behaviour-over-time pattern mode of the business model is used as the basis to decide on the sustainability performance of the business model.

Chapter 7 answers the research questions. The policy and research implications of the research are discussed in this chapter followed by the identification of the research limitations. The chapter then continues with a summary of the research conclusions and formulates a number of recommendations based on the research results. The chapter concludes with the identification of areas for future research.
2 End-of-life vehicle treatment: a literature review

2.1 INTRODUCTION

This chapter presents the results of an extensive literature review focusing on the various aspects of end-of-life vehicle (ELV) treatment both in Australia and elsewhere. The initial section of the chapter provides a comprehensive overview of the key elements of the current Australian ELV recycling network including car dismantlers, ELV shredding plants, post-shredding facilities, car manufacturers, and car insurance companies. This serves as the basis for a benchmarking between the Australian ELV recycling network and the ELV recycling networks in some other countries.

The second section of the chapter provides a comprehensive overview of the current international mandatory and voluntary ELV programs. These include review of the ELV mandatory policies in Japan, South Korea, China, Taiwan and the members of the European Union (EU) and the review of the voluntary ELV program in the United States. Furthermore, the chapter presents an overview of the current Australian product stewardship scheme. The section concludes by presenting the key challenges facing the countries with mandatory ELV legislation.

The chapter continues with an overview of the early research studies focused on ELV reclamation. These studies are analysed from different perspectives, including the sustainability domains that were included in the studies, the applied assessment tools, and the applied decision-making methods (e.g. expert opinion or group decision-making). The chapter concludes with a discussion of the current research gaps relating to sustainable ELV treatment and the context for this research.

The chapter then provides a comprehensive overview of the international best practice ELV reclamation options that were listed in Table 1-6. The overview includes some discussions about the challenges and opportunities associated with each individual ELV reclamation option in Australia.
2.2 END-OF-LIFE VEHICLE TREATMENT NETWORK

2.2.1 Dismantlers

The function of a car dismantling facility is to remove operating fluids and merchantable second-hand parts and prepare the vehicle for shredding. The main operations within a dismantling plant are shown in Figure 2-1. This figure represents an advanced car dismantling facility similar to those visited during the course of this study. Some of the Australian car dismantling facilities are small businesses with a limited number of personnel. As indicated in Figure 2-1, the processes involved in a car dismantling operation include removal of working fluids (Stage 1) and detachable parts such as car seats (Stage 2), removal of merchantable parts such as engines (Stage 3 to 5) and compressing ELV hulk at the final stage. The small-scale car dismantlers might not utilise all of the processes shown in Figure 2-1.

![Figure 2-1 A dismantler process flow (GITSRL, 2002)](image)

The precise number of Australian firms whose primary business is auto parts recycling is unknown, but a study conducted more than a decade ago (Australian Government, 2002) has reported that around 1000-1200 auto parts recycling firms are operating in Australia. Of those approximately 800-900 are regarded as ‘competent’ or legitimate operators (Australian Government, 2002). The relative portion of ‘illegitimate’ ELV businesses – a businesses without a licence to operate as an ELV treatment business– in Australia (around 20%) is less than the corresponding figure in some other countries that possess developed ELVs operations, such as
France and Belgium, where the ratio of the illegal dismantlers to the total dismantlers are 40% and 50% respectively (European Parliament, 2010).

The dismantling facilities in Australia are broadly divided into two main groups based on the type of their business model (Sustainability Victoria, 2007). The first group includes facilities that operate based on the concept of ‘self-service’ or ‘pick-a-part’ business model. This group deals with older vehicles (10-15 years or older). Customers remove the parts themselves and as such they may remove any parts that are of use to them – a switch, a brake disc or a whole engine. After a period of time or when all useful parts are removed, the remainder of the vehicle will be sold to a metal shredder.

In the second group that is regarded as a ‘conventional dismantling’ business model, the operation is mainly focused on younger vehicles. These vehicles are drained of fluids and merchantable parts are dismantled, catalogued and stored. The parts are then sold to the motor body or mechanical repair industries. Parts may include engines, transmissions, alternators, radiators, body panels or trim parts. When all marketable parts are removed, the ELV body is compressed and then transferred to a shredding plant for further processing.

2.2.2 Shredding plants

Following the dismantling stage, the compressed ELV hulk is sent to a shredding plant in which the ELV is crushed and shredded into small pieces. The product streams from a shredding plant are ferrous metals and nonferrous metals. These streams are shown in Figure 2-2.
As indicated in Figure 2-2, the ELV is conveyed to the pre-shredder box (the purple box at the left side of the figure) and then passed into an electrically-powered shredder supplied by the shredder power house. The dust generated is collected in the dust collection stage, and the magnetic separation drums separate ferrous metals and nonferrous metals. As discussed in Chapter 1, the stream from the aeraulic separator process is called automobile shredder residue (ASR). This stream is not shown in Figure 2-2.

The main Australian metal shredding companies are OneSteel, SIMS, Sell & Parker and Norstar. These companies operate 12 shredders in Australia (Australian Government, 2014b). These plants are mainly supplied by ELVs from the local dismantling facilities. However, some metal shredding facilities are supplied with ELVs directly from their final owners. In this case, the shredding facilities only remove hazardous materials and operating fluids, without removing marketable parts (Sustainability Victoria, 2007).

### 2.2.3 Car manufacturers

New vehicles sold in Australia are sourced from the local car makers and imported new cars. Approximately 86% of new cars sold in Australia are imported and the remaining are made by the
local car makers (DoIISRTE, 2012). In recent years, the relative contribution of locally-made cars in total sales has been declining (RAAI, 2008). This trend is expected to continue, even in a faster speed in the coming years, given the recent announcement by the local car makers, Ford Motor Company of Australia (Ford), General Motors Holden (Holden) and Toyota Motor Corporation Australia (Toyota) that the companies will close their car manufacturing plants in Australia in 2017 (Australian Government, 2014a). Australia is a very small player in the global context of automobile manufacturing. Around 85 million passenger and commercial vehicles are sold globally in 2013 (Australian Government, 2014a). Australia’s new vehicle sales of just over 1 million units were about 1.3 per cent of the total vehicles sold globally in 2013. Australia’s share of global production, at just over 200,000 units, was about 0.25 per cent in 2013 (Australian Government, 2014a).

2.2.4 Car insurance companies

The car insurance companies can play an important role in the management of non-metallic materials of ELVs in Australia. They can develop and apply policies by which the applications of some second-hand parts (e.g. bumpers) are promoted in the auto repair shops. However, at present, there is no evidence indicating that the car insurance companies in Australia have developed such policies.

Another way in which the car insurance companies can contribute to the management of non-metallic materials of ELVs is via the ‘written-off’ vehicles. Limited studies have been conducted to measure the average age of the ELVs entering the Australian recycling systems. A study conducted in the State of Victoria (Sustainability Victoria, 2007) reported that approximately 4% of ELVs treated in the State have an average age of less than five years (Figure 2-3). Given the relatively high financial value of young cars, it can be assumed that most of the ELVs of age less than five years possess insurance policies. The decision made by an insurance company to sell their ELVs directly to the official (or registered) dismantlers or sell them at public auctions, where anyone can purchase the written-off vehicles. If the written-off vehicles are sold to the legitimate car dismantlers, the likelihood of reusing auto parts would be higher than if the ELVs are sold to the competitors of car dismantlers at public auctions.
2.3 BENCHMARKING THE AUSTRALIAN END-OF-LIFE VEHICLE RECYCLING INDUSTRY

According to Halabi and Doolan (2013) the automobile recycling in Australia comprises 793 legitimate firms employing around 3400 people. This corresponded to an average number of 4 employers per each firm. The ratio between the number of ELV shredding plants and the number of car dismantlers in Australia is relatively higher than the corresponding ratio in some European countries (Table 2-4) (Australian Government, 2014b, European Parliament, 2010, EFR, 2007).

<table>
<thead>
<tr>
<th>Country</th>
<th>No. of legitimate dismantling plants</th>
<th>No. of ELV shredding plants</th>
<th>Average no. of dismantlers per one ELV shredder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>1178</td>
<td>45</td>
<td>26</td>
</tr>
<tr>
<td>France</td>
<td>1000</td>
<td>54</td>
<td>18</td>
</tr>
<tr>
<td>Italy</td>
<td>1800</td>
<td>53</td>
<td>34</td>
</tr>
<tr>
<td>Spain</td>
<td>540</td>
<td>26</td>
<td>21</td>
</tr>
<tr>
<td>UK</td>
<td>732</td>
<td>35</td>
<td>21</td>
</tr>
<tr>
<td>Australia</td>
<td>800-900</td>
<td>11</td>
<td>77</td>
</tr>
</tbody>
</table>

As indicated in Table 2-1, the number of car dismantlers per ELV shredder in Australia is approximately three to four times more than the corresponding figures in the compared European countries.
countries. This implies a relatively strong competition between the car dismantlers in Australia to sell ELVs to a particular shredder.

Another important characteristic of the Australian ELV recycling industry, as indicated in Table 2-2, is the relatively low number of the ELVs that are treated by one car dismantler. The corresponding number is higher than the US, Canada, and UK.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of legitimate dismantlers</td>
<td>800-900</td>
<td>3000-6000</td>
<td>400</td>
<td>732</td>
</tr>
<tr>
<td>ELV treated per dismantler</td>
<td>600</td>
<td>1600</td>
<td>1000</td>
<td>2883</td>
</tr>
</tbody>
</table>

* The number in the bracket indicates the year in which the respected data is related

The number of ELVs per one specific car brand is also lower in Australian than in comparison to the USA, Canada, and the UK (Table 2-3). As indicated in Table 2-3, in 2013, around 1.1 million new cars, from 67 different vehicle brands, were sold in Australia. This will result in the generation of around 16.6 thousand ELVs when the sold vehicles are retired. The figure (the ELV generation rate per one vehicle brand in Australia) is higher than the corresponding figure in the USA, Canada, and the UK.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Australia</th>
<th>USA</th>
<th>Canada</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of vehicle brands</td>
<td>67</td>
<td>51</td>
<td>49</td>
<td>53</td>
</tr>
<tr>
<td>Number of the total sold vehicles</td>
<td>1,112,032</td>
<td>13,040,632</td>
<td>1,620,221</td>
<td>2,249,483</td>
</tr>
<tr>
<td>ELV per one vehicle brand*</td>
<td>16,597</td>
<td>255,699</td>
<td>33,066</td>
<td>42,443</td>
</tr>
</tbody>
</table>

* Assuming an equivalent market share for each car brand in the countries
Chapter 2

2.4 END-OF-LIFE VEHICLE LEGISLATION

2.4.1 Mandatory product stewardship schemes related to vehicle

2.4.1.1 Extended producer responsibility in Europe

Product stewardship is an environmental policy approach based on a ‘shared responsibility’ between the manufacturer and the relevant stakeholders of a product, with respect to the management of toxic materials contained in a product and the management of the product at its end-of-life stage (Wagner et al., 2013). In a more responsive form, when the producer takes the whole responsibility, a product stewardship policy is called an extended producer responsibility (EPR) policy (Oliveira et al., 2012).

The number of products covered by the product stewardship schemes (or extended producer responsibility) is increasing. For example, in Canada alone, as of 2011, there were approximately 65 mandated producer responsibility programs (Hickle, 2013). According to Oliveira et al. (2012), recycling of discarded electronics products (e-waste), mainly through product stewardship schemes, is expanding in both developed countries and in developing countries located in Africa, Asia and Latin America.

According to a number of publications (Chen and Zhang, 2009, European Parliament, 2010, Gerrard and Kandlikar, 2007, Mazzanti and Zoboli, 2006), product stewardship schemes are the main government policy for recovery of non-metallic materials of ELVs in Europe, Japan, South Korea, and China. Such scheme requires development and implementation of effective strategies from all participants within the car supply chain. For example, the automobile industry has adopted different strategies including design-focused strategies (e.g. design for recycling). According to Mayyas et al. (2012), some of the car makers in Europe (including Volvo and Ford) have integrated ELV reclamation in the design stage of their products. The sustainability index (SI) developed by Ford of Europe (Schmidt, 2006, Schmidt et al., 2004) is one of the automobile industry’s attempts to integrate sustainability and product recovery in the vehicle design process.

Extended producer responsibility (EPR) in the car industry was first introduced in Europe, where each year approximately 14 million vehicles become retired (European Parliament, 2010). Some of these ELVs are exported outside of the European Union while some of them are treated within
the Member States (MS) of the Union. The information related to the ELVs generated and treated in some Member States are shown in Table 2-4.

<table>
<thead>
<tr>
<th>Country</th>
<th>Approximate number of ELVs generated (Thousand ELVs/year)</th>
<th>Approximate number of ELVs treated within or outside the MS (Thousand ELVs/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>254</td>
<td>64</td>
</tr>
<tr>
<td>Belgium</td>
<td>455</td>
<td>141</td>
</tr>
<tr>
<td>Denmark</td>
<td>302</td>
<td>101</td>
</tr>
<tr>
<td>Italy</td>
<td>1,796</td>
<td>1,203</td>
</tr>
<tr>
<td>Netherlands</td>
<td>209</td>
<td>152</td>
</tr>
<tr>
<td>Sweden</td>
<td>950</td>
<td>150</td>
</tr>
</tbody>
</table>

When the ELV generation rates presented in Table 2-4 are compared to the ELV generation rate in Australia (around 600 to 700 thousand units per year), only Sweden and Italy generate more ELVs than Australia. This implies that ELV legislations can be imposed in a country regardless of the size of ELV generation volume in that country.

The Member States of the European Union approved the EPR-based ELV legislations called the European Union ELV Directive (2000/53/EC). The legislations are implanted through a planned timeframe starting in 2002 and completed in 2015. This timeframe along the ELV recovery targets in each of the implementation phases is shown in Figure 2-4.
According to the ELV Directive, the EU Member States are required to establish a collection system for ELVs and ensure that all vehicles are transferred to authorized treatment facilities through a system of vehicle deregistration based on a certificate of destruction (Directive, 2000). The last holder of an ELV may dispose of it free of charge ("free take-back"). Vehicle dismantlers must obtain permits to handle ELVs. Under Annex I of the Directive, storage and treatment of ELVs are strictly controlled through depollution procedures and designated parts removal requirements. Vehicle manufacturers are obligated to compile specific data and report regularly to the designated authorities.

2.4.1.2 Product stewardship schemes in Asia

Four countries in Asia have ELV legislation based on the concept of extended producer responsibility for recovery of the non-metallic fraction of ELVs (Japan, South Korea, China and Taiwan). Japan was the first country in Asia that applied extended producer responsibility in the automobile industry. Japan’s Law for the Recycling of End-of-life Vehicles was approved in 2002 but put into practice from 2005 (Wang and Chen, 2013). The law was prompted by the problem of insufficient landfill space, which led to illegal disposal of ASR generated when vehicles are scrapped (Zhao and Chen, 2011). The law is based on a "shared responsibility" principle: consumers in Japan pay a fee when they purchase a new car or at the time of mandated regular inspection. The fee is managed by a third party, the Japan Automobile Recycling Promotion
Centre (JARC). An electronic manifest system is used to help ensure ELVs are properly recycled. Law in Japan also mandates the final disposition of the air conditioning gases of CFCs/HFCs, shredder residue, and airbags from vehicles (USEPA, 2013).

The ELV management in South Korea was regulated in 2007 by the *Circulation of Resource from ELV and WEEE ACT* (Wang and Chen, 2013). The act was modelled based on the EU’s initiative and required the recovery and the recycling target rates for ELVs as 80% and 85%, respectively, beginning from January 1, 2009 to December 31, 2014, and 85% and 95%, respectively, after January 1, 2015 (Wang and Chen, 2013). The ELV recycling legislation in South Korea includes five major requirements for both car producers and car importers. These are restrictions on the use of hazardous substances (e.g. heavy metals), improvement to materials and structure for ease of recycling (e.g. using fewer and more easily recyclable materials), separate collection of waste products, and a mandatory recycling rate (RsjTechnical, 2012).

The rapid expansion of the vehicle fleet in China will lead to a significant amount of ELVs in years to come (Chen et al., 2015). Around 121 million passenger cars were registered in China in 2012, of which around 4.8 million vehicles became ELV on that year and only one-fourth of them were formally recycled (Chen et al., 2015). The majority of ELVs possibly escaped into the black market (Chen et al., 2015). China enacted ‘End-of-Life Vehicle Recycling Regulations’ in 2001. ‘End-of-Life Vehicle Recycling Regulations’ mainly stipulates scrap automobile recycling businesses access conditions including registration capital of more than $8000, the area for dismantling activities of more than 5000 m\(^2\), the dismantling capacity of more than 500 vehicles/year, and the enterprise should have more than 20 employees, including more than five technicians. There must be no illegal dismantling activities and the enterprise must meet national environment protection standards (Zhao and Chen, 2011).

The recycling of ELVs in Taiwan has gradually become systematic since the publishing of ‘End-of-life vehicle recycling guidelines’ in 1994 (Chen et al., 2010). The Recycling Fund Management Board (RFMB) was established in Taiwan in 1998 to collect a Collection–Disposal–Treatment Fee (recycling fee) from responsible enterprises for recycling and related tasks. Since then, the recycling channels, processing equipment, and techniques for ELVs in Taiwan have gradually become established (Chen et al., 2010). The management of ASR, which is estimated to be produced annually around 40 to 60 thousand tonnes, is still a major concern in Taiwan (Tai and He, 2015).
2.4.2 Voluntary programs for end-of-life vehicle treatment

Approximately 7.7 million ELVs from passenger cars were recycled in the US in 2008 (Amelia et al., 2009). Unlike the EU countries, Japan, and Korea, ELV recovery in the United States is driven by the market rather than by government regulation (Amelia et al., 2009). The focus of most ELV recycling programs at the national level in the United States has been on voluntary measures to address contaminants of particular concern or to further specific recycling goals (USEPA, 2013). The recent ELV related initiatives in the US include a voluntary effort to promote safe removal of mercury switches from ELVs before they are shredded for recycling and a national program focusing on vehicle tyres recycling (USEPA, 2013). Some of the States in the US apply automobile shredder residue (ASR) as alternative daily cover in landfill sites (Boughton and Horvath, 2006a).

2.4.3 Product stewardship schemes in Australia

Australia has recently approved the Product Stewardship Act 2011 as a key commitment under the Australian Government's long-term National Waste Policy to avoid and reduce the amount of waste generated and increase the amount of resources recovered from end-of-life products (Australian Government, 2012). The Product Stewardship Act 2011 includes voluntary, co-regulatory and mandatory product stewardship. To date several products have been covered by the Act including televisions and computers. The National Television and Computer Recycling Scheme involves a combination of government regulation and industry action to take responsibility for the collection and recycling of waste televisions, computers, printers and computer products. According to this scheme, households and small businesses can drop off these items for free at designated access points, which may include permanent collection sites, take-back events or through a mail-back option.

While ELVs have not been included yet in the Australian product stewardship scheme, an industry-government working group has finalised guidelines describing the operations of an industry-led tyre product stewardship scheme (SEWPaC, 2013). The scheme aims to increase domestic tyre recycling, expand the market for tyre-derived products and reduce the number of Australian end-of-life tyres that are sent to landfill, illegally dumped or exported as bald tyres for environmentally unsustainable use.
2.4.4 Unsuccessful attempt in Malaysia to establish end-of-life vehicle legislation

An unsuccessful attempt was made in Malaysia in 2009 to establish the ELV legislation in the country (Azmi et al., 2013). The public rejected the proposed ELV legislation as they believed that the legislation had been introduced without proper research (Azmi et al., 2013). Several research studies since then have been conducted in Malaysia. These studies will be further discussed in Section 2.7.1.

2.4.5 Challenges facing the international vehicle product stewardship schemes

The countries and regions with ELV legislations (i.e. the EU, Japan, Korea, China, and Taiwan) have experienced some challenges in meeting the requirements of their ELV recycling legislations. Some of these challenges are similar among the countries and regions and some of the challenges are specific to each country and region (Sakai et al., 2014).

One of the common challenges is meeting the ELV recycling targets. Most of the countries aim to recycle 95% of the mass of an ELV. An international workshop aimed to gather data and to discuss the international ELV recycling systems concluded that apart from Japan, the difficulties associated with the recycling of ASR is the main problem to meet the recycling target for the countries and regions with ELV recycling legislations (Sakai et al., 2014). The workshop also concluded that ASR recycling is becoming increasingly important in the total ELV recycling lately, since the types of materials in ASRs have become diversified due to the employment of lightweight materials to improve fuel efficiency.

The EU legislations in the EU are based on two main directions: (i) intensive dismantling involving the separation and collection of materials at the dismantling stage; and (ii) post-shredder treatments (PSTs) involving the collection of materials from ASR after the shredding stage (Sakai et al., 2014). There are some concerns about the economic efficiency of the intensive dismantling direction (Vermeulen et al., 2012d). Given the increasing labour costs and the fall in the price of collectable materials, the approach of intensive dismantling might not be regarded in the future as

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3 International Workshop on 3R Strategy and ELV Recycling 2012 that was held in Nagoya, Japan, from September 19-21, 2012.
an efficient approach. As such, the EU might experience some serious challenges to meet its ELV recycling target of 95%.

In Japan, the thermal recovery of ASR is commonly practiced, and the total ELV recovery rate is approximately 99% (Yoshida and Hiratsuka, 2012). The high ELV recovery rate in Japan is due to a recycling system that incorporates cost incentives and promotes transparency of information, and regulation permits the thermal recycling of ASR mixed with other wastes (Yoshida and Hiratsuka, 2012).

In China, several problems on ELV recycling are reported. Cases reported are (i) ELVs ending up in the used car market and are being used illegally, (ii) improper recycling processes that are causing serious environmental pollution at the facilities, (iii) illegal extension of the life time of a vehicle without permission, and (iv) illegal remanufacturing (Sakai et al., 2014). Such cases were pointed out to occur in the absence of a comprehensive management system (Li, 2012).

It would be very challenging for South Korea to achieve its target of recycling 95% of an ELV weight (Sakai et al., 2014). This is due to several factors including (i) the presence of the undefined takers of responsibility for the achievement of the target, (ii) inadequate recyclers who are incapable of carrying out sound recycling, and (iii) the improper treatment of ASR and refrigerants (GJ, 2012). The Korean ELV recycling system has two-sided characteristics; on one side the recyclers assume the responsibility of carrying out recycling if the ELV is economically valuable and on the other side manufacturers assume such responsibility if the recycling incurs cost (GJ, 2012). Thus the system makes it unclear whose responsibility it is for achieving the target. In addition, less valued or costly materials are likely to be avoided during the dismantling process, since those components that are of higher value are preferentially separated (GJ, 2012). This tendency leads to a lower recycling rate.

The ELV legislations in Taiwan exclude mandatory ELV recovery rates of 95%. However, the desirable efficiency of the current legislations has been questioned mainly because of the environmental issues associated with the current ASR treatment practices in the country. In addition, research in Taiwan has shown that ASR should be regarded as a commodity for the country not a waste (Tai and He, 2015). Landfill disposal is the dominant ASR treatment practice in Taiwan with some ASR being burnt in the municipal incineration plants that mostly do not include the energy recovery systems. Both practices treat around 40–60 thousand tonnes of ASR
that are produced annually in the country (Tai and He, 2015). Disposing of ASR in landfill in a high populated country that has a small area (Tai and He, 2015) can be regarded as an inefficiency of the current ELV legislations in Taiwan.

2.5 REVIEW OF THE END-OF-LIFE VEHICLE RECLAMATION STUDIES

2.5.1 Investigated end-of-life vehicle reclamation options

The investigated ELV reclamation options in the research studies conducted during 2000-2015 are summarised in Table 2-5 (Cossu and Lai, 2015). As indicated in Table 2-5, there is a growing trend in the number of the ELV reclamation studies, especially since 2011. Among the investigated ELV reclamation options, the ELV reclamation options of ‘thermo-chemical treatment of ASR’ and ‘mechanical-physical separation processes’ possess the highest number of the research studies. The former ELV reclamation option has been the subject of 20 research studies and the former ELV reclamation option has been the subject of 15 research studies.

2.5.2 Comparative and non-comparative end-of-life vehicle studies

The previously conducted ELV reclamation studies can be classified into two main categories: (i) comparative studies (Jenseit et al., 2003, Boughton and Horvath, 2006a, Mergias et al., 2007b, Ciacci et al., 2010a, Morselli et al., 2011, Santini et al., 2012, Vermeulen et al., 2012e), and (ii) non-comparative studies (Roy and Chaala, 2001b, Rossetti et al., 2006, Boughton, 2007a, Reddy et al., 2007, Viganò et al., 2010, Vermeulen et al., 2012c, Cossu and Lai, 2013).

In the comparative ELV reclamation studies, two or more ELV reclamation options have been compared against a set of assessment indicators, whereas in the non-comparative ELV reclamation studies, the various aspects of a particular ELV reclamation option (e.g. ASR reclamation by cement kiln) has been investigated.
<table>
<thead>
<tr>
<th>Time</th>
<th>Pre-treatment before further processes or disposal</th>
<th>Mechanical-physical separation processes to recover recyclables materials (e.g. plastics)</th>
<th>Recovery by incorporation into manufactured products (composites, asphalt, concrete)</th>
<th>Thermal treatment and co-incineration with other waste streams</th>
<th>Reuse in metallurgical processes</th>
<th>Thermo-chemical treatment (pyrolysis, gasification, hybrid processes)</th>
</tr>
</thead>
</table>
2.5.3 Sustainability dimensions included in the comparative end-of-life vehicle reclamation studies

The considered sustainability dimensions in the previously conducted comparative ELV reclamation studies are listed in Table 2-6.

<table>
<thead>
<tr>
<th>Study</th>
<th>Authors (Year)</th>
<th>Sustainability dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental assessment of shredder residue management.</td>
<td>Boughton and Horvath (2006a)</td>
<td>Environmental</td>
</tr>
<tr>
<td>A study to examine the benefits of the End of Life Vehicles Directive and the costs and benefits of a revision of the 2015 targets for recycling, reuse and recovery under the ELV Directive.</td>
<td>GHK/Bios (2006)</td>
<td>Environmental and economic</td>
</tr>
<tr>
<td>Multi-criteria decision aid approach for the selection of the best compromise management scheme for ELVs: The case of Cyprus.</td>
<td>Mergias et al., (2007)</td>
<td>Environmental, social, and economic</td>
</tr>
<tr>
<td>A comparison among different automotive shredder residue treatment processes.</td>
<td>Ciacci et al. (2010a)</td>
<td>Environmental</td>
</tr>
<tr>
<td>LCM applied to Auto Shredder Residue (ASR).</td>
<td>Morselli et al. (2011)</td>
<td>Environmental</td>
</tr>
<tr>
<td>Auto shredder residue recycling: Mechanical separation and pyrolysis.</td>
<td>Santini et al. (2012)</td>
<td>Environmental</td>
</tr>
<tr>
<td>Environmental impact of incineration of calorific industrial waste: Rotary kiln vs. cement kiln</td>
<td>Vermeulen et al. (2012e)</td>
<td>Environmental</td>
</tr>
<tr>
<td>Sustainability assessment of industrial waste treatment processes: The case of automotive shredder residue</td>
<td>Vermeulen et al. (2012b)</td>
<td>Environmental, social, and economic</td>
</tr>
</tbody>
</table>

As indicated in Table 2-6, the majority of the previously conducted ELV studies (six studies out of the ten listed studies) are based entirely on environmental dimension of sustainability. Only two
studies (Mergias et al., 2007b, Vermeulen et al., 2012b) have included the social, environmental and economic domains in their studies. The remaining studies, (two studies) are the eco-efficiency type studies that integrate both environmental and economic domains.

One of the most comprehensive studies among the studies listed in Table 2-6 is the study conducted by GHK/Bios (2006). This study was prepared for the European Commission conducted by two international consulting firms of GHK and Bios and was focused on firstly reporting the economic and environmental benefits arising from the ELV Directive up to 2006 and secondly an appraisal of the costs and benefits of a range of potential targets for reuse, recycling and recovery of ELVs from 2015. Given the comprehensives of this study, it has been used extensively in this research for the purpose of comparing the environmental and economic performance of different ELV reclamation options.

2.5.4 Assessment indicators

The assessment indicators vary among the comparative ELV reclamation studies. The considered sustainability indicators in the previously conducted ELV reclamation studies are summarised in Table 2-7. As indicated in Table 2-7, some of the assessment indicators such as greenhouse gas (GHG) emission or the climate change indicator has been considered more than some assessment indicators such as the assessment indicator of ‘safety’.

2.5.5 Assessment levels

The previously conducted comparative ELV treatment studies (Table 2-6) have all been focused on the process-level only (i.e. technology assessment). None of the studies attempted to investigate the performance of the selected ELV reclamation option at the system level (i.e. the assessment of the interactions between the selected ELV reclamation option and other elements of an ELV recycling network).
Table 2-7 Assessment indicators that have been used in the previously conducted ELV reclamation studies

<table>
<thead>
<tr>
<th>Assessment indicator</th>
<th>Study in which the indicator has been applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG emissions/climate change</td>
<td>(Ahmed et al., 2016, Vermeulen et al., 2012e, Vermeulen et al., 2012a, Morselli et al., 2011, Ciacci et al., 2010b, Jeong et al., 2007, GHK/Bios, 2006, Boughton and Horvath, 2006b)</td>
</tr>
<tr>
<td>Water conversations</td>
<td>(Ahmed et al., 2016, Vermeulen et al., 2012a, Morselli et al., 2011, Ciacci et al., 2010b, Jeong et al., 2007, GHK/Bios, 2006, Boughton and Horvath, 2006b)</td>
</tr>
<tr>
<td>Energy use</td>
<td>(Ahmed et al., 2016, Vermeulen et al., 2012a, Morselli et al., 2011, Ciacci et al., 2010b, Jeong et al., 2007)</td>
</tr>
<tr>
<td>Human toxicity</td>
<td>(Ahmed et al., 2016, Ciacci et al., 2010b)</td>
</tr>
<tr>
<td>Solid waste residues</td>
<td>(GHK/Bios, 2006, Mergias et al., 2007a)</td>
</tr>
<tr>
<td>Air pollution</td>
<td>(Ahmed et al., 2016, Mergias et al., 2007a)</td>
</tr>
<tr>
<td>Noise pollution</td>
<td>(Ahmed et al., 2016, Mergias et al., 2007a)</td>
</tr>
<tr>
<td>Depletion of minerals</td>
<td>(Ahmed et al., 2016, Ciacci et al., 2010b, Morselli et al., 2011, Vermeulen et al., 2012a)</td>
</tr>
<tr>
<td>Depletion of fossil fuels</td>
<td>(Ahmed et al., 2016, Morselli et al., 2011, Vermeulen et al., 2012a)</td>
</tr>
<tr>
<td>Land requirement</td>
<td>(Ciacci et al., 2010b, Mergias et al., 2007a, Vermeulen et al., 2012a)</td>
</tr>
<tr>
<td>Social acceptance</td>
<td>(Ahmed et al., 2016)</td>
</tr>
<tr>
<td>Treatment costs</td>
<td>(Ahmed et al., 2016, Ciacci et al., 2010b, Mergias et al., 2007a, Vermeulen et al., 2012a)</td>
</tr>
<tr>
<td>Safety</td>
<td>(Ahmed et al., 2016)</td>
</tr>
<tr>
<td>Health risks</td>
<td>(Ahmed et al., 2016)</td>
</tr>
<tr>
<td>Aesthetic harmful effect</td>
<td>(Mergias et al., 2007a)</td>
</tr>
<tr>
<td>Acidification/Eutrophication</td>
<td>(Boughton and Horvath, 2006b, GHK/Bios, 2006, Jeong et al., 2007, Morselli et al., 2011, Vermeulen et al., 2012e)</td>
</tr>
<tr>
<td>Radiation</td>
<td>(Morselli et al., 2011)</td>
</tr>
<tr>
<td>Depletion of the ozone layer</td>
<td>(Jeong et al., 2007, Morselli et al., 2011, Vermeulen et al., 2012c)</td>
</tr>
<tr>
<td>Creation of photochemical smoke</td>
<td>(Boughton and Horvath, 2006b, GHK/Bios, 2006, Jeong et al., 2007)</td>
</tr>
<tr>
<td>Water pollution</td>
<td>(GHK/Bios, 2006, Boughton and Horvath, 2006b)</td>
</tr>
</tbody>
</table>
### 2.5.6 Assessment tools

The assessment tools applied in previously conducted comparative ELV reclamation studies are presented in Table 2-8. As indicated in Table 2-8, the life cycle assessment tool is the most dominant tool in the comparative studies followed by the multi-criteria analysis tool.

### 2.5.7 Decision-making methods

All of the previously conducted comparative ELV reclamation studies (Table 2-6) are based on the expert opinion as the predominant decision-making approach. The expert, as defined by Krueger et al. (2012), is someone having specialist knowledge acquired through practice, study, or experience. It can be assumed that the author(s) of these studies have the expertise required for making the various decisions required in the studies. Those aspects of the ELV reclamation studies that the expert opinion approach has been applied as a decision-making method are: (i) selection of a set of ELV treatment options for the assessment (Ciacci et al., 2010b, Mergias et al., 2007a, Jeong et al., 2007, GHK/Bios, 2006), (ii) selection of the assessment indicators (Vermeulen et al., 2012a, Mergias et al., 2007a), and (iii) weighting the assessment indicators (Mergias et al., 2007a).

None of these studies have applied the collective decision-making approaches (i.e. decision-making involving stakeholders) (Voinov and Bousquet, 2010), such as the Delphi method (Seuring and Müller, 2008). The application of the collective decision-making approaches in the context of the ELV treatment studies is emerging. For example, Halabi and Doolan (2013) have included the ELV stakeholders in their study focused on the development of a policy decision tool that helps stakeholders in the Australian automobile recycling sector discuss policy options and their implications.
### Table 2-8 Sustainability dimensions considered in some comparative ELV reclamation studies

<table>
<thead>
<tr>
<th>Study</th>
<th>Authors (Year)</th>
<th>Assessment Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>A study to examine the benefits of the End of Life Vehicles Directive and the costs and benefits of a revision of the 2015 targets for recycling, reuse and recovery under the ELV Directive.</td>
<td>GHK/Bios (2006)</td>
<td>Cost-benefit analysis</td>
</tr>
<tr>
<td>Multi-criteria decision aid approach for the selection of the best compromise management scheme for ELVs: The case of Cyprus.</td>
<td>Mergias et al. (2007b)</td>
<td>Multi-criteria analysis</td>
</tr>
<tr>
<td>A comparison among different automotive shredder residue treatment processes.</td>
<td>Ciacci et al. (2010a)</td>
<td>Life cycle assessment</td>
</tr>
<tr>
<td>LCM applied to Auto Shredder Residue (ASR).</td>
<td>Morselli et al. (2011)</td>
<td>Life cycle assessment</td>
</tr>
<tr>
<td>Auto shredder residue recycling: Mechanical separation and pyrolysis.</td>
<td>Santini et al. (2012)</td>
<td>Life cycle Assessment</td>
</tr>
<tr>
<td>Environmental impact of incineration of calorific industrial waste: Rotary kiln vs. cement kiln</td>
<td>Vermeulen et al. (2012e)</td>
<td>Life cycle assessment</td>
</tr>
<tr>
<td>Sustainability assessment of industrial waste treatment processes: The case of automotive shredder residue</td>
<td>Vermeulen et al. (2012b)</td>
<td>Multi-criteria analysis</td>
</tr>
</tbody>
</table>
2.5.8 Obtained results

A comparison between the results of the previously conducted ELV reclamation studies is a challenging task as different ELV reclamation options and different assessment indicators have been used in the studies. The task is still challenging to compare the results of the studies that are similar in either the considered ELV reclamation options or in the applied assessment indicators (Ciacci et al., 2010a, GHK/Bios, 2006, Passarini et al., 2012, Santini et al., 2012, Vermeulen et al., 2012e). This is mainly attributed to the applications of different system boundaries or the consideration of different assumptions. Therefore, sufficient attention should be paid to the interpretation of the results obtained from the early ELV research studies.

2.5.9 Sustainability assessment models

Two different sustainability assessment models have been used in the previously conducted ELV reclamation options. The first model that is often called triple bottom line (TBL) has been used in the research by Mergias et al. (2007a) and the second model that is referred in the present research as the ‘multi-dimensionality’ model has been used in the research by Vermeulen et al. (2012b).

In the model of TBL, a sustainability indicator can only represent one dimension of sustainability (i.e. social, economic and environmental); whereas, in the multi-dimensionality model, a sustainability indicator can represent more than one dimension of sustainability. The difference can be elaborated through providing an example in which ‘water consumption’ is regarded as a sustainability indicator. The example is supported by Figure 2-5 and Figure 2-6 in which the three dimensions of sustainability are represented as three circlers. As shown in Figure 2-5 (for the TBL model), the indicator is inside a circle labelled ‘environmental’. This indicates that the indicator represents only the environmental dimension of sustainability. However, in Figure 2-6 (for the multi-dimensionality model), the indicator is in the overlap area between the ‘economic’ and ‘environmental’ circles. This indicates that the indicator represents both the economic dimension and the environmental dimension of sustainability. Further information about the rational for this representation will be provided in Chapter 5.
The TBL model is an established sustainability assessment model and has been used in many waste management studies. The recent studies in which the TBL model has been applied to assess the sustainability performance of a set of waste treatment technologies are: Venkatesh et al. (2015), Schimmoller et al. (2015), Plakas et al. (2015), and Elenbaas et al. (2015). As opposed to the TBL model, the multi-dimensionality model is an emerging model and only has been applied in the ASR treatment practices conducted by Vermeulen et al. (2012b).
2.5.10 Characteristics of the successful business models for ELV reclamation

Sustainable business models have been the subject of several research studies. Most of the studies (Bocken et al., 2014, Casadesus-Masanell and Ricart, 2011, Osterwalder and Pigneur, 2010, Lüdeke-Freund, 2010, Osterwalder et al., 2005) provide information on how to develop a business model and what should be the characteristic of a successful business model. Only one study (Bohnsack et al., 2014) is focused on the development of a sustainable business model for a specific technology. The study provides information about the evolution of electric vehicle business model.

In the context of sustainable business models for waste treatment technologies, there is a lack of publicly available studies in which a business model has been identified as the most sustainable business model for the implementation of a waste treatment practice in a given region. This includes the studies related to the treatment of the waste generated in the ELV recycling industry.

There is also a limited number of the studies in which a set of assessment indicators has been introduced to compare the effectiveness of different business models. Only the research by Casadesus-Masanell and Ricart (2011) provides the key general characteristics of the successful business models. It appears that the research has identified the characteristics through a comprehensive analysis of a number of the successful business models. The research provides an in-depth analysis of the feedback loops related to each of the reviewed business models and the role that the identified characteristics played in the success of the business models.

The three key characteristics of a successful business model, according to the research by Casadesus-Masanell and Ricart (2011), are: being aligned with the company’s goal, being self-reinforced, and being robust.
2.6 OVERVIEW OF THE INTERNATIONAL BEST PRACTICE END-OF-LIFE VEHICLE RECLAMATION OPTIONS

2.6.1 Deep ELV dismantling for the collection and reuse of non-metallic parts

Little information is available about the reuse rate of auto-parts made from metallic materials both in Australia and internationally. A study conducted in the United States (Duranceau, 1999) estimated the reuse rates for the top 20 components of ELVs (Figure 2-7).

![Figure 2-7 Reuse rate of the automobile parts in the United States (Duranceau, 1999)](image)

As indicated in Figure 2-7, the metallic parts (e.g. wheels, transmissions, and engines) have the highest rate of reuse; whereas the reuse rates for non-metallic parts (e.g. front bumper) are relatively low.

The main constraint associated with the ELV reclamation option is the small number of ELVs of each car brand that are processed by the individual dismantling facilities in Australia. (As discussed in Section 2.3, there are around 16,500 ELVs per each car brand in Australia.) Such a relatively small number of ELVs could cause some challenges – such as the nation-wide collection of the parts made from non-metallic materials for reuse.
2.6.2 Remanufacturing of non-metallic auto-parts

There is little information available about the remanufacturing of non-metallic parts of ELVs in Australia. There are two main constraints in Australia relating to the ELV reclamation option of ‘Remanufacturing of non-metallic parts’: the high labour costs and the small market per car brand in the country (section 2.3). The first constraint reduces the competitiveness of the remanufactured parts in Australia when compared with new parts that are typically manufactured in countries with relatively low wages. As shown in Figure 2-8, the hourly labour costs in Australia are around five times higher than the corresponding costs in Taiwan and around 32 times higher than in The Philippines.

![Figure 2-8 Hourly compensation costs (U.S. dollars in 2011) in manufacturing (BLS, 2012)](image)

The second constraint reduces the economies of scale for remanufacturing parts for a specific car brand and model.

2.6.3 Use of plastics from end-of-life vehicles as reducing agents in blast furnaces

A blast furnace is a kind of metallurgical furnace used for smelting ore metals, mainly ore iron, to produce industrial metals. A blast furnace for the production of iron metal chemically reduces and
physically converts iron oxides into liquid iron called ‘hot metal’ (Steelworks, 2013). In a blast furnace, the yield is up to 10,000 tonnes of hot metal per day (PlasticsEurope, 2009). To chemically reduce iron oxides, a reducing agent such as carbon monoxide is required. This agent is usually generated by gasification of coke and heavy oil or coal. Both in Australia (PACIA, 2011) and internationally (PlasticsEurope, 2009), plastic waste has been considered as an alternative for conventional reducing agents of coke and heavy oil.

Waste plastics, as shown in Figure 2-9, are fed into the lower side of the blast furnace, where the temperature reaches between 2100°C and 2300°C (PlasticsEurope, 2009). Under these conditions the organic materials of plastic waste are gasified with the hot air into synthesis gas (i.e. a gas mixture consisting mainly of hydrogen and carbon monoxide). The synthesis gas reduces the iron oxides inside the blast furnace to hot metal by extracting oxygen. The gas has a temperature of between 900°C to 1200°C thus making the iron melt. The hot metal is gathered at the bottom of the blast furnace and is poured out at regular intervals (PlasticsEurope, 2009).

![Figure 2-9 Blast furnace process involving plastic injection (PlasticsEurope, 2009)](image)

Injection of plastic wastes into a blast furnace has been considered as a waste management strategy in Australia (DSEWPC, 2011, PACIA, 2011). Polymer and plastics arising from ELV treatment in Australia can be integrated into this plastic waste management system in Australia.
2.6.4 Use of treated automobile shredder residue as construction aggregate or other construction products

The main purpose of treating ASR is to immobilise hazardous materials (e.g. heavy metals) that might be present in ASR (Gonzalez-Fernandez et al., 2008, Rossetti et al., 2006, Cossu and Lai, 2013). A process diagram, showing a typical ASR treatment for the purpose of its application as an alternative daily cover for landfill, is shown in Figure 2-10.

![Figure 2-10 Process flow diagram of daily cover production from auto shredding (Guatney and Trezek, 2012)](image)

Germany and the US use treated ASR as construction product. The application of treated ASR as a backfilling material in 2008 in Germany has also been reported (European Parliament, 2010),
and some States of the US use treated ASR as a daily landfill cover\(^4\) (DTSC, 2014, Calrecycle, 2009). The US Environmental Protection Agency (EPA) has also investigated the application of treated ASR as a raw material in the cement industry (US EPA, 2010).

There are some constraints in Australia that should be considered for the application of using treated ASR as a construction material. The first constraint is the quality standards that waste-driven materials should meet prior to their adoption by the Australian construction industry (ABCB, 2013). Given the stringent nature of the standards, ASR should be passed through a comprehensive pre-treatment stage.

Other constraints are related to the current intense competition between the various industry sectors in Australia (including the construction industry itself) to use their production residues (waste) as an alternative construction material. A competitive material to ASR for the application in the construction industry is the waste generated by the broken packaging glass industry. A significant amount of broken packaging glass is produced in Australia during the collection from the end-users, and the separation of packaging glass from other waste materials in Material Recycling Facilities (MRF)\(^5\). The recycling process of the broken packaging glass is relatively simple and cost effective (Hedayati, 2012).

### 2.6.5 Thermal treatment of automobile shredder residue and its co-incineration with other waste streams

Energy recovery from ASR, through its co-combustion in a municipal waste incinerator, has been practiced in some countries including Japan (Nissan, 2007). The incineration of ASR in Japan is carried out in modified incinerators, which were previously used for incineration of other waste

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\(^4\) At the end of each day, the surface of waste materials in landfill sites is covered by 150–300 mm of virgin excavated natural material or other material known as ‘alternative daily cover’ (ADC). This practice is put in place primarily for health and safety reasons as it helps to control odour, reduce litter and prevent scavengers such as rodents, ibis and pelicans from going through the waste.

\(^5\) An estimated 257,000 tonnes of glass waste is generated each year in Victoria and while 195,000 tonnes or 76 per cent is recovered, only 124,000 tonnes or 48 per cent is recycled back into glass cullet for glass manufacturing. The remaining 52 per cent is made up of glass fines.
materials, including the municipal solid wastes. One of the ASR incinerator plants in Japan (Oppama Plant), has been modified by the Nissan car maker for material/energy recovery from ASR (Nissan, 2007). The system for energy recovery in this type of incinerator plant is shown in Figure 2-11.

![Figure 2-11 System for energy recovery from ASR incineration at Oppama Plant in Japan (Nissan, 2007)](image)

**2.6.6 Thermo-chemical treatment of automobile shredder residue (pyrolysis and gasification)**

Gasification and pyrolysis are the main thermo-chemical conversion technologies. The former technology requires a low oxygen environment to produce fuel gases (e.g. synthesis gas) and the latter technology requires an environment without the addition of any air or oxygen to produce char and tar (a mixture of hydrocarbons, resins, alcohols, and other compounds) (CalRecycle, 2011).

The application of thermo-chemical processes for material and energy recovery from ASR has been investigated by some researchers (Roy and Chaala, 2001b, Santini et al., 2012, Vermeulen et al., 2012e, Viganò et al., 2010). In comparison with pyrolysis, the application of the gasification
process for ASR treatment has been used to a greater extent, especially in Japan (GHK/Bios, 2006), where there are several operating gasification plants recovering material and energy from ASR. A schematic representation of the ASR gasification technology is shown in Figure 2-12.

![Figure 2-12 Schematic representation of the ASR gasification technology (Viganò et al., 2010)](image)

Port Headland in Western Australia which will convert around 100,000 tonnes of waste (both residential and industrial waste) to electricity and a solid residue when it becomes operational (NEC, 2013). There is evidence of increased attractiveness of thermal processes in Australia such as the gasification process, as a preferred waste management solution. This is reflected in a position paper published by the waste management authorities in Western Australia (WAWA, 2013b).

### 2.6.7 Mechanical-physical separation of automobile shredder residue to recover its materials

A schematic representation of a mechanical-physical plant is shown in Figure 2-13. As shown in Figure 2-13, the main material families (e.g. plastics, textiles) within ASR are segregated into several discrete waste streams, with each stream enriched from a particular material (e.g. aluminium) or material family (e.g. urethane foams).
There could be another process to purify the materials that constitute an individual material family.

In the next stage, each segregated stream is purified to the desired level. For example, in the case of material family of polyurethane foam (PUF), the segregated stream is purified through a number of processes, including washing and drying, to produce a clean and highly pure PUF (ANL, 2010).

There are some examples of applications of the mechanical separation process for material recycling from end-of-life products in Australia. For example, as part of the National Television and Computer Recycling Scheme (SEWPaC, 2013), some of the material recycling companies have recently commissioned plants involving a mechanical separation process for recycling of end-of-life computers and television sets (SIMS, 2013).
Chapter 2

2.7 PROPOSED ELV TREATMENT NETWORK FOR OTHER COUNTRIES

2.7.1 Proposed framework for ELV recycling in Malaysia

The Malaysian Government, as discussed in Section 2.4.4, introduced the ELV legislation for the country in 2009. Later, the legislation was withdrawn because the public believed that the legislation had been introduced without proper research (Azmi et al., 2013). Several research studies have been conducted since then to investigate various aspects of ELV management in Malaysia (Azmi et al., 2013, Hamzah et al., 2012, Amelia et al., 2009). One of the research studies (Azmi et al., 2013) proposed a framework for ELV recycling in Malaysia Figure 2-14.

![Proposed framework for ELV recycling system in Malaysia](image)

*Figure 2-14 Proposed framework for ELV recycling system in Malaysia (Azmi et al., 2013) (Reproduced)*
As indicated in Figure 2-14, the proposed treatment practice for ASR is ‘energy recovery’ either through its combustion in the incineration plants or through its combustion in power plants. The framework proposes to collect ELV plastics, melt them, and use the recycled plastics in manufacturing of the new vehicles that are produced in that country. The proposed ELV recycling in Malaysia (Figure 2-14) was developed based on interviews conducted with eight Malaysian companies including five ELV recycling companies, two ELV workshops and one used-tyre reseller.

2.7.2 Proposed framework for end-of-life vehicle recycling in India

There is currently no legislation in India relating to the proper management of the ELVs that are generated in that country. However, the ELV legislation might be established in the new future to address the concerns about the negative environmental impacts of the current ELV management practices in India (Express News Service, 2015). A study conducted by Sivakumar et al. (2014) has proposed a new recycling model for India (Figure 2-15).

![Figure 2-15 Proposed ELV recycling model for India (Sivakumar et al., 2014) (Reproduced)](image)

As indicated in Figure 2-15, different treatment practices have been proposed for ASR generated in India in the new ELV recycling model. These practices, according to the study proposing the model (Sivakumar et al., 2014), include energy recovery from ASR in cement plants, polymer
Chapter 2

recycling, and landfill disposal of waste where mass should be less than 5% of the total ELV mass.
No information has been presented in the study on the rationales underpinning the selection of
ASR treatment practices.

2.8 EXISTING DECISION-MAKING SUPPORT FRAMEWORKS

Waste management hierarchy is one of the most widely used DSFs. It is often used by waste
management authorities to identify the optimum waste treatment strategy from a list of alternative
waste treatment strategies for a geographical region (DSEWPC, 2011, EPHC, 2010, WAWA,
2013b). It has also been used in research studies related to the waste management practices in a
given region (Gertsakis and Lewis, 2003, Sakai et al., 2011, Yuan and Shen, 2011).

The hierarchy is waste-specific and the rank order of the waste management strategies can be
different from one waste management hierarchy to another. Figure 2-16 shows the waste
management hierarchy developed by Yuan et al. (2011) for the management of construction and
demolition waste.

![Waste management hierarchy for the construction and demolition industry (Yuan et al., 2011)](image)

The waste management strategies located at the top of the hierarchy (e.g. reduction and reuse in
Figure 2-16) have less environmental impacts than those often located lower down (e.g. waste
landfill disposal in Figure 2-16).
A major issue with the waste management hierarchy framework is the lack of consideration of social and economic values. Some waste management authorities, including Northern Tasmanian Waste Management (NTWM), aim to combine the waste management hierarchy with the need for flexibility based on economic, social and environmental conditions when developing their waste management strategies (NTWMG, 2013). Given the frequent lack of social and economic aspects in the waste management hierarchy, it cannot be used as a suitable decision-making framework for the purpose and context of the present research, which involves analysing the social, economic and environmental aspects of the ELV reclamation options.

There are some DSFs that help identify an optimum waste treatment practice for a region based on indicators other than just the environmental indicators (e.g. social and economic) (Harrison et al., 2001, Kijak and Moy, 2004, Den Boer et al., 2007). Only one of these DSFs, that developed by Kijak and Moy (2004) for the management of municipal waste, is based on the social, economic and environmental aspects of the waste treatment practices (Figure 2-17).

![Diagram of the Decision Support Framework (DSF) developed by Kijak and Moy (2004) for the management of municipal solid waste]

*Figure 2-17 DSF developed by Kijak and Moy (2004) for the management of municipal solid waste*
The framework shown in Figure 2-17 includes five stages starting with quantifying the environmental impact (in a streamlined approach) of a limited number of waste management strategies for the region considered in the study. The quantified environmental impacts are supplemented with some selected social and economic impacts. The social, environmental, and economic impacts are then applied within a multi-criteria analysis stage so as to select the optimum strategy for the management of municipal solid waste for the region considered in the study.

The main issue associated with the application of the DSF developed by Kijak and Moy (2004) in this research is the use of a streamlined Life Cycle Assessment (LCA) tool in the DSF. It can be argued that the LCA tool is not an appropriate tool for the present research. The waste generated in Australian ELV recycling is a heterogeneous waste containing many different materials (e.g. different plastic types, textiles, rubbers). These materials, when recycled, are the co-products of the ELV reclamation option (e.g. mechanical-physical separation technology) that has recycled them. As such, the environmental impacts of the recycling should be assigned to the co-products of the recycling process (Pelletier et al., 2015).

The treatment of co-products is one of the most challenging issues of the LCA studies (Pelletier et al., 2015, Weidema and Schmidt, 2010, Weidema, 2000). One of the most recommended approaches for the treatment of co-products, according to ISO 14044:2006 Standard (ISO, 2006), is the application of ‘system expansion’. The system expansion approach is based on expanding the system under study to include the additional functions related to the co-products. For this reason, LCA studies based on the system expansion approach are often referred to as Consequential Life Cycle Assessment (CLCA) studies (McManus and Taylor, 2015, Thomassen et al., 2008).

There are some main issues associated with the application of the system expansion method (or CLCA) in ELV reclamation studies involving LCA. The CLCA modelling is a time and resource intensive exercise as it takes into account the consequences of co-production in the system considered in the study on other production systems in the economy (Hedayati et al., 2015). The co-products from ELV reclamation options (e.g. plastics, rubbers, textiles, metals and others) can affect many production systems in the economy. The time and resources required for the identification and quantification of these consequences are generally prohibitive, including in the present research.
Another issue is the uncertainty associated with results obtained in the CLCA modelling studies. This issue is thoroughly discussed in recent research conducted by the candidate that applied CLCA modelling to determine the climate change impact of the cotton production system on its co-products of cotton fibre and cotton seed (Hedayati et al., 2015). This study identified the main causes of the uncertainties in the production system considered in the study, then developed and applied strategies to address some of these uncertainties (e.g. developing and analysing different scenarios). However, the research concluded that the remaining uncertainties were still considerable and prevented a decisive conclusion about the impact of climate change on the co-products.

2.9 THE CONTEXT FOR THIS RESEARCH

The literature review presented in this chapter has provided an insight into the current body of knowledge related to the recovery of non-metallic materials of ELVs both in Australia and at the international level. The analysis of the previously conducted ELV reclamation studies helped identify the well-developed research areas and the areas that have received little attention to date. For instance, the environmental impacts associated with landfill disposal of non-metallic materials of ELVs have been well investigated to date; however, no attention has been given to develop a sustainable business model for the recovery of non-metallic materials.

The most covered research topic in the context of ELV reclamation options is related to the environmental assessment of the ELV reclamation options. Most of the early comparative ELV treatment studies focused on the assessment of a set of ELV reclamation options against a set of environmental indicators through a life cycle assessment (LCA) type study. It can thus be argued that the body of knowledge relating to the environmental impacts of various ELV reclamation options is well developed.

On the other hand, very little work has been done to date to compare a set of ELV reclamation options against a set of assessment indicators relating to the social, economic and environmental performance of the options. Only two ELV studies have compared a set of reclamation options against a set of sustainability assessment indicators, and only one of these selected a specific ELV reclamation option as the preferred option for the region within the study (Mergias et al., 2007b). The second study only compared the options against the sustainability assessment indicators without selecting any of the options as the preferred option (Vermeulen et al., 2012b). Therefore,
the body of knowledge relating to a sustainability assessment of a set of ELV reclamation options has not been well developed to date.

Reviewing the early ELV studies has helped identify the current knowledge gaps in relation to the sustainability assessment of the business models for ELV reclamation in a region. To date, no published study has attempted to develop a sustainable business model for the implementation of a selected ELV reclamation option for a location. The behaviour pattern mode of a business model (e.g. growing mode, overshoot and collapse, oscillation, and others) can reflect the possible interactions between the selected ELV reclamation option and other elements within the ELV recycling system. This research topic has not received any attention to date.

Furthermore, reviewing literature on the subject of ELV management in Australia revealed that little attention has been given to date to characterise the Australian ELV recycling industry. As explained in this chapter, the number of published studies addressing the ELV practices in Australia is very limited. Some of these studies might be considered outdated as they were conducted more than ten years ago or were conducted based on the information collected many years ago. With respect to the comparative ELV reclamation studies, no study has been conducted to date to compare a set of ELV reclamation options within the Australian context.

These gaps in knowledge about ELV reclamation options justify the need for the present research study especially in the Australian context. This study aims to identify, based on the Australian context, both a sustainable ELV reclamation option and a sustainable business model for the implementation of the identified ELV reclamation option. As explained in this chapter, the current practices applied in Australia for the treatment of the non-metallic fractions of ELVs (i.e. landfill disposal) are socially unacceptable, economically inefficient and environmentally incompatible. A particular concern about the current ELV treatment practices is the increasing costs of landfill disposal of ASR in Australia. This cost increase, in an environment where limited profit is gained by the metal shredders through selling the recycled metals, might eventually change the preference of the Australian metal shredders to accept ELVs as a feedstock. This would adversely affect the recycling rate of ELVs and increase the abandonment rate of ELVs in Australia. A sustainable ELV reclamation practice can improve the social, economic and environmental performance of the Australian ELV recycling industry.
Reviewing literature on the subject of ELV management in Australia has identified the need for research in the following areas:

1. The identification of the most technically viable ELV reclamation options in the Australian context.
2. The identification of a set of sustainability indicators relevant to the Australian ELV recycling industry.
3. The identification of the most sustainable ELV reclamation option in the Australian context.
4. The identification of the most sustainable business model for ELV reclamation in Australia.

Each of the above identified knowledge gaps has been formulated into a research question and will be answered in the chapters following Chapter 3, which is the chapter where the research methodology is developed.

2.10 SUMMARY

The chapter has presented a comprehensive overview of the ELV recycling industry both in Australia and internationally. Following an overview of the key functional entities associated with ELV treatment in Australia, both international mandatory and voluntary ELV policies were reviewed. These include the mandatory ELV policies in Japan, South Korea, China, Taiwan, and the members of the European Union. The voluntary ELV reclamation programs in the United States have also been reviewed in the chapter. The chapter then presented a comprehensive summary of the key aspects of the early research studies relating to the assessment of ELV reclamation options. These aspects were: (i) investigated ELV reclamation options, (ii) comparative and non-comparative studies, (iii) sustainability dimensions included in the studies, (iv) assessment indicators, (v) assessment level, (vi) assessment tools, (vii) decision-making methods, (viii) obtained results, (ix) sustainability assessment models, and (x) characteristics of the successful business models.

This chapter has presented a comprehensive overview of the existing decision-making support frameworks (DSFs) that are used to identify an optimum waste treatment practice for a region. It showed that that existing DSFs, including a widely used DSF called ‘waste management hierarchy’, are not appropriate for the present research as their underpinning assessment tools (e.g.
LCA) are not applicable for this research. This finding provides the context for the development of a customised DSF in this study.

The chapter concluded with a comprehensive discussion about the current knowledge gaps relating to the sustainability assessment of ELV reclamation options, in particular in the Australian context and the needs for the present research study.
3 Research design and methods

3.1 INTRODUCTION

The second chapter presented a comprehensive overview of the existing decision-making support frameworks (DSFs) that are used to select an optimum waste treatment practice from a list of alternatives for a region. It was shown that the existing DSFs are based on some assessment tools that have little relevance to the goal and objectives of the present research; as such, a customised DSF should be developed specifically for this research project. That DSF should be based on sustainability assessment tools allowing both technical assessment and sustainability assessment of the ELV reclamation options, as well as multi-criteria and sustainability assessment of a set of business models for ELV reclamation in Australia.

A challenge in the present chapter is the identification of the most effective sustainability assessment tools for the customised DSF from the more than 30 such tools that have been developed (Ness et al., 2007).

The chapter provides a comprehensive overview of the selected sustainability assessment tools for the customised DSF and relates them to the research questions. The key methodological aspects of the selected tools – such as the methods to verify and validate the results from the application of each individual tool – are described. The chapter concludes with a comprehensive discussion about the developed DSF in the research and describes the steps involved in the customised DSF.

3.2 DEVELOPING A CUSTOMISED DECISION-MAKING SUPPORT TOOL

3.2.1 Framework for sustainability assessment tools

A framework called ‘Framework for Sustainability Assessment Tools’ (or FSAT), developed by Ness et al. (2007), has identified the most practiced sustainability assessment tools (or methods), and has categorised them into three distinct umbrella groups. These groups are called Indicators/Indices tools, Product-related tools, and Integrated Assessment tools. The criteria used for this classification are as follows:
• Temporal characteristics, i.e. if the tools are prospective or retrospective.
• The coverage areas, i.e. if the tools are focused at the product level or on a proposed change in policy.
• Integration of nature-society, i.e. to what extent the tool is focused on economic, social, and environmental aspects.
Figure 3-1 Framework for sustainability assessment tools ((Ness et al., 2007) (Reproduced)
The FSAT includes monetary valuation tools, located at the bottom of the FSAT, which are useful when monetary valuations are needed in the above located tools. The other benefit of the FSAT is its ability to identify sustainability tools and to integrate relevant aspects of the nature–society system into a single evaluation. These tools are specified in the framework with thick lines around the boxes.

The FSAT could be regarded as a useful guide for the identification and comparison of the most practiced sustainability assessment tools for the sustainability assessment exercises relating to this research. These sustainability assessment exercises, as detailed in Chapter 1, are related to the identification of a sustainable ELV reclamation option for Australia as well as the identification of a sustainable business model for the implementation of the identified ELV reclamation option in Australia. However, prior to this, some selection criteria should be defined by which the tools located in the different clusters of the FSAT are compared.

The criteria by which the appropriate sustainability assessment tools can be selected for a research are research-specific and there is no general consensus among researchers on this topic (Singh et al., 2012). In the context of this research, the most relevant criteria for the selection of the appropriate sustainability assessment tools and the rational for these selections are summarised in Table 3-1.
### Table 3-1 Criteria for the selection of sustainability assessment methods in the research

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Relevance to the research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Being prospective</td>
<td>This research involves the development and assessment of different scenarios (business models) for the implementation of the identified sustainable ELV reclamation in Australia. The selected sustainability tool(s) should be ex-ante focused (i.e. ‘before the event’ focus) and allow an effective assessment of possible interactions between the selected sustainable ELV reclamation and the various elements of the ELV reclamation system in Australia. The retrospective tools could be used for assessing future sustainability patterns, but they may not be optimal for gauging longer-term sustainability since they have been developed for analysing the past (Ness et al., 2007).</td>
</tr>
<tr>
<td>Ability to assess different ELV reclamation options based on social, economic and environmental aspects</td>
<td>This research aims to assess a set of ELV reclamations in Australia based on the social, economic and environmental aspects of the reclamation options. However, the sustainability assessment tools only cover one or two sustainability aspects and would not meet the requirements of this research.</td>
</tr>
<tr>
<td>Ability to assess different ELV reclamation options in the Australian context</td>
<td>This research aims to assess a set of ELV reclamation options at a national level. Some sustainability assessment tools are applied. These are retrieved from those locally or regionally assessed to be at the most risk of impact from the most from the project proposal; national and global impacts are often not part of the scope of the assessment (Ness et al., 2007).</td>
</tr>
</tbody>
</table>
It can be argued that both of these objectives can be effectively met through the application of relevant sustainability assessment tools located in the ‘Integrated Assessment’ cluster of the FSAT.

The methods located in the cluster of ‘Integrated Assessment’, as opposed to the methods located in the other two clusters of the FAST, are used for supporting decisions related to a policy or a project in a specific region (Ness et al., 2007). This is highly relevant to the key objectives of this research – namely the identification and implementation of a sustainable ELV reclamation practice in Australia. Furthermore, as opposed to the tools located in the other two clusters of the FAST, the tools located in the cluster of ‘Integrated Assessment’ have an ex-ante focus (i.e. ‘before the event’ focus) and often are carried out in the form of scenarios (Ness et al., 2007). The forward looking nature (prospective, forecasting) of the integrated assessment tools (tools located in the ‘Integrated Assessment, cluster of the FAST) will help this research in the development and assessment of different scenarios (business models) for the implementation of the identified sustainable ELV reclamation in Australia. The exercise in this research, relating to the development and assessment of a sustainable business model, involves the identification and analysis of possible future interactions between the identified sustainable ELV reclamation option and other elements of the Australian ELV recycling network. Thus, this exercise will be best conducted with the prospective sustainability assessment tools.

Many of the integrated assessment methods are based on systems analysis approaches that integrate nature and society aspects of the project (Ness et al., 2007). This characteristic is highly useful for the present research that aims to assess a set of viable ELV reclamations in Australia based on social, economic and environmental aspects. The tools, located in the other clusters of the FAST (e.g. LCA tool), only assess one or two aspects of sustainability. As such, they are not useful for the purpose and context of the present research.

### 3.2.2 Integrated sustainability assessment methods

The cluster of ‘Integrated Assessment’ in the FSAT includes ten sustainability assessment methods. This cluster is shown in Figure 3-2.
A short description for each of the methods included in the selected cluster is presented in Table 3-2.
### Table 3-2 Integrated sustainability assessment tools

<table>
<thead>
<tr>
<th>No.</th>
<th>Tool</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Conceptual Modelling</td>
<td>Analyses qualitative (causal) relationships or causal loop diagrams. It can be used for visualising and detecting where changes in a given system can be made for increasing sustainability or as the initial conceptualisation mechanism in a larger computer modelling approach.</td>
</tr>
<tr>
<td>2</td>
<td>System Dynamics</td>
<td>Building of computer models of complex problem situations for the purpose of experimenting with and studying the behaviour of these models over time.</td>
</tr>
<tr>
<td>3</td>
<td>Multi-Criteria Analysis</td>
<td>Assessing situations when there are competing evaluation criteria. It identifies, in general, goals or objectives and then seeks to spot the trade-offs between them; the ultimate goal is to identify the optimal policy.</td>
</tr>
<tr>
<td>4</td>
<td>Risk Analysis</td>
<td>It begins with identification of the risk, and moves on to a qualitative and/or quantitative assessment of the risk—leading to certain management decisions regarding the minimisation of that risk. The final stage of the Risk Analysis includes communication with stakeholders concerning the assessment and the corresponding decisions involved with minimising the risk.</td>
</tr>
<tr>
<td>5</td>
<td>Uncertainty Analysis</td>
<td>It involves stochastic uncertainties, i.e. natural variability of the system, and fundamental uncertainty, i.e. the inability to predict, due to lack of knowledge, about the system. It estimates the probability of events and predicting the events using the knowledge that is available.</td>
</tr>
<tr>
<td>6</td>
<td>Vulnerability Analysis</td>
<td>It evaluates the vulnerability of coupled human–environment systems with the aim to determine how sensitive and resilient systems are to changes, and how capable systems are to cope with changes.</td>
</tr>
<tr>
<td>7</td>
<td>Cost Benefit Analysis</td>
<td>It is used for evaluating public or private investment proposals by weighing the costs of the project against the expected benefits.</td>
</tr>
<tr>
<td>8</td>
<td>Impact Assessment</td>
<td>A small group of forecasting tools used for improving the basis for policy making and project approval process. The Impact Assessment tools are classified into three categories: (I) Environmental Impact Assessment, (ii) Strategic Environmental Assessment and (iii) Sustainability Impact Assessment tools developed by the European Union (the EU).</td>
</tr>
</tbody>
</table>
Some of the integrated sustainability assessment tools (Table 3-2) are more relevant to this research than others. The most relevant sustainability assessment tools to the purposes and context of this research, along with the evidence supporting the relevance of the tools to the research questions, are presented in Table 3-3. The rationales for the exclusion of the other integrated sustainability assessment tools to be used in this research project are provided in Table 3-4.
<table>
<thead>
<tr>
<th>Most relevant integrated sustainability assessment tools</th>
<th>Relevant research Question(s)</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptual Modelling</td>
<td>What is the most sustainable business model to implement the selected most sustainable ELV reclamation option in Australia?</td>
<td>This research question should be addressed through the identification of the relationships, or causal loop diagrams, between the different elements of the ELV reclamation system in Australia and the visualisation and detection of where changes in a given element of the system can be made for increasing sustainability of the system. Given the description of the conceptual modelling tool (Table 3-2), it can effectively address the research the research question.</td>
</tr>
<tr>
<td>System Dynamics</td>
<td>What is the most sustainable business model to implement the selected most sustainable ELV reclamation option in Australia?</td>
<td>The research question requires building of computer models for studying the behaviour of the business model in order to determine its sustainability performance. According to the description of the System Dynamic tool (Table 3-2), the tool can affectively support the sustainability assessment of the business model.</td>
</tr>
<tr>
<td>Multi-Criteria Analysis</td>
<td>Which of the international best practice ELV reclamation options are technically viable in Australia? Which of the international best practice ELV reclamation options is the most sustainable ELV reclamation option for Australia?</td>
<td>These research questions should be addressed through conducting assessment involving competing evaluation criteria. Thus, the assessment tool should be able to identify, in general, goals or objectives of the assessment and then seek to spot the trade-offs between them. According to the description of the Multi-criteria tool (Table 3-2), the tool can effectively address the assessment tasks relating to the research question.</td>
</tr>
</tbody>
</table>
### Table 3-4 Rational for the exclusions of other integrated sustainability assessment methods in the research

<table>
<thead>
<tr>
<th>Integrated sustainability assessment methods</th>
<th>Rational for the exclusion of the method in the present research study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk Analysis and Uncertainty Analysis</td>
<td>Risks defined as “the possibility that certain losses or damages occur as the result of a particular event or series of events” (Rotmans, 1998). Since risk is closely related to uncertainty, risk analysis cannot be separated from uncertainty analysis (Rotmans, 1998). This justifies why Risk Analysis and Uncertainty Analysis tools are considered together in this table. These tools are less relevant to the questions of this research than the tools described in Table 3-3.</td>
</tr>
<tr>
<td>Vulnerability Analysis</td>
<td>The Vulnerability Analysis tools are effective to show how sensitive and resilient different systems (under the consideration of a research) are to changes (e.g. climate change), and how capable different systems are to cope with change (Turner et al., 2003). The systems assessed by the Vulnerability Analysis tools are often societies and ecosystems in nature (O'Brien et al., 2004). It can be argued that the Vulnerability Analysis tools are less relevant to the purposes and context of this research, as ELV reclamation practices included in the research do not constitute entire societies or the entire ecosystem of nature. Furthermore, this research is not aiming to compare the sensitivity and resilience of different ELV reclamation practices to a change. The research aims to compare the reclamation options against some relevant sustainability indicators.</td>
</tr>
<tr>
<td>Cost Benefit Analysis</td>
<td>Cost Benefit Analysis (CBA) is an applied welfare economics tool (Johansson, 1993) used for evaluating public or private investment proposals by weighing the costs of the project against the expected benefits (Ness et al., 2007). The CBA tool places monetary units on all different benefits of an investment (e.g. social benefits). This is regarded as the main problem with the CBA tools (Moberg, 1999, Finnveden and Moberg, 2005). As this research is based on maintaining the nature of the sustainability assessment indicators, the applications of CBA tools were excluded in the present research study.</td>
</tr>
<tr>
<td>Impact Assessment</td>
<td>The Impact Assessment tools are all based on methodologies that attempt to incorporate concerns from diverse stakeholder groups into an assessment process of a public project (Ness et al., 2007). Two of the three categories of the Impact Assessment tools are mainly focused on the environmental aspects of the projects, as such, they are not be considered as sustainable tools for this research which involves social, economic and environmental aspects of ELV reclamation options. The EU Sustainability Impact Assessment (SIA) tools can cover the environmental, economic and social parameters but they are most effective when a limited number of sustainability impacts are included in assessment (Ness et al., 2007, Finnveden and Moberg, 2005). The present research aims to include a broad range of sustainability indicators in the sustainability assessment of the viable ELV reclamation options. This would a challenge for the SIA tools.</td>
</tr>
</tbody>
</table>
3.2.3 Overview of the selected sustainability assessment methods

3.2.3.1 Multi-criteria analysis

This research aims to compare the performance of a set of ELV reclamation options against a set of social, economic and environmental indicators. This is a highly challenging task as, according to Milutinović, Stefanović et al. (2014), the social, economic and environmental indicators related to waste management options are partially or completely conflicting and, by nature, very diverse and expressed in different units. This challenge has been addressed, according to the Achillas et al. (2013), in the waste management studies which utilises and applies the multi-criteria analysis method, or as often referred as Multi-Criteria Decision-Making method (MCDM) (Annema et al., 2015, Triantaphyllou, 2013).

The success of the MCA method in addressing this challenge, according to Morrissey and Browne (2004), is the ability of the method to take several individual and conflicting indicators into account in a multidimensional way, which thus leads to more robust decision-making – rather than optimising a single dimensional objective function (e.g. the cost-benefit analysis method). The ability of the MCA method to incorporate a mixture of quantitative and qualitative information allows the method to go beyond the evaluation of purely economic consequences and also allows non-economic criteria to be assessed on an equal basis (Morrissey and Browne, 2004).

The other benefits of the MCA include the ability of the method to assist the decision-makers of waste problem to learn about the problem and alternative courses of actions from several points of view (Morrissey and Browne, 2004). The MCA method identifies several alternatives (i.e. several waste management scenarios) which are then evaluated in terms of indicators that are important for the waste management study. The result is a ranking of the alternatives. It can be argued that these benefits are important for the decision-makers related to the Australian ELV treatment industry, as no previously conducted research has offered such Australian-based benefits to date.

There are different available techniques for the application of the MCA method in this research. These include: Analytic Hierarchy Process (AHP), Simple Additive Weighting (SAW), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Wang, 2015). According to the research by Achillas et al. (2013), AHP is the most widely used technique for
the application of the MCDM method in waste management studies. This could be due to the
simple theory of the AHP technique which eases the description of AHP to different stakeholders
of a waste management study and also due to its simplicity in application (Wang et al., 2009). For
these reasons, this research will use AHP as a technique for the application of the MCA method.
The selection of AHP as a technique for the application of the MCA in this research is not expected
to influence the type of the selected sustainable ELV reclamation option for Australia. According
to Huang et al. (2011), the recommended course of action (e.g. the selected waste management
option) in an MCA study is independent of the type of selected technique needed for the
application of the MCA method in a study.

The AHP technique is based on four principles. According to the first principle of the AHP
technique, the problematic decision should be deconstructed into a hierarchy containing some
levels. Each level also can have some sub-levels. In the context of the present research, all of the
AHP-based assessment will contain three levels namely: (1) goal, (2) assessment indicators (e.g.
sustainability indicators), and (3) alternatives (e.g. ELV reclamation options).

Based on the second principle of the AHP technique, the relative importance of the elements
within each level of the hierarchy should be evaluated through the pairwise comparison approach
– with respect to the individual elements located in an upper level. As such, in the context of the
present research, there will be two sets of pairwise comparisons. In the first set, the relative
abilities of the alternatives to meet the requirements of the assessment indicators are evaluated.
This drives the ‘local’ priorities, or the performance ranking, of the alternatives with respect to the
assessment indicators. In the second set, the relative importance of the individual assessment
indicators with respect to the assessment goal is evaluated. This drives the ‘weighting factors’ of
the technical indicators.

Based on the third principle of the AHP technique, the results should be synthesised through the
multiplication of the ‘local priority’ of a specific alternative and the ‘weighting factor’ of the
relevant assessment indicator and then added. The analysis produced the ‘global priorities’ of the
alternatives. The calculated amounts of the ‘global priorities’ are then used to develop the
performance ranking of the alternatives with respect to the assessment goal.
The present research utilises the AHP-based computer software of Expert Choice (Expert Choice, 2008). Expert Choice has been applied to date in some waste management studies (Qdais and Alshraideh, 2014, Kim et al., 2013, Chitsazan et al., 2013). The software has the ability of presenting the normalised ‘local priority’ and ‘global priority’ of the considered alternatives. Further information about the normalisation process in AHP is provided in Appendix C and further information about the Expert Choice software is provided in Appendix D.

The application of the MCA method to assess the sustainability performance of a set of ELV reclamation options is not new to this research. The method has already been applied by Mergias et al. (2007b) to compare a set of ELV reclamation options based on the technical, social, economic and environmental indicators in the context of Cyprus.

3.2.3.2 Conceptual modelling method

One of the main objectives of this research is to identify a sustainable business model for the implementation of an identified sustainable ELV reclamation option in Australia. As described in Chapter 1, a sustainable business model for ELV reclamation in Australia is a business model that contributes to sustainable development of the company and society through creating value from non-metallic materials of ELVs. The main challenge in achieving the objective is that the ELV recycling industry in every country, including Australia, contains various activities, implemented by various independent stakeholders with differing business logics (Farel et al., 2013). This challenge can be effectively addressed by the conceptual modelling method. The method has the ability to create an abstract of a model from a real or proposed system (Robinson, 2008) allowing a thorough investigation of the possible interactions, (or feedback loops) between the various elements of the recycling system and the selected ELV reclamation option.

The application of the conceptual modelling method in ELV treatment studies is not new to this research. Zamudio-Ramirez (1994) developed a conceptual model to investigate the economics of ELV recycling in North America, Farel et al. (2013) applied the method to estimate the costs and benefits of future ELV glazing recycling in France, Halabi et al. (2012) applied the conceptual modelling method to analyse the workforce dynamics of the Australian automobile recyclers, and Stasinopoulos et al. (2012) used the method to investigate the impact of replacing steel
components with aluminium components and the potential impact of legislation requiring car manufacturers to recover, recycle, and reuse the materials of ELVs.

Despite the importance of the conceptual modelling method, surprisingly there is no developed technique for the application of the conceptual modelling in the ELV reclamation studies or in other research subjects. This could be related to the fact that conceptual modelling is more of an ‘art’ than a ‘science’ and thus it is difficult to define techniques and procedure for its application in research (Robinson, 2008).

3.2.3.3 System dynamics method

This research will apply the system dynamics method to assess the sustainability performance of a proposed business model for ELV reclamation in Australia. The method will also test the robustness of the business model when it is exposed to a number of extreme conditions imposed by other elements of the Australian ELV recycling network.

The system dynamics, as defined by Forrester (1999), is a professional field that deals with the complexity of systems. It deals with how things change through time, which covers most of what most people find important. It involves interpreting real life systems into computer simulation models that allow one to see how the structure and decision-making policies in a system create its behaviour. The system dynamics is linked to ‘systems thinking’ that is defined by Richmond (1994) as the art and science of making reliable inferences about behaviour by developing an increasingly deep understanding of underlying structure. The system dynamics is necessary for effective thinking about systems (Forrester, 1999).

The business model, ideally, will be expected to resolve the challenges and continue its growth trend, possibly with a time delay. If the business model fails to continue its growing trend of value creation (material or energy) then the structure of the system should be reviewed. If the failure is identified as being related to the business model of the sustainable ELV reclamation option, the business model should be revised or replaced.

The system dynamic method is based on the principle that the structure of a system determines the behaviour over time pattern of that system (Cai, 2011, Sterman, 2000, Forrester, 1987, Maani and Cavana, 2003). According to this principle, if the structure of the proposed business model for
ELV reclamation in Australia is a well-structured system, this should be reflected in the behaviour over time (BOT) pattern of the model. It can be argued that the most relevant parameter to develop the BOT pattern mode of the proposed business model for ELV reclamation in Australia is the ‘amount of value (material or energy)’ that is created by the system. This selection is based on the fact that the primary purpose of the Australian ELV recycling industry is to create value (material or energy) from ELVs (McNamara, 2009). A relatively small number of the BOT pattern modes is common to a large variety of systems (Sterman, 2000). These pattern modes are shown in in Figure 3-3.

![Figure 3-3 Common behaviour over time pattern (BOT) modes of systems (Sterman, 2000)]

It can be argued that among the generic BOT modes shown in Figure 3-3, the only desirable BOT pattern modes for the proposed business model for ELV reclamation in Australia would be the ‘Exponential Growth’ and ‘S-shaped Growth’ BOT pattern modes. As discussed above, the overall objective of the Australian ELV recycling system is to create value (material or energy) from the ELVs generated in Australia. A BOT pattern mode of ‘Exponential Growth’ or ‘S-shaped Growth’ for the proposed business model containing a sustainable ELV reclamation option, (plotted based on the amount of the recovered materials or energy by the system), would imply that more value is created by the system over time. However, a BOT pattern other than the ‘Exponential Growth’ mode (e.g. the ‘Overshoot and Collapse’ pattern mode), would imply the existence of a problem with the structure of the proposed business model, as the structure of a system determines the BOT pattern mode of that system (Cai, 2011, Sterman, 2000, Forrester, 1987, Maani and Cavana, 2003).
The application of the system dynamics method in the ELV reclamation studies is not new to this research. The research by Amaral et al. (2006) applied the method to Portuguese ELV-processing infrastructure in order to evaluate how current practices, under different recycling strategies, depend on recycled materials markets and on car composition. In the research by Zamudio-Ramirez (1994), the system dynamics method was applied to investigate the economics of ELV recycling in North America. However, no study has yet applied the method to analyse the interactions between a proposed business model for ELV reclamation and other elements within an ELV recycling network.

3.2.4 Decision-making related to the pairwise comparisons in the research

Both technical and sustainability assessment of the ELV reclamation options in this research are based on the pairwise comparisons of the ELV reclamation options against a set of technical or sustainability assessment indicators. The overall objective of every pairwise comparison made in this research is to answer the following two key questions:

1. Which of the two compared ELV reclamation options is more capable to satisfy the requirements of the assessment indicator that the pair is compared against?
2. How much more capable is the selected ELV reclamation option than the compared ELV reclamation option?

AHP often uses a scale from ‘1–9’ to help determine how many times more important, or dominant, one element is over another element with respect to the criterion or property that they are compared to (Saaty, 2008). This research will use the same numerical scale but in a customised form (Table 3-5).
### Table 3-5 Numerical scale used in this research for pairwise comparisons based on the numerical scale developed by Saaty (2008)

<table>
<thead>
<tr>
<th>Intensity of capability</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal capable</td>
<td>Two ELV reclamation options are equally capable (capable to meet the requirements of the assessment indicator)</td>
</tr>
<tr>
<td>2</td>
<td>Weak or slight</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Moderate capable</td>
<td>Experience and judgement slightly favours one ELV reclamation option over another</td>
</tr>
<tr>
<td>4</td>
<td>Moderate plus</td>
<td>Experience and judgement strongly favours one ELV reclamation option over another</td>
</tr>
<tr>
<td>5</td>
<td>Strong importance</td>
<td>An ELV reclamation option is favoured very strongly over another; its dominance demonstrated in practice</td>
</tr>
<tr>
<td>6</td>
<td>Strong plus</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Very strong or demonstrated importance</td>
<td>The evidence favouring one ELV reclamation option over another is of the highest possible order of affirmation</td>
</tr>
<tr>
<td>8</td>
<td>Very, very strong</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
<td></td>
</tr>
</tbody>
</table>

**Reciprocals of above**

If ELV reclamation \(i\) has one of the above non-zero numbers assigned to it when compared with ELV reclamation \(j\), then \(j\) has the reciprocal value when compared with \(i\).

A reasonable assumption

**1.1-1.9**

If the ELV reclamation options are very close

May be difficult to assign the best value but when compared with other contrasting ELV reclamation options the size of the small numbers would not be too noticeable, yet they could still indicate the relative capability of the ELV reclamation options.

The application of the numerical scale presented in Table 3-5 in this research is best explained through an example. The example is based on the comparison of the capability of two ELV
The ELV reclamation options considered in the example are:

1. Thermo-chemical treatment of ASR (pyrolysis, and gasification)
2. Mechanical-physical separation of ASR to recover its materials

In the cost analysis of these options (GHK/Bios, 2006), the average treatment costs of these reclamation options for 2015 were predicated at around €108 per tonne of ASR (~AU$168 per tonne ASR) for the first ELV reclamation option and around €68 per tonne of ASR (~AU$106 per tonne ASR) for the second ELV reclamation option. Based on these figures, the second option is more capable of saving capital resources than the first.

The intensity of capability assigned for the pairwise comparison in which the second option is compared with the first is 3, meaning that experience and judgement slightly favours the second option. The assigned intensity of capability for the same pairwise comparison would be 7 if the treatment cost for the first option was around AU$ 50 per tonne ASR and it would be 9 if the treatment cost of the first ELV reclamation was very small (e.g. less than AU$10 per tonne ASR).

It should be noted that there is no need to determine the intensity of capability for a pairwise comparison in which the first option is compared against the second option. The assigned intensity of capacity for this pairwise comparison would be the reciprocal value of what it was assigned above (1/3).

Generally, the selection of the best numerical value for a pairwise comparison in the AHP method is conducted either through the top-down approaches or through the bottom-up approaches. In the top-down approaches, the decisions are made by experts and researchers, while in the bottom-up approaches the decisions are made through consultation with stockholders of the study (Singh et al., 2009). According to Mori and Christodoulou (2012), bottom–up approaches are suitable for local and regional level studies where a specific problem can be approached, but they are unsuitable for studies looking at the broader picture which compare many different cases. There are some examples in the literature that support the recommendation made by Mori and Christodoulou (2012) to apply top-down approaches in the studies focused on the levels above the
local and regional levels (Mori and Christodoulou, 2012) – such as national and global level studies. For instance, Babalola (2015) applied top-down approaches in a study aimed at identifying the best option for the treatment of food and biodegradable waste in Japan through the application of the AHP method. In that study, the author made all of the key decisions including: the selection of the assessment criteria (technical, social, economic and environmental) indicators and the selection of the most appropriate numerical value (the AHP numerical scale between 1-9) for the pairwise comparisons made in that study. An example relevant to this research is the application of top-down approaches in the ELV reclamation study conducted by Mergias et al. (2007a) where the study aimed to select the optimum ELV reclamation study for Cyprus.

Given that this research is not a local but a national study (it is a level study), and it compares different cases (i.e. technical assessment of ELV reclamation options, sustainability assessment of ELV reclamation options, and multi-criteria assessment of different business models), the top-down approach will be applied in this research – meaning that the most appropriate numerical scale from Table 3-5 for the individual pairwise comparison made in this research is based on the judgement of the candidate.

### 3.2.5 Methods to build further confidence in the results

#### 3.2.5.1 Methods related to the results of the multi-criteria assessments

The most common validation approach in the AHP-based studies is to quantify the logical consistency of the AHP assessments. This approach has been applied in various research studies including the studies conducted by Ahmed et al. (2016), Babalola (2015), Koç and Burhan (2014) and Subramoniam et al. (2013). The validation of the AHP results in this research is also based on the same validation practice.

The consistency in the judgements made in this research in relation to the pairwise comparisons of the ELV reclamation options are examined through the amount of an index called Inconsistency Ratio (IR) (Alonso and Lamata, 2006). The quantity of IR is calculated through the following equation (Karamouz et al., 2007):

\[
\text{IR} = \frac{II}{CRI}
\]

**Equation 1**
Chapter 3

Where, CRI is the Inconsistency Index of the random matrix obtained by calculating II for the randomly filled matrix A. II is called Inconsistency, and it is calculated through the following equation (Karamouz et al., 2007):

\[ II = \frac{\lambda_{\text{max}} - n}{n - 1} \]  \hspace{1cm} \text{Equation 2}

Where \( \lambda_{\text{max}} \) is the dominant eigenvalue of the pairwise comparison matrix (matrix A) and n is the number of alternatives.

If the CR is in excess of 0.1 (or 10%), the judgments are untrustworthy because they are too close to randomness and the exercise is valueless or must be repeated (Saaty, 1980). The AHP-based computer software used in this research, Expert Choice (Expert Choice, 2008), evaluates the CR values related to the paired comparisons of the alternatives (e.g. ELV reclamation options) against each criteria (e.g. a covering technical indicator). Methods related to the results of the conceptual modelling.

According to the research by Sargent (2013), conceptual models based on existing systems can be validated, but conceptual models based on proposed systems cannot be validated. That research argues that the validation of a conceptual model confirms that the theories and assumptions underlying the conceptual model are correct, and that the model’s representation of the problem entity is ‘reasonable’ for the intended purpose of the evaluation. Such validation requires a

---

6 If \( a_{ij} \) is considered as the relative capability of the ELV reclamation \( i \) when it is compared to the ELV reclamation option \( j \) \((i, j = 1, 2, 3 \ldots n, \text{where } n \text{ is the number of ELV reclamation options})\) with respect to a covering assessment indicator, then the relative importance of all combinations for that assessment indicator can form a pairwise comparison matrix, A:

\[
A = (a_{ij}) = \begin{bmatrix}
  a_{11} & a_{12} & a_{13} & \ldots & a_{1n} \\
  a_{21} & a_{22} & a_{23} & \ldots & a_{2n} \\
  a_{31} & a_{32} & a_{33} & \ldots & a_{3n} \\
  \vdots & \vdots & \vdots & \ddots & \vdots \\
  a_{n1} & a_{n2} & a_{n3} & \ldots & a_{nn}
\end{bmatrix}
\]
comparison between the outcomes of the conceptual model developed in a study and the outcomes of an existing system (Sargent, 2013).

For a conceptual model based on a proposed system, including the proposed conceptual model of the present research, there is no existing system to be compared with that conceptual model. Thus, no validation can be made. This could be the main reason that none of the previously conducted waste management studies in which conceptual modelling has been applied to a proposed waste treatment option (Yuan et al., 2011, Chaerul et al., 2008, Karavezyris et al., 2002) have neither validated the correctness of their conceptual models, nor confirmed that their representation of the problem entities are ‘reasonable’ for the intended purpose of the exercise.

### 3.2.5.2 Methods related to the results of the system dynamics modelling

According to the research by Sargent (2013), a model should be developed for a specific purpose (or application) and its validity determined with respect to that purpose. This research presents a sustainable business model for ELV reclamation in Australia. As such, the validation of this model should be determined with respect to its contribution to sustainability, specifically its promotion of sustainable development of the company and society through creating value (materials or energy) from non-metallic materials of the ELVs.

The model validation confirms that the proposed business model maintains its value creation (sustainability) under the business-as-usual scenario, and under the conditions in which the business model is adversely affected by other business entities within the Australian ELV reclamation network. An example of these conditions is when the proposed ELV reclamation business competes with other businesses for non-metallic materials. If the proposed business model is a sustainable model, its value creation should not be permanently dropped or ceased because of the effects of other businesses. This means that the proposed business model should possess a strong ‘resilience’. According to O’Connell et al. (2015), the resilience of a system is its ability to maintain high-level objectives (e.g. sustainability, rural livelihoods, ecosystem services sustainability) in the face of unknown changes or disturbance. As such, the validation of the business model in this research is to determine the ability of the proposed business model in maintaining its high-level objectives (i.e. sustainability) in the face of unknown changes.
As for the validation, this research verifies the identified BOT pattern mode of the proposed business model through a number of confidence-building techniques (Sargent, 2013, Sterman, 2000, Forrester and Senge, 1996) including: (i) ‘sensitivity analysis’ that determines the sensitivity of the model to its key underlying assumptions, (ii) a ‘dimensional consistency test’ that determines the parameters used in the model have real-life meanings, and (iii) a ‘unit consistency test’ that checks all equations used in the stocks and flows modelling for consistency in units. That is to make sure the left and right side of all equations have the same units.

3.2.6 Proposed decision-making support framework

The proposed decision-making support framework (DSF) (Figure 3-4) acts as a road map showing the type and the purpose of the individual assessments that will be conducted in the present research. The DSF includes four main stages; three of them represent the major assessments that will be conducted in the research. These stages aim to: (i) review the literature relating to the ELV reclamation options, (ii) provide technical assessment of the international best practice ELV reclamation options in the Australian context, (iii) provide sustainability assessment of the technically viable ELV level modelling of the viable treatment options in the Australian context, and (iv) identify the most sustainable business model to implement the identified most sustainable ELV reclamation option in Australia.

The first stage of the DSF identifies the international best practice ELV reclamation options, the sustainability indicators, the sustainability assessment tools, and the Australian constraints to implement each of the identified ELV reclamation options. These constraints will be considered throughout the research for the relevant technical and sustainability assessments.

The second stage of the DSF is focused on the technical assessment of the international best practice ELV reclamation options in the Australian context. The AHP technique will be applied to compare the technical performance of the ELV reclamation options with respect to a set of assessment indicators relevant to the ELV recycling industry. The results will be analysed and the

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7 According to Sargent (2013), model verification is defined as ‘ensuring that the computer program of the computerised model and its implementation are correct’. Model validation is defined as the ‘substantiation that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model’.
best performed ELV reclamation options will be regarded as the most technically viable ELV reclamation options in the Australian context.

The third stage of the DSF is related to the sustainability assessment of the technically viable ELV reclamation options in the Australian context. The AHP technique will be applied to compare the sustainability performance of the technically viable ELV reclamation options against a set of Australian-specific sustainability assessment indicators. The results will be analysed and the best performed ELV reclamation option will be considered as the most sustainable ELV reclamation option in the Australian context.

The fourth stage identifies the most sustainable business model to implement the most sustainable ELV reclamation option that was selected in the previous stage. The existing business models relevant to the selected ELV reclamation options will be compared against each other through the AHP technique based. The assessment indicators will be the essential criteria that a successful business model should possess. The best performed business model will be advanced to the sustainability assessment step in which the sustainability performance of the business model will be tested through both the conceptual modelling method and the system dynamics method.

The behaviour-over-time (BOT) pattern mode of the business model will be used to comment on the sustainability performance of the business model. A desirable and validated BOT pattern mode will confirm the sustainability performance of the business model. If an undesirable BOT pattern mode was observed, some strategies will be developed and applied to make the business model sustainable.
Figure 3-4 Decision support framework (DSF) for system model for sustainable end-of-life vehicle treatment in the Australian context
3.3 DISCUSSION AND CONCLUSIONS

The decision support framework developed (Figure 3-4) is the main outcome of the chapter. The DSF illustrates how the present research will achieve its goal and objectives. It details the type and the purpose of the assessments included in the research and how these assessments are linked together.

One of the key observations of the proposed DSF is the notable presence of the AHP technique in the DSF. The technique will be used in the stages related to the technical and sustainability assessments of the ELV reclamation options:

1. Deep ELV dismantling for the collection and reuse of non-metallic parts
2. Remanufacturing of non-metallic auto-parts
3. Use of plastics from end-of-life vehicles as reducing agents in blast furnaces
4. Use of treated automobile shredder residue (ASR) as construction aggregate or other construction products
5. Thermal treatment of ASR and its co-incineration with other waste streams
6. Thermo-chemical treatment of ASR (pyrolysis and gasification)
7. Mechanical-physical separation of ASR to recover its materials

As stated earlier in Section 3.2.3.1, the AHP technique is one of the techniques used to conduct a multi-criteria assessment. As such, it can be concluded that the decision-making relating to the identification of a sustainable ELV reclamation option and its associated business model is fundamentally a multi-criteria decision-making process.

In addition to the multi-criteria assessment tool, the proposed DSF includes other assessment tools including conceptual modelling tool and the system dynamics tool. As stated earlier in Section 3.2.3.2 and Section 3.2.3.3, the conceptual modelling tool and the system dynamics tool are ‘system-based’ assessment tools. The conceptual modelling tool can create an abstract of a proposed system allowing an analysis of the feedback loops within the system and the system dynamics tool allows analysis of the behaviour of a system over time. As such, the sustainability assessment of a business model for ELV reclamation is fundamentally a system-based assessment.

The proposed DSF has been developed for the decision-making related to the sustainable treatment of non-metallic materials of ELV in the Australian context. However, it can be argued that the
proposed DSF is general enough to be used for the sustainable treatment of non-metallic materials of other end-of-life products in the Australian context or in the context of other countries. Examples of such end-of-life products include end-of-life airplanes, end-of-life ships, and end-of-life gymnasium equipment.

### 3.4 SUMMARY

The development of a customised DSF was found to be a challenging task as there are more than 30 sustainability assessment tools. An existing framework called ‘Framework for Sustainability Assessment Tools’ (or FSAT) helped identify the most applicable sustainability assessment tools for the research. A comprehensive analysis of the three clusters within the FSAT led to the conclusion that the characteristics of the tools included in one of the FSAT clusters, Integrated Assessment Cluster, are more relevant for the present research than the characteristics of the other clusters.

The chapter has provided the rationale for the selection of three, out of eight, sustainability assessment tools included in the Integrated Assessment Cluster to be used in the research. The rationale was also provided for the exclusion of other sustainability assessment tools in the research. A comprehensive overview of the selected sustainability assessment tools, namely the multi-criteria analysis tool, conceptual modelling tool, and system dynamics tool was then provided.

The key methodological aspects of the selected tools, including the methods to verify and validate the results of the selected sustainability assessment tools, were then described. The chapter described the DSF in detail, and concluded with a comprehensive discussion about the key aspects of the DSF and its potential application in decision-making related to the sustainable treatment of other end-of-life products.
4 Technical assessment of the end-of-life vehicle reclamation options

4.1 INTRODUCTION

The technical assessment of the ELV reclamation options is a multi-criteria decision-making (MCDM) assessment, as discussed in Chapter 3. The MCDM assessment involves many steps, including the identification of the assessment goal and the assessment indicators, the estimation of the relative importance of the assessment indicators, and the assessment of the alternatives (i.e. the international best practice ELV reclamation options) against the decision criteria (i.e. technical indicators). The assessment of the ELV reclamation options against the technical indicators (e.g. reliability) is based on the best available information in the literature. As such, no attempt is made in the chapter to measure quantitatively the performance on a specific technical indicator (e.g. measuring the reliability of a specific ELV reclamation option). The best available information in the literature is used for the pairwise comparison of the ELV reclamation options against the technical indicators, according to the procedure described in Section 3.2.4.

Prior to the technical assessment, a customised MCDM process diagram is developed showing the sequences of the assessment steps and how the steps are linked. The proposed MCDM provides a systematic approach to help identify the most technically viable ELV reclamation options in the Australian context. The proposed MCDM process is then used to conduct a comparative assessment of the ELV reclamation options to identify the most technically-viable ELV reclamation options in the Australian context.
4.2 A CUSTOMISED MULTI-CRITERIA DECISION-MAKING PROCESS FOR THE TECHNICAL ASSESSMENT

The conducted review in the previous section, focused on the international best practice ELV reclamation options, and provided a context for the technical assessment of the reviewed ELV reclamation options based on the Multi-Criteria Analysis (MCA) method.

The MCA studies often include many steps (Rousis et al., 2008, Mergias et al., 2007b, Milutinović et al., 2014, Babalola, 2015, Ahmed et al., 2016). These steps aim to (i) structure the decision problem (ii) represent and quantify its elements, (iii) relate those elements to an overall goal, and (iv) evaluate alternative solutions. Some research studies (Milutinović et al., 2014, Hajkowicz, 2008) have developed ‘weighting factor’ multi-criteria decision-making (MCDM) to systematically apply the MCA method and to facilitate the relevant decision-making process.

A MCDM process (based on the AHP method) was developed in this research (Figure 4-1) to systematically apply the MCA method in the technical assessment of the ELV reclamation options, and to facilitate the process of the identification of the most technically viable ELV reclamation options in the Australian context. This research used the MCDM process developed by Hajkowicz (2008), and the MCDM developed by Milutinović et al. (2014) as platforms for the development of a customised MCDM for the technical assessment of ELV reclamation options.

As indicated in Figure 4-1, the developed MCDM has ten steps, commencing from the definition of the goal of the MCDM analysis in Step 1. The goal of the decision-making process is to identify the most technically viable ELV reclamation options in the Australian context. Formulating the ELV reclamation options based on the best practice ELV reclamation options is the purpose of Step 2. The best practice ELV reclamation options introduced in Section 1.3 will be considered in the MCDM process.
Chapter 4

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>Goal: identify the most technically viable ELV reclamation options for Australia</td>
</tr>
<tr>
<td>Step 2</td>
<td>Formulate the best practice ELV reclamation options</td>
</tr>
<tr>
<td>Step 3</td>
<td>Identify a set of relevant technical indicators</td>
</tr>
<tr>
<td>Step 4</td>
<td>Structure the decision hierarchy according to the goal</td>
</tr>
<tr>
<td>Step 5</td>
<td>Determine the weighting factors of the selected technical indicators</td>
</tr>
<tr>
<td>Step 6</td>
<td>Develop the pairwise comparison matrix of the assessment</td>
</tr>
<tr>
<td>Step 7</td>
<td>Identify the performance ranking of the ELV reclamation options with respect to each technical indicator and with respect to the goal of the assessment</td>
</tr>
<tr>
<td>Step 8</td>
<td>Identify the ELV reclamation options with the global priority greater than 0.5 as the most technically viable ELV reclamation options</td>
</tr>
<tr>
<td>Step 9</td>
<td>Examine the robustness of the results through a set of sensitivity tests</td>
</tr>
<tr>
<td>Step 10</td>
<td>Interpret the results of the sensitivity analysis and conclude the decision-making</td>
</tr>
</tbody>
</table>

Figure 4-1 MCDM process developed in this research to assess the technical performance of best practice ELV reclamation options

Step 3 identifies a set of technical indicators that are specific to the ELV recycling industry. The technical indicators will be identified through the literature review of the previously conducted ELV reclamation studies or the waste management studies. This is followed by the structuring of the MCDM ‘decision hierarchy’ in Step 4. The decision hierarchy shows the key elements of the
MCDM namely goal, technical indicators, and the best practice ELV reclamation options and illustrates how these elements are linked.

Step 5 focuses on the evaluation (weighing) of the relative importance of the technical indicators with respect to the goal of the analysis. This step is one of the most critical steps of a MCDA process (Babalola, 2015, Milutinović et al., 2014, Triantaphyllou, 2013). The pairwise comparison of the ELV reclamation options, with respect to the individual technical indicators and the assessment goals is conducted in Step 6. The performance ranking of the best practice ELV reclamation options in the Australian context is identified in Step 7. This will be achieved through the synthesis of the results of the pairwise comparisons with respect to the individual technical indicator. The ELV reclamation options will be ranked based on the amount of their ‘global weight’ (see Section 3.2.3.1) where the top ranked ELV reclamation has the global weight of 1 and the amount of the other ELV reclamation options would less than 1.

In Step 8, the most technically viable ELV reclamation options are identified based on their individual ‘global weight’. The research considers the ELV reclamation options with the ‘global weight’ of more than 0.5, with respect to the assessment goal, as the most technically viable ELV reclamation options. A ‘global weight’ of less than 0.5 for an ELV reclamation option implies that the difference between the technical performance of that ELV reclamation option and the technical performance of the first ranked ELV reclamation option, with respect to the requirements of the technical indicators, is more than 50%. The relatively poor performance of that ELV reclamation is regarded in the present research as the main barrier for the adoption of the ELV reclamation option by the Australian ELV recycling industry.

In Stage 9 a set of sensitivity tests is used to assess the robustness of the identified performance ranking of the ELV reclamation options. The final stage of the MCDM, Stage 10, interprets the results of the main multi-criteria assessment and its related sensitivity tests. Stage 10 concludes the MCDM process by the identification of technically viable ELV reclamation options in the Australian context.
4.3 TECHNICAL ASSESSMENT OF THE END-OF-LIFE VEHICLE RECLAMATION OPTIONS

4.3.1 Technical assessment indicators

Technical indicators, according to Staikos and Rahimifard (2007b), should be product-specific, otherwise the list will be endless (Staikos and Rahimifard, 2007a). The technical indicators presented in two ELV reclamation studies (Mergias et al., 2007a, Ahmed et al., 2016) were considered in this research, as presented in Table 4-1.

<table>
<thead>
<tr>
<th>Study</th>
<th>Technical indicator</th>
<th>Description/example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mergias et al.</td>
<td>(1) Functionality</td>
<td>The potential of constant and smooth operation and the simplicity of operation</td>
</tr>
<tr>
<td>(2007a)</td>
<td>(2) Existing experience – reliability</td>
<td>The existence of experience relevant to the treatment practice or similar treatment practices</td>
</tr>
<tr>
<td></td>
<td>(3) Adapatability to local conditions</td>
<td>Unhindered application of the treatment practice in the region considered in the study (e.g., available quantities of waste for management, minimal required capacity for the practice to remain viable, etc.)</td>
</tr>
<tr>
<td></td>
<td>(4) Flexibility</td>
<td>The adjustment ability of the treatment practice to the potential changes in the quantity of non-metallic materials of ELVs</td>
</tr>
<tr>
<td>Ahmed et al.</td>
<td>(1) Technology transfer</td>
<td>Technological flexibility, capability and availability for ELVs management</td>
</tr>
<tr>
<td>(2016)</td>
<td>(2) Green technology innovation</td>
<td>Environmental technology innovation for ELV Management</td>
</tr>
<tr>
<td></td>
<td>(3) Research &amp; development (R&amp;D) for new product</td>
<td>Capability and availability of R&amp;D and design for recovery</td>
</tr>
<tr>
<td></td>
<td>(4) Expert’s decisions &amp; skill manpower</td>
<td>Technological decision for disassembly, remanufacturing, recycling and energy recovery and availability of skilled workforce</td>
</tr>
</tbody>
</table>

For this study, the four technical indicators proposed in the research by Mergias et al. (2007a) are considered more appropriate than the four indicators proposed by Ahmed et al. (2016). In Mergias et al. (2007a), the proposed technical indicators were applied to assess the technical performance of a set of ELV reclamation options for Cyprus. However, in Ahmed et al. (2016), the technical
indicators were not used to compare the technical performance of a set of ELV reclamation options. That research only evaluated the relative importance of the indicators with respect to the goal of the study through the application of two different MCDM techniques (i.e. the AHP method and a modified version of the AHP method). As such, the suitability of the technical indicators developed by Ahmed et al. (2016) in the assessment of a set of ELV reclamation options is yet to be determined.

### 4.3.2 Decision hierarchy for the technical assessment

A decision hierarchy in the AHP method deconstructs the decision to be made into a hierarchy to capture the essential variables (goal, criteria, alternatives) of the problem (Staikos and Rahimifard, 2007a). A decision hierarchy was developed in the present research (Figure 4-2) consisting of three levels. The top level represents the overall objective or goal of the problem. The criteria (the technical indicators) upon which this goal is dependent are assigned in the second level. The lower level of the hierarchy contains the alternatives (i.e. the best practice ELV reclamation options) through which the goal may be achieved.
Figure 4-2 Decision hierarchy developed in the research for technical assessment of the best practice ELV reclamation option in the Australian context
4.3.3 Relative importance of the technical indicators

In the present research, the relative importance of each individual assessment indicator, either the technical or sustainability indicator, to the goal of the relevant assessment is represented by a term called ‘weighting factor’. This factor has been differently named in the literature. For instance, in the research by Mergias et al. (2007a), it has been called ‘weight coefficients’ and it was presented in that research as a percentage (%).

As stated earlier in Section 4.3.1, the technical indicators of the present research are those used in the research by Mergias et al., (2007). Likewise, the weighting factors of the technical indicators in the present research are those used in the research by Mergias et al., (2007). The weighting factors are presented in Table 4-2. A set of sensitivity tests in this chapter will determine the sensitivity of the results (i.e. the ranking order of the ELV reclamation options) with respect to the quantities of the weighting factors.

<table>
<thead>
<tr>
<th>Technical indicator</th>
<th>Weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality</td>
<td>0.25</td>
</tr>
<tr>
<td>Existing experience – reliability</td>
<td>0.30</td>
</tr>
<tr>
<td>Adaptability to local conditions</td>
<td>0.25</td>
</tr>
<tr>
<td>Flexibility</td>
<td>0.20</td>
</tr>
</tbody>
</table>

As indicated in Table 4-2, the technical indicator of ‘Existing experience – reliability’ is the most important technical indicator to the goal, and the indicator of ‘Flexibility’ is the least important technical indicator to the goal. Two technical indicators of ‘Functionality’ and ‘Adaptability to local conditions’ are equally important to the goal of the technical assessment.

4.3.4 Pairwise comparison matrix of the technical assessment

The numerical scale presented in Table 3-5 was used to make pairwise comparison among the international best practice ELV reclamation options (Table 1-6), with respect to the individual technical indicator. The results are presented in Table 4-3. An overview of the considerations related to the judgements made about the relative abilities of the ELV reclamation options (as
listed below) to meet the requirements of the individual technical indicators is provided in this section:

Option 1: Deep ELV dismantling for the collection and reuse of non-metallic parts
Option 2: Remanufacturing of non-metallic parts of ELVs
Option 3: Use of ELV plastics as reducing agents in blast furnaces
Option 4: Use of treated ASR as construction aggregate or other construction products
Option 5: Thermal treatment of ASR and its co-incineration with other waste streams
Option 6: Thermo-chemical treatment of ASR (pyrolysis, and gasification)
Option 7: Mechanical-physical separation of ASR to recover its materials

Technical indicator of ‘Functionality’: As presented in Table 4-1, the key requirements of the technical indicator are constant and smooth operation of the ELV reclamation options and their simplicity of operation. Option 1 is a manual ELV reclamation option and its operation is not a simple operation. To reclaim non-metallic materials of ELVs through Option 2, the remanufacturing of a large number of ELV parts are required. As such, whilst Option 2 is not a manual operation, it is not regarded as a simple operation.

Option 3 is a relatively simple operation involving the separation and collection of easy access plastics parts (e.g. bumpers) and their transportation to blast furnaces. The option can be carried out in a constant and smooth state. In Option 4, ASR should be passed through a pre-treatment stage to ensure it contains an acceptable level of hazardous chemicals. The treated ASR then can be used as construction aggregate or other construction products. The pre-treatment stage adds some complexity to the ELV reclamation option.

Option 5 is a relatively simple operation that can be carried out in a smooth and constant state. The major processes involved in the ELV reclamation option are the collection and transport of ASR to a waste incinerator. As for Option 5, Option 6 also involves two smooth and simple processes of the collection and the transportation of ASR to a treatment plant. Option 7, in comparison to Option 5 and Option 6, involves more ASR separation processes. However, the separation processes are automatic and can be carried out in a smooth and constant state.
Technical indicator of ‘Existing experience – reliability’: As presented in Table 4-1, the key requirement of the technical indicator is the existence of experience relevant to the ELV reclamation options or similar treatment practices. The existence of experience relevant to Option 7 is considered more than the existence experience relevant to the other options. At present, televisions and computers are covered by the relevant Australian product stewardships schemes. The discarded televisions and computers are collected across Australia and their non-metallic materials are reclaimed through the mechanical-physical separation technology. The existence of experience about other individual options is almost the same. A thermo-chemical plant is in the construction stage in Western Australia and some small thermo-chemical plants are in operation across Australia.

Technical indicator of ‘Adaptability to local conditions’: As presented in Table 4-1, the key requirement of the technical indicator is unhindered application of the ELV reclamation options in the region considered in the study (e.g., available quantities of waste for management, minimal required capacity for the practice to remain viable, etc.). The number of ELVs in Australia per one car brand is not significant (see Section 2.3). This limits the adaptability of Option 1 and Option 2 to Australian conditions. These two options are based on the reuse and remanufacturing of non-metallic materials of ELVs. The adaptability of the other options to Australian conditions are not greatly different from each other.

Technical indicator of ‘Flexibility’: As presented in Table 4-1, the key requirement of the technical indicator is the adjustment ability to the potential changes in the quantity of non-metallic materials of ELVs. From the technical perspective, little technical changes are needed to be made in the processes involved in Option 1 and Option 3 when the quantity of non-metallic materials of ELVs is reduced. However, some changes should be made in the processes involved in Option 5, Option 6, and Option 7. A reduction in the quantity of non-metallic materials might result in an increase in metallic materials such as lightweight metal alloys. As such, in Option 7, for example, some of the existing separation processes might be replaced with the new processes capable of separating the new materials. This indicates that Option 7 has less flexibility than the compared options of Option 1 and Option 3.
Table 4-3 Pairwise comparison matrix related to the technical assessment of the ELV reclamation options

<table>
<thead>
<tr>
<th>Technical indicator</th>
<th>Option 1</th>
<th>ELV reclamation options</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4</th>
<th>Option 5</th>
<th>Option 6</th>
<th>Option 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>1/2</td>
<td>1/5</td>
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<td>1/5</td>
<td>1/5</td>
<td>1/2</td>
<td>1/4</td>
</tr>
<tr>
<td>Option 2</td>
<td>2</td>
<td>1</td>
<td>1/5</td>
<td>1/4</td>
<td>1/5</td>
<td>1/5</td>
<td>1/2</td>
<td>1</td>
</tr>
<tr>
<td>Option 3</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Option 4</td>
<td>2</td>
<td>4</td>
<td>1/4</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Option 5</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>3</td>
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<td>Option 6</td>
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<td>5</td>
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<tr>
<td>Option 7</td>
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<td>1/5</td>
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<td>1</td>
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<tr>
<td>Existing experience – reliability</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>1/4</td>
<td>1/8</td>
<td></td>
</tr>
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<td>1/2</td>
<td>1/2</td>
<td>1</td>
<td>1/4</td>
<td>1/7</td>
<td></td>
</tr>
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<td>Option 6</td>
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<td>4</td>
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<td>8</td>
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<tr>
<td>Adaptability to local conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Option 1</td>
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<td>1/5</td>
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<td>1/3</td>
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<td>1/4</td>
</tr>
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<td>Option 2</td>
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<td>1/4</td>
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<td>1/4</td>
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</tr>
<tr>
<td>Option 3</td>
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<td>5</td>
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</tr>
<tr>
<td>Option 4</td>
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<td>1/5</td>
<td>1</td>
<td>2</td>
<td>1/3</td>
<td>1/3</td>
<td></td>
</tr>
<tr>
<td>Option 5</td>
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<td>1/2</td>
<td>1/4</td>
<td>1/2</td>
<td>1</td>
<td>1/3</td>
<td>1/3</td>
<td></td>
</tr>
<tr>
<td>Option 6</td>
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<td>4</td>
<td>1/2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Option 7</td>
<td>4</td>
<td>4</td>
<td>1/2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Flexibility</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Option 2</td>
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<td>1</td>
<td>1/3</td>
<td>1/3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Option 3</td>
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<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Option 4</td>
<td>1/2</td>
<td>3</td>
<td>1/3</td>
<td>1</td>
<td>4</td>
<td>3</td>
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<tr>
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<td>3</td>
<td></td>
</tr>
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<td>Option 6</td>
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<td>1/3</td>
<td>1/3</td>
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<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Option 7</td>
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<td>1/4</td>
<td>1/3</td>
<td>1/3</td>
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<td></td>
</tr>
</tbody>
</table>
4.3.5 Results with respect to the individual technical indicator

The performance ranking of the ELV reclamation options with respect to the individual technical indicators are shown in Figure 4-3. The figure has been generated through application of the Expert Choice software as per the mathematical processes described in Appendix C.

### Synthesis with respect to: Functionality

<table>
<thead>
<tr>
<th>Option</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo-chemical treatment of ASR (pyrolysis, and gasification)</td>
<td>1.000</td>
</tr>
<tr>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>.897</td>
</tr>
<tr>
<td>Thermal treatment of ASR and its co-incineration with other waste streams</td>
<td>.897</td>
</tr>
<tr>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>.380</td>
</tr>
<tr>
<td>Use of treated ASR as construction aggregate or other construction products</td>
<td>.309</td>
</tr>
<tr>
<td>Remanufacturing of non-metallic parts of ELVs</td>
<td>.155</td>
</tr>
<tr>
<td>Deep ELV dismantling for the collection and reuse of non-metallic parts</td>
<td>.138</td>
</tr>
</tbody>
</table>

Overall Inconsistency = .05

### Synthesis with respect to: Existing experience and reliability

<table>
<thead>
<tr>
<th>Option</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>1.000</td>
</tr>
<tr>
<td>Thermo-chemical treatment of ASR (pyrolysis, and gasification)</td>
<td>.262</td>
</tr>
<tr>
<td>Deep ELV dismantling for the collection and reuse of non-metallic parts</td>
<td>.248</td>
</tr>
<tr>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>.121</td>
</tr>
<tr>
<td>Use of treated ASR as construction aggregate or other construction products</td>
<td>.103</td>
</tr>
<tr>
<td>Remanufacturing of non-metallic parts of ELVs</td>
<td>.098</td>
</tr>
<tr>
<td>Thermal treatment of ASR and its co-incineration with other waste streams</td>
<td>.067</td>
</tr>
</tbody>
</table>

Overall Inconsistency = .06

### Synthesis with respect to: Adaptability to local conditions

<table>
<thead>
<tr>
<th>Option</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>1.000</td>
</tr>
<tr>
<td>Thermo-chemical treatment of ASR (pyrolysis, and gasification)</td>
<td>.631</td>
</tr>
<tr>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>.631</td>
</tr>
<tr>
<td>Use of treated ASR as construction aggregate or other construction products</td>
<td>.320</td>
</tr>
<tr>
<td>Thermal treatment of ASR and its co-incineration with other waste streams</td>
<td>.216</td>
</tr>
<tr>
<td>Remanufacturing of non-metallic parts of ELVs</td>
<td>.182</td>
</tr>
<tr>
<td>Deep ELV dismantling for the collection and reuse of non-metallic parts</td>
<td>.162</td>
</tr>
</tbody>
</table>

Overall Inconsistency = .06

### Synthesis with respect to: Flexibility

<table>
<thead>
<tr>
<th>Option</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>1.000</td>
</tr>
<tr>
<td>Deep ELV dismantling for the collection and reuse of non-metallic parts</td>
<td>.852</td>
</tr>
<tr>
<td>Use of treated ASR as construction aggregate or other construction products</td>
<td>.670</td>
</tr>
<tr>
<td>Remanufacturing of non-metallic parts of ELVs</td>
<td>.311</td>
</tr>
<tr>
<td>Thermo-chemical treatment of ASR (pyrolysis, and gasification)</td>
<td>.298</td>
</tr>
<tr>
<td>Thermal treatment of ASR and its co-incineration with other waste streams</td>
<td>.258</td>
</tr>
<tr>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>.163</td>
</tr>
</tbody>
</table>

Overall Inconsistency = .05

Figure 4-3 Performance ranking of the ELV reclamation options with respect to the individual technical indicators
4.3.6  Results with respect to the goal of the technical assessment

The performance ranking of the ELV reclamation options with respect to the assessment goal is shown in Figure 4-4. The figure has been generated through application of the Expert Choice software as per the mathematical processes described in Appendix C.

<table>
<thead>
<tr>
<th>Synthesis with respect to:</th>
<th>Goal: identification of the most technically viable ELV reclamation options for Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>1.000</td>
</tr>
<tr>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>.825</td>
</tr>
<tr>
<td>Thermo-chemical treatment of ASR (pyrolysis, and gasification)</td>
<td>.767</td>
</tr>
<tr>
<td>Thermal treatment of ASR and its co-incineration with other waste streams</td>
<td>.492</td>
</tr>
<tr>
<td>Use of treated ASR as construction aggregate or other construction products</td>
<td>.454</td>
</tr>
<tr>
<td>Deep ELV dismantling for the collection and reuse of non-metallic parts</td>
<td>.453</td>
</tr>
<tr>
<td>Remanufacturing of non-metallic parts of ELVs</td>
<td>.248</td>
</tr>
</tbody>
</table>

Overall Inconsistency = .04

Figure 4-4 Performance ranking of the ELV reclamation options with respect to the goal of the technical assessment

As indicated in Figure 4-4, three ELV reclamation options have achieved the global weight of more than 0.5. These ELV reclamation options, subject to the results of the sensitivity analysis, are the most technically viable ELV reclamation options in the Australian context (see Section 4.2).

4.3.7  Sensitivity analysis of the technical assessment

As stated in Section 4.3.6, there is a noticeable difference between the global priority of the third and the fourth ranked ELV reclamation options (see Figure 4-4). The global priority of the fourth ranked ELV reclamation option and the global priority of the individual ELV reclamation options, following the fourth ranked ELV reclamation options, are less than 0.5. This implies that these ELV reclamation options, in comparison to the top three best ranked ELV reclamation options, have performed poorly against the technical indicators.

The main purpose of the sensitivity tests is to examine if the top three best ranked ELV reclamation options (see Figure 4-4) can maintain their positions as the best ranked ELV reclamation options when the weighting factors of the technical indicators are changed. This would create sufficient confidence to regard the top three best ranked ELV reclamation options as the most technically viable ELV reclamation options in the Australian context.
Four sensitivity tests were conducted to determine the sensitivity of the performance ranking of the ELV reclamation options (with respect to the goal of the assessment), to the applied weighting factors of the technical indicators. In each of the tests, the weighting factor of one of the technical assessment indicators was assigned twice (i.e. the value of 0.4) for the weighting factor of every other three indicators (the value of 0.2). The normalised results of the sensitivity tests are presented in Figure 4-5 to Figure 4-8. These figures have been generated through application of the Expert Choice software as per the mathematical processes described in Appendix C.

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**Figure 4-5 Performance ranking of the ELV reclamation options based on the weighting factor of 0.4 for the technical indicator of ‘functionality’ and the weighting factor of 0.2 for the other technical indicators**

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**Figure 4-6 Performance ranking of the ELV reclamation options based on the weighting factor of 0.4 for the technical indicator of ‘existing experience’ and the weighting factor of 0.2 for the other technical indicators**

---

**Figure 4-7 Performance ranking of the ELV reclamation options based on the weighting factor of 0.4 for the technical indicator of ‘adaptability’ and the weighting factor of 0.2 for the other technical indicators**
Figure 4-8 Performance ranking of the ELV reclamation options based on the weighting factor of 0.4 for the technical indicator of ‘flexibility’ and the weighting factor of 0.2 for the other technical indicators

4.3.8 Interpretation of the results of the technical assessment

An effective approach to interpret the results of the technical assessment, with respect to the goal of the assessment, is to simultaneously consider the relative weighting factors of the technical assessment (Table 4-2) and the performance ranking of the ELV reclamation options with respect to the individual assessment indicators (Figure 4-3).

As presented in Table 4-2, the technical assessment indicators have different weighting factors ranging from 0.3 (or 30% of the total weighting factor) for the technical indicator of ‘existing experience – reliability’ to 0.2 (or 20% of the total weighting factor) for the technical indicator of ‘flexibility’. As such, it is more important that an ELV reclamation option performs better against the technical indicator of ‘existing experience – reliability’ than performing better against the technical indicator of ‘flexibility’. This could partially justify why the ELV reclamation option of ‘use of treated ASR as construction aggregate or other construction products’ is not among the top four ranked ELV reclamation options shown in Figure 4-4 even though that option performed relatively well against the technical indicator of ‘flexibility’.

When the weighting factors of the technical indicators were changed, the performance ranking of the ELV reclamation options were changed (Figure 4-5 to Figure 4-7). However, the top three ranked ELV reclamation options based on the main assessment (Figure 4-4) were able to maintain their positions as the top three ranked ELV reclamation options in all of the conducted sensitivity tests. This creates enough confidence for the identification of the top three ranked ELV reclamation options as the most technically viable ELV reclamation options in the Australian context.
4.4 TECHNICALLY VIABLE ELV RECLAMATION OPTIONS IN THE AUSTRALIAN CONTEXT

The results of both technical assessment and its related sensitivity analysis provide enough confidence to identify the following international best practice ELV reclamation options as the most technically viable ELV reclamation options in the Australian context:

1. Use of ELV plastics as reducing agents in blast furnaces
2. Mechanical-physical separation of ASR to recover its materials
3. Thermo-chemical treatment of ASR (pyrolysis and gasification).

The other four investigated international best practice ELV reclamation options are considered technically unviable in the Australian context at the present time.

4.5 DISCUSSION AND CONCLUSIONS

One of the key outcomes of the chapter is the development of a multi-criteria decision-making (MCDM) process that helped apply the multi-criteria analysis (MCA) method in the research which systematically compared the technical performance of the international best practice ELV reclamation options against a set of relevant technical indicators in the Australian context.

It can be argued that the MCDM developed in the chapter is general enough to apply to the technical assessment studies related to the treatment of non-metallic materials of other end-of-life products such as end-of-life aircrafts and end-of-life ships. Furthermore, the MCDM is not a region-specific decision-making support framework; as such, it can be used both in Australia and elsewhere for the decisions related to the end-of-life treatment practices of a broad range of products.

Another important outcome of the chapter is the identification of the most technically viable ELV reclamation options in the Australian context. This outcome is new to the present research as no previously conducted research has identified a set of technically viable ELV reclamation options for Australia. The analysis conducted in the chapter concluded that the performances of three international best practice ELV reclamation options against the applied technical indicators are far better than the other four ELV reclamation options.
In this chapter the robustness of the above conclusion is tested through a comprehensive sensitivity analysis in which the relative importance of each of the applied technical indicators, with respect to the assessment goal, was significantly changed. The results of the sensitivity analysis confirmed the conclusion made in the assessment. This provided enough confidence to regard the three best performed ELV reclamation options as the most technically viable ELV reclamation options in the Australian context.

4.6 SUMMARY

This chapter initially provided a comprehensive overview of the international best practice ELV reclamation options that were listed in Table 1-6. The overview included some discussions about the challenges and opportunities associated with each individual ELV reclamation option in Australia. The overview provided a context for the technical assessment of the international best practice ELV reclamation options in the chapter.

The chapter continued with the development of a customised multi-criteria decision-making (MCDM) process that showed the sequences of the steps involved in the planned technical assessment and expressed how these steps are linked. The MCDM provided a systematic approach to help identify the most technically viable ELV reclamation options in the Australian context.

An important step in the MCDM was the identification of the technical indicators and the evaluation of the relative importance (weighting factor) of the indicators with respect to the goal of the technical assessment. The research conducted a comprehensive literature analysis to identify the technical indicators and their respective weighting factors. The technical indicators provided in two existing ELV studies were analysed. The analysis concluded that the technical indicators provided in one of the studies were more suitable to be used in the present research. These indicators were (1) functionality, (2) existing experience-reliability, (3) adaptability to local conditions, and (4) flexibility. The chapter also applied the same weighting factors that were used in the research that developed the technical indicators.

The MCA analysis of the ELV reclamation options was conducted based on the principles of a MCA technique called ‘Analytical Hierarchy Process (AHP)’. According to the first principle of the AHP technique, the problematic decision was deconstructed into a hierarchy containing three levels namely: (1) goal, (2) assessment criteria (the technical indicators), and (3) alternatives (the
ELV reclamation options). Based on the second principle of the AHP technique, the relative importance of the elements within each level of the hierarchy was evaluated with respect to the individual elements located in an upper level. The evaluation was conducted through the pairwise comparison approach.

Two sets of the pairwise comparisons were made. In the first set, the relative abilities of the ELV reclamation options to meet the requirements of the technical indicators were identified. This drove the ‘local’ priorities or the performance ranking of the ELV reclamation options with respect to the technical indicators. In the second set, the relative importance of the individual technical indicators with respect to the assessment goal was identified. This drove the ‘weighting factors’ of the technical indicators.

Based on the third principle of the AHP technique, the results were synthesised through the multiplication of the ‘local priority’ of a specific ELV reclamation option and the ‘weighting factor’ of the relevant technical indicator and then added together the multiplication results. The analysis produced the ‘global priorities’ of the ELV reclamation options. The calculated amounts of the ‘global priorities’ were used to develop the performance ranking of the ELV reclamation options with respect to the assessment goal.

The research considered the ELV reclamation options with the ‘global priorities’ between 0.5 to 1 as the technically viable ELV reclamation options in the Australian context and, with the ‘global priorities’ less than 0.5, as the ELV reclamation options that are not currently technically viable in Australia. Three of the ELV reclamation options had ‘global priorities’ between 0.5 to 1; and as such were identified as the most technically viable ELV reclamation options in the Australian context. The most technically viable ELV reclamation options were identified as: (1) injection of ELV plastics as reducing agents in blast furnaces, (2) thermo-chemical treatment of automobile shredder residue (ASR), and (3) mechanical-physical separation of ASR.
5 Sustainability assessment of the end-of-life vehicle reclamation options

5.1 INTRODUCTION

In this chapter, the sustainability performance of the three international best practice ELV reclamation options in the Australian context is assessed. These ELV reclamation options have already been identified as the most technically-viable ELV reclamation options for Australia (see Section 4.4).

As discussed in Section 2.5.9, the sustainability assessment of a set of ELV reclamation options can be conducted through two models: an established model called ‘triple bottom line (TBL)’, and an emerging model called, in the present research, ‘multi-dimensionality’. This chapter will apply both sustainability assessment models.

The sustainability assessment tool of multi-criteria analysis (MCA) is applied to identify the most sustainable ELV reclamation option for Australia. As the MCA method involves many steps, initially a customised multi-criteria decision-making (MCDM) process is developed. The MCDM process involves many steps, including the identification of the assessment goal and the assessment indicators, the estimation of the relative importance of the assessment indicators, and the assessment of the alternatives (i.e. the ELV reclamation options) against the decision criteria (i.e. sustainability indicators). The assessment of the ELV reclamation options against the sustainability indicators (e.g. climate change mitigation) is based on the best available information in the literature. As such, no attempt is made in the chapter to measure the actual amount of a specific sustainability indicator (e.g. measuring the climate change impact of a specific ELV reclamation option). The best available information in the literature is used for the pairwise comparison of the ELV reclamation options against the sustainability indicators, according to the procedure described in Section 3.2.4.
An important step in the sustainability assessment of the ELV reclamation options is the identification of the Australian-based sustainability assessment indicators, and the evaluation of the relative importance of the sustainability indicators with respect to the goal of the assessment. A comprehensive analysis in conducted in the chapter to identify the most relevant assessment indicators, and the relative importance (weighting factors) of the indicators with respect to the assessment goal. The previous research studies have highlighted the effects of the applications of different weighting factors on the results of a MCA study. Here a comprehensive sensitivity analysis is conduct in which different weighting factors will be assigned to assessment indicators. The results of sensitivity tests are critical in the decision-making regarding the identification of the most sustainable ELV reclamation option in the Australian context.

5.2 A customised MCDM process for the sustainability assessment

A MCDM process, based on the AHP method, has been developed in this research (Figure 5-1) to facilitate the process of decision-making regarding the identification of the most sustainable ELV reclamation options for Australia. As indicated in Figure 5-1, the developed MCDM has ten steps, commencing from the definition of the goal of the MCDM analysis (step 1), that is, the identification of the most sustainable ELV reclamation options for Australia. Step 2 focuses on the identification of the alternatives (i.e. ELV reclamation options) for this MCDM analysis. These alternatives have already identified in Chapter 4 (see Section 4.4) based on the technical assessment of international best practice ELV reclamation options in the Australian context.

Step 3 includes a literature review to identify the most relevant indicators for the sustainability assessment of the research. These indicators will be applied in both the considered sustainability assessments of the TBL model as well as the multi-dimensionality model. For the multi-dimensionality model, the number of the sustainability dimensions that each individual indicator represents is determined through an evidence-based analysis.

A decision hierarchy is constructed in step 4 to show how the key elements of the assessment namely goal, criteria (i.e. sustainability assessment indicators) and the alternatives (i.e. the ELV reclamation options) are linked together. Step 5 focuses on the estimation of the weighting factors of the sustainability assessment indicators based on their relative importance to the goal of the analysis.
The comparative assessments of the ELV reclamation options against the selected sustainability indicators are conducted in Step 6. The comparative assessment will be based on the pairwise comparisons of the ELV reclamation options with respect to the sustainability assessment indicators. The performance ranking of the ELV reclamation options is identified in Step 7. To achieve this, the results of the conducted pairwise comparisons are synthesised, considering the relative importance of the individual sustainability indicators to be the goal.
Step 1: Goal: identification of the most sustainable ELV reclamation option for Australia

Step 2: Formulate the ELV reclamation options

Step 3: Identify a set of Australian-specific sustainability indicators

Step 4: Structure the decision hierarchy of the AHP technique

Step 5: Identify the relative importance (weighting factor) of each sustainability indicator

Step 6: Develop the pairwise comparison matrix of the AHP technique

Step 7: Identify the performance ranking of the ELV reclamation options with respect to each sustainability indicator and with respect to the goal of the assessment

Step 8: Is there more than 10% difference between the amounts of the global priority of the first and the second ranked ELV reclamation options?

- No
  - Repeat the sustainability assessment from Step 5.
- Yes
  - Increase the number of sustainability indicators

Step 9: Examine the robustness of the preference ranking of the ELV reclamation options with respect to the goal of the assessment through conducting a set of sensitivity tests

Step 10: Interpret the results of the sensitivity analysis and conclude the decision-making

Figure 5-1 MCDM process developed in this research to select the most sustainable ELV reclamation option for Australia
Step 8 tests if there is a reasonable difference (>10%) between the amounts of the global priority of the first and the second best ranked ELV reclamation options with respect to the goal of the assessment. If the condition is met, the MCDM process is advanced to step 9 in which the robustness of the identified performance ranking is tested through comprehensive sensitivity tests. Otherwise, the number of sustainability indicators is increased and the MCDM processes is started again from Step 5. Step 10 interprets the results of the base assessment and the results of the sensitivity tests, and concludes the decision-making process.

5.3 SUSTAINABILITY ASSESSMENT THROUGH THE MULTI-DIMENSIONAL MODEL

5.3.1 Sustainability assessment indicators

As discussed in Section 2.5.4, there is a significant inconsistency among the previously conducted ELV reclamation studies with respect to the applied assessment indicators representing the social, economic and environmental dimensions of sustainability. Thus, the scope for the selection of the sustainability assessment for this research is expanded from the literature related to ELV treatment studies, and covers the sustainability indicators that have been used in waste management studies.

According to Achillas et al. (2013), there are some assessment indicators that have been used frequently in waste management studies aimed at identifying an optimal waste management strategy for a region. These assessment indicators are presented in Table 5-1.

There are some issues associated with the direct application of the assessment indicators presented in Table 5-1 in this research. Some of the assessment indicators presented in Table 5-1 are strongly related to the technical aspects of the ELV reclamation options (e.g. technical reliability, feasibility). As the technical assessment of the ELV reclamation options has already been undertaken in this research (see Chapter 4), the technical assessment indicators presented in Table 5-1 should be excluded in the sustainability assessment of the research.
Table 5-1 Most frequently applied assessment criteria for the identification of optimal waste management strategy in the existing publications (Achillas et al., 2013)

<table>
<thead>
<tr>
<th>No.</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cost (capital and operational)</td>
</tr>
<tr>
<td>2</td>
<td>Technical reliability</td>
</tr>
<tr>
<td>3</td>
<td>Feasibility</td>
</tr>
<tr>
<td>4</td>
<td>Applicability</td>
</tr>
<tr>
<td>5</td>
<td>Environmental impacts (e.g. greenhouse gas emissions)</td>
</tr>
<tr>
<td>6</td>
<td>Employment</td>
</tr>
<tr>
<td>7</td>
<td>Waste-energy recovery</td>
</tr>
<tr>
<td>8</td>
<td>Diversion from landfill</td>
</tr>
<tr>
<td>9</td>
<td>Land demand</td>
</tr>
<tr>
<td>10</td>
<td>Population affected or served capacity</td>
</tr>
<tr>
<td>11</td>
<td>Safety and public health</td>
</tr>
<tr>
<td>12</td>
<td>Social acceptance</td>
</tr>
<tr>
<td>13</td>
<td>Risks</td>
</tr>
</tbody>
</table>

It can be also argued that one of the assessment indicators presented in Table 5-1, the assessment indicator of ‘land demand’, might not be an important sustainability assessment indicator for the studies focused on the comparative assessment of a set of waste treatment practices in the Australian context. There is some evidence of the wide-spread applications of some land-intensive waste treatment practices such as lagoons (for wastewater treatment) in Australia (Jensen et al., 2014, Mosse et al., 2011, Wilkinson, 2011), whereas these land-intensive treatment practices are not generally used in the countries such as Japan where land is scarce (JETRO, 2006). Thus, given the minor relevance of the assessment indicator of ‘land demand’ to the Australian conditions, this indicator is excluded in the research.

A modification in the name of the assessment indicators presented in Table 5-1 can facilitate the pairwise comparisons of the ELV reclamation options with respect to the assessment indicators. As recommended by the developer of the AHP technique (Saaty, 2008), consistent naming of the assessment indicators significantly reduces the risks of misjudgement in the pairwise comparison process. The names of the some of the assessment indicators presented in Table 5-1, including the indicator of ‘greenhouse gas emissions’, imply that the indicator represents a negative impact of
the waste treatment practices, whereas the name of some other indicators, including ‘diversion from landfill’, imply that the indicators represent a positive impact of the waste treatment practices.

Based on the above discussions, two changes were made in the assessment indicators presented in Table 5-1 to develop a list of sustainability assessment indicators for the present research (Table 5-2). Firstly, the technical indicators and the assessment indicator of ‘land demand’ were excluded based on the discussion made earlier in this section. Secondly, a consistent name was applied to the assessment indicators – an example being the change of name of the assessment indicator ‘employment’ to the modified name of ‘job creation’.

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Climate-change mitigation</td>
</tr>
<tr>
<td>2</td>
<td>Water conservation</td>
</tr>
<tr>
<td>3</td>
<td>Job creation</td>
</tr>
<tr>
<td>4</td>
<td>Safety and public health</td>
</tr>
<tr>
<td>5</td>
<td>Capital conservation</td>
</tr>
<tr>
<td>6</td>
<td>Social acceptance</td>
</tr>
<tr>
<td>7</td>
<td>Minerals conservation</td>
</tr>
<tr>
<td>8</td>
<td>Fossil fuel conservation</td>
</tr>
<tr>
<td>9</td>
<td>Landfill space conservation</td>
</tr>
</tbody>
</table>

### 5.3.2 Identification of the dimensionality of the sustainability indicators

The dimensionality of a sustainability assessment indicator is the number of the sustainability dimensions (i.e. social, economic and environmental) that is represented by that indicator. The indicators representing one, two, and three dimensions of sustainability are regarded as 1D, 2D, and 3D respectively (Table 5-3). The research by Vermeulen et al. (2012b) has already identified the dimensionality of the some of the sustainability assessment indicators that will be used in the present research. Given that the research by Vermeulen et al. (2012b) was based on the European context, there could some differences between the dimensionality assigned by the present research and those assigned by the research conducted by Vermeulen et al. (2012b).
Table 5-3 Dimensionality of the sustainability indicators considered in this research

<table>
<thead>
<tr>
<th>Sustainability indicator</th>
<th>Dimensionality</th>
<th>Represented sustainability dimension(s)</th>
<th>Evidence supporting the assigned dimensionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change mitigation</td>
<td>3D</td>
<td>societal, economic, environmental</td>
<td>As discussed earlier in this section.</td>
</tr>
<tr>
<td>Water conservation</td>
<td>3D</td>
<td>societal, economic, environmental</td>
<td>As discussed earlier in this section.</td>
</tr>
<tr>
<td>Job creation</td>
<td>2D</td>
<td>societal, economic</td>
<td>From the social perspective, creating new jobs, particularly in rural areas, positively improves the social well-being of the local community (Tonts et al., 2012, Domac et al., 2005). From the economic perspective, creating new jobs uses the money that otherwise would be paid to job seekers (DHS, 2013) to invest in the economy of the region.</td>
</tr>
<tr>
<td>Safety and public health</td>
<td>2D</td>
<td>societal, environmental</td>
<td>As described by Vermeulen et al. (2012b), the indicator helps achieve some social benefits including emitting less toxic materials which not only protects human health (a social benefit) but also protects the surrounding environment. The economic dimension of the indicator is self-explanatory. The social dimension is based on the research by Vermeulen et al. (2012b). That study argues that the indicator improves the general affordability of a community to adopt sustainable waste management options through conservation of capital.</td>
</tr>
<tr>
<td>Capital conservation</td>
<td>2D</td>
<td>societal, economic</td>
<td>The economic dimension of the indicator is self-explanatory. The social dimension is based on the research by Vermeulen et al. (2012b). That study argues that the indicator improves the general affordability of a community to adopt sustainable waste management options through conservation of capital.</td>
</tr>
<tr>
<td>Social Satisfaction</td>
<td>1D</td>
<td>societal</td>
<td>There is no evidence that the indicator can represent the economic and environmental dimensions of sustainability. The indicator has been considered as a social indicator in the ELV reclamation study conducted by Ahmed et al. (2016).</td>
</tr>
<tr>
<td>Minerals conservation</td>
<td>1D</td>
<td>environmental</td>
<td>The economic benefits of conserving minerals in Australia through the reclamation of non-metallic materials of ELVs would be insignificant, as minerals are plentiful and readily available in Australia (Geoscience Australia,</td>
</tr>
<tr>
<td>Sustainability indicator</td>
<td>Dimensionality</td>
<td>Represented sustainability dimension(s)</td>
<td>Evidence supporting the assigned dimensionality</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>----------------</td>
<td>-----------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Fossil fuel conservation</td>
<td>1D</td>
<td>environmental</td>
<td>The economic benefits of conserving fossil fuels in Australia through the reclamation of non-metallic materials of ELVs would be insignificant, as fossil fuels are plentiful and readily available in Australia (BREE, 2013). The relationship between conserving fossil fuels and the social dimension of sustainability (in the context of waste management) has been not documented to date. The relationship between the indicator, and the environmental dimension of sustainability, has been considered in the previously conducted ELV reclamation studies (Ahmed et al., 2016, Vermeulen et al., 2012a, Morselli et al., 2011, Ciacci et al., 2010b).</td>
</tr>
<tr>
<td>Landfill space conservation</td>
<td>1D</td>
<td>environmental</td>
<td>The indicator helps reduce the occupied land for the purpose of waste dumping. This reduces the risks of any environmental impact associated with landfill sites (e.g. leaking heavy metals to the groundwater resources). However, there is a lack of sufficient evidence to conclude that the indicator can contribute considerable social or financial benefits. There is no scarcity of landfill spaces in Australia (DEWHA, 2009a) and the current landfill spaces can be economically expanded, if required (DEWHA, 2009b).</td>
</tr>
</tbody>
</table>
5.3.3 Decision hierarchy for the sustainability assessment

As stated in Section 4.3.2, a decision hierarchy in the AHP method deconstructs the assessment decision into a hierarchy to capture the essential variables (goal, criteria, alternatives) of the problem (Staikos and Rahimifard, 2007a). A decision hierarchy was developed in this research (Figure 5-2) consisting of three levels. The top level represents the overall objective, or the goal of the problem. The criteria (the technical indicators) upon which this goal is dependent are located in the second level. The lower level of the hierarchy contains the alternatives (i.e. the technically viable ELV reclamtion options) through which the goal may be achieved.
Figure 5-2 Decision hierarchy developed in the research for sustainability assessment of the best practice ELV reclamation options in the Australian context.
5.3.4 **Relative importance of the sustainability assessment indicators**

No study has yet determined the relative importance (weighting factors) of a set of assessment indicators based on the multi-dimensionality model. The research by Vermeulen et al. (2012a) has applied the multi-dimensionality model for the sustainability assessment of a set of ELV reclamation options in the European context but concluded the research prior to the evaluation of the relative importance of the sustainability assessment indicators. As such, that study did not conclude which of the considered ELV reclamation options is the most sustainable ELV reclamation option.

In the absence of any recommended approach to estimate the weighting factors of the sustainability indicators, this research applies the ‘best case-worst case’ analysis. The analysis has been applied extensively in the environmental assessment studies including some waste management studies (Ongondo et al., 2011, Latsios et al., 2009, Sahely et al., 2006, Williams and Sasaki, 2003). Further to this some studies focused on renewable energy sources (Malik and Sukhera, 2012, Stichnothe and Schuchardt, 2011, Ajayebi et al., 2013), and others focused on life cycle assessment (LCA) studies (Edwards-Jones et al., 2009, Stamford and Azapagic, 2014).

The best case-worst case analysis often produces decision variable solutions for the two extremes which do not contain a set of stable intervals for generating decision alternatives (Yeomans et al., 2003). There is no generally accepted procedure to set the two extremes of best case-worst case analysis, and the extremes should be defined based on the decision variables that are considered in a study.

In this research, the extremes of the best case–worst case analysis are considered as two scenarios. The first scenario that is regarded here as the best-case scenario, the relative importance (weighting factor) of each indicator category (3D, 2D or 1D) is assumed to be proportional to the number of the sustainability dimensions that is covered by that category. This means that the weighting factor for the assessment indicator category of 3D is three times more than that of the category of 1D, and the relative importance of the assessment indicator category of 2D is twice that of the indicator category of 1D.
Based on the above described approach, the weighting factor of the 3D, 2D, and 1D indicator categories will be 50.00% of the total weightings, 33.44% of the total weightings, and 16.66% of the total weightings, respectively.

In the second scenario that is regarded here as worst-case scenario, an equal weighting factor is assumed for each of the assessment indicator categories of 3D, 2D, and 1D. As such, each assessment indicator category has the relative importance of 33.33%.

To calculate the relative importance (or the weighting factor) of each sustainability indicator, the weighting factor of the respective sustainability indicator group is divided by the total number of assessment indicators in that indicator category. The relative importance of the individual sustainability indicators in each category (3D, 2D, or 1D) for the best case scenario and for the worst case scenario are presented in Table 5-4 and Table 5-5 respectively.

<table>
<thead>
<tr>
<th>Sustainability indicator</th>
<th>Relevant indicator category (group)</th>
<th>Weighting factor of the relevant indicator category (group)</th>
<th>Weighting factor of the individual sustainability indicator*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change mitigation</td>
<td>3D</td>
<td>0.500</td>
<td>0.250</td>
</tr>
<tr>
<td>Water conservation</td>
<td>3D</td>
<td>0.500</td>
<td>0.250</td>
</tr>
<tr>
<td>Job creation</td>
<td>2D</td>
<td>0.333</td>
<td>0.110</td>
</tr>
<tr>
<td>Safety and public health</td>
<td>2D</td>
<td>0.333</td>
<td>0.110</td>
</tr>
<tr>
<td>Capital conservation</td>
<td>2D</td>
<td>0.333</td>
<td>0.110</td>
</tr>
<tr>
<td>Social acceptability</td>
<td>1D</td>
<td>0.250</td>
<td>0.042</td>
</tr>
<tr>
<td>Minerals conservation</td>
<td>1D</td>
<td>0.250</td>
<td>0.042</td>
</tr>
<tr>
<td>Fossil fuel conservation</td>
<td>1D</td>
<td>0.250</td>
<td>0.042</td>
</tr>
<tr>
<td>Landfill space conservation</td>
<td>1D</td>
<td>0.250</td>
<td>0.042</td>
</tr>
</tbody>
</table>

*The sum of the column is slightly less than one due to rounding precision.
Table 5-5 Relative importance (weighting factor) of the sustainability indicators in the worst case scenario

<table>
<thead>
<tr>
<th>Sustainability indicator</th>
<th>Relevant indicator category (group)</th>
<th>Weighting factor of the relevant indicator category (group)</th>
<th>Weighting factor of the individual sustainability indicator*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change mitigation</td>
<td>3D</td>
<td>0.333</td>
<td>0.166</td>
</tr>
<tr>
<td>Water conservation</td>
<td>3D</td>
<td>0.333</td>
<td>0.166</td>
</tr>
<tr>
<td>Job creation</td>
<td>2D</td>
<td>0.333</td>
<td>0.110</td>
</tr>
<tr>
<td>Safety and public health</td>
<td>2D</td>
<td>0.333</td>
<td>0.110</td>
</tr>
<tr>
<td>Capital conservation</td>
<td>2D</td>
<td>0.333</td>
<td>0.110</td>
</tr>
<tr>
<td>Social acceptability</td>
<td>1D</td>
<td>0.333</td>
<td>0.083</td>
</tr>
<tr>
<td>Minerals conservation</td>
<td>1D</td>
<td>0.333</td>
<td>0.083</td>
</tr>
<tr>
<td>Fossil fuel conservation</td>
<td>1D</td>
<td>0.333</td>
<td>0.083</td>
</tr>
<tr>
<td>Landfill space conservation</td>
<td>1D</td>
<td>0.333</td>
<td>0.083</td>
</tr>
</tbody>
</table>

*The sum of the column is slightly less than one due to rounding precision.

5.3.5 Pairwise comparison matrix of the sustainability assessment

The numerical scale presented in Table 3-5 was used to make pairwise comparison of the ELV reclamation options (as listed below) with respect to the sustainability indicators. The results are presented in Table 5-9. The rationale for each assigned numerical value is provided in this section:

Option 1: Use of ELV plastics as reducing agents in blast furnaces
Option 2: Thermo-chemical treatment of ASR
Option 3: Mechanical-physical separation of ASR to recover its materials

**Sustainability indicator of ‘climate change mitigation’**: The study conducted by Ciacci et al. (2010a) was regarded as a comprehensive information source for the comparison between Option 2 and Option 3. The study provides the performance of a set of ELV management scenarios against a broad range of environmental indicators as summarised in Table 5-6.
Given the exclusion of Option 3 in the study conducted by (Ciacci et al., 2010a), the pairwise comparisons related to that ELV reclamation option were based on other information sources, particularly the study conducted by GHK/Bios (2006) and the study conducted by Jenseit et al. (2003). The former study provides the environmental performance of a set of end-of-life management options for used car plastics and the latter provides the environmental performance of a set of end-of-life management options for used car bumpers (Table 5-7).

**Table 5-6 Environmental performance of different ELV management scenarios (Ciacci et al., 2010a)**

<table>
<thead>
<tr>
<th>Impact categories</th>
<th>Unit</th>
<th>End-of-life scenarios</th>
<th>Landfill</th>
<th>Further metals recovery</th>
<th>Thermal treatment with energy recovery</th>
<th>Advanced material recovery and incineration</th>
<th>Feedstock recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens</td>
<td>DALY</td>
<td>3.26E+03</td>
<td>3.03E+03</td>
<td>2.42E+05</td>
<td>-6.51E+05</td>
<td>-2.75E+04</td>
<td></td>
</tr>
<tr>
<td>Respiratory organics</td>
<td>DALY</td>
<td>1.11E+07</td>
<td>-4.63E+08</td>
<td>-1.14E+07</td>
<td>-1.22E+06</td>
<td>-1.19E+06</td>
<td></td>
</tr>
<tr>
<td>Respiratory inorganics</td>
<td>DALY</td>
<td>4.94E+05</td>
<td>-3.72E+04</td>
<td>-3.80E+04</td>
<td>-8.34E+04</td>
<td>-7.45E+04</td>
<td></td>
</tr>
<tr>
<td>Climate change</td>
<td>DALY</td>
<td>1.94E-05</td>
<td>-5.44E+05</td>
<td>1.98E+06</td>
<td>-1.17E+04</td>
<td>-1.66E+05</td>
<td></td>
</tr>
<tr>
<td>Human health total damage</td>
<td>DALY</td>
<td>3.33E+03</td>
<td>2.61E+03</td>
<td>-3.54E+04</td>
<td>-1.02E+03</td>
<td>-1.04E+03</td>
<td></td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>PDF<em>m²</em>yr</td>
<td>6.41E+01</td>
<td>-6.55E+00</td>
<td>1.13E+02</td>
<td>6.38E+01</td>
<td>-1.12E+02</td>
<td></td>
</tr>
<tr>
<td>Acidification/ Eutrophication</td>
<td>PDF<em>m²</em>yr</td>
<td>2.08E+00</td>
<td>-4.33E+00</td>
<td>-2.22E+00</td>
<td>-1.16E+01</td>
<td>-1.39E+01</td>
<td></td>
</tr>
<tr>
<td>Land use</td>
<td>PDF<em>m²</em>yr</td>
<td>2.16E+00</td>
<td>-5.70E+00</td>
<td>-8.37E+00</td>
<td>-7.76E+00</td>
<td>-1.32E+01</td>
<td></td>
</tr>
<tr>
<td>Ecosystem quality total damage</td>
<td>PDF<em>m²</em>yr</td>
<td>6.83E+01</td>
<td>-1.66E+01</td>
<td>1.02E+02</td>
<td>4.44E+01</td>
<td>-1.39E+02</td>
<td></td>
</tr>
<tr>
<td>Minerals</td>
<td>MJ surplus</td>
<td>9.59E+01</td>
<td>-2.00E+02</td>
<td>-2.00E+02</td>
<td>-2.05E+02</td>
<td>-3.17E+02</td>
<td></td>
</tr>
<tr>
<td>Fossil fuels</td>
<td>MJ surplus</td>
<td>9.95E+01</td>
<td>-2.08E+02</td>
<td>-6.49E+02</td>
<td>-2.08E+03</td>
<td>-1.63E+03</td>
<td></td>
</tr>
<tr>
<td>Resources depletion total damage</td>
<td>MJ surplus</td>
<td>1.00E+02</td>
<td>-4.08E+02</td>
<td>-8.48E+02</td>
<td>-2.29E+03</td>
<td>-1.95E+03</td>
<td></td>
</tr>
</tbody>
</table>

*DALY disability adjusted life year, PDF*m²*yr potentially disappeared fraction of plant species*

**Table 5-7 Environmental performance of different end-of-life management scenarios for car bumper (Jenseit et al., 2003)**

<table>
<thead>
<tr>
<th>Full life cycle (production, use and recycling option)</th>
<th>Landfill</th>
<th>Waste incin.</th>
<th>Cement kWh</th>
<th>Syngas-production</th>
<th>Blast furnace</th>
<th>Mech. Recyling</th>
<th>Product only</th>
<th>Use only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw material use</td>
<td>kg/a*1000</td>
<td>563</td>
<td>576</td>
<td>569</td>
<td>551</td>
<td>516</td>
<td>515</td>
<td>120</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>MJ</td>
<td>1128</td>
<td>1027</td>
<td>992</td>
<td>944</td>
<td>977</td>
<td>919</td>
<td>307</td>
</tr>
<tr>
<td>Emissions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>g CO₂-equiv</td>
<td>68.2E+3</td>
<td>72.9E+3</td>
<td>64.6E+3</td>
<td>67.6E+3</td>
<td>64.2E+3</td>
<td>9.3E+3</td>
<td>58.6E+3</td>
</tr>
<tr>
<td>POCP</td>
<td>g ethene-equiv</td>
<td>49</td>
<td>49</td>
<td>49</td>
<td>46</td>
<td>46</td>
<td>4</td>
<td>45</td>
</tr>
<tr>
<td>AP</td>
<td>g SO₂-equiv</td>
<td>210</td>
<td>210</td>
<td>210</td>
<td>174</td>
<td>199</td>
<td>161</td>
<td>81</td>
</tr>
<tr>
<td>Water</td>
<td>Critical volume in m³</td>
<td>945</td>
<td>822</td>
<td>801</td>
<td>915</td>
<td>795</td>
<td>700</td>
<td>132</td>
</tr>
<tr>
<td>Waste</td>
<td>Weight mass</td>
<td>3.2</td>
<td>3.0</td>
<td>3.1</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Sustainability indicator of ‘water conservation’:** Little water is used in Option 1 whereas the other two options use water in their processes. Option 3 involves several washing stages to remove impurities from the recycled materials (e.g. polyurethane as shown in Figure 5-3) (ANL, 2006,
Such level of water is not used in Option 2. Furthermore, the net electricity generated by Option 2 replaces the electricity generated by the coal burning power plants. In these plants, water is used for the cooling purposes. Therefore, Option 2 saves the cooling water which otherwise would be used for electricity generation.

In some cases, the produced secondary materials from Option 3 replace virgin materials. Depending on product type and the applied manufacturing process, the replacement of the virgin materials by the secondary materials might save some water which otherwise would be used to produce the virgin materials. It is considered that the net water saving from the replacement of the virgin materials by the secondary materials is not at the level to equal the net water saving of Option 2.

**Sustainability indicator of ‘job creation’**: There are some indicative data about the job creation potential of Option 2 and Option 3 (ANL, 2006, ANL, 2009, ANL, 2010). For example, a thermal-based ASR recycling plant has employed 50 people and a mechanical separation plant (for foam stream recycling) has employed five people (ANL, 2010).

With respect to the job creation potential of Option 1, little information is available in the literature. However, it can be considered that the main job creation opportunities by the option would be created by the plastics dismantling stage within car dismantlers. However, it would be less likely
that the majority of the Australian car dismantling facilities hire new staff for plastics dismantling under Option 1. This is based on the current average size of Australian car dismantling businesses. The average number of employees in the Australian car dismantling facilities is around four people and on average each facility treat around 600 ELVs per year or around 2 ELVs per day (see Section 2.3). It can be considered that available employees in each of the car dismantling facilities would be sufficient to remove the accessible plastics without the need of hiring new staff. The approximate time for removing 70 kg plastic parts would be around 60 minutes (Figure 5-4).

**Figure 5-4 Dismantling time for plastics removal from a typical ELV (GHK/Bios, 2006)**

**Sustainability indicator of ‘safety and public health’**: All three options are considered to be safe and free from a risk to the public health. No evidence was found indicating any potential safety risk from the viable ELV reclamation options. As such, the assigned numerical values to the pairwise comparisons of the options with respect to the considered sustainability assessment indicator are in the numerical scale of 1 and 2.

Both Option 2 and Option 3 were considered to have the same level of risks to the workers. Given the application of some washing chemicals in Option 3, the research weakly favours Option 2 against Option 3.

**Sustainability indicator of ‘capital conservation’**: the indicative treatment costs of Option 2 and Option 3 for different technologies are provided in Figure 5-5.
As indicated in Figure 5-5, the indicative cost of ASR treatment for Option 2 (the TwinRec gasification process) is around €90 (approximately A$130), whereas the indicative treatment cost for Option 3 is between €20 (the Sicon process) to €65 (the Reshment process). In the pairwise comparison, the treatment cost of the gasification process was compared to the most costly process. The experience and judgement of the candidate moderately (plus) favours to Option 3. The capital investment required for Option 1 was considered insignificant as the plastic materials are injected to the existing blast furnaces.

Sustainability indicator of ‘social satisfaction’: The research equally favours towards both Option 2 and Option 3. Option 1 is based on the treatment of non-metallic materials of ELVs in the existing infrastructure in Australia (i.e. the current existing blast furnace facilities); whereas, Option 2 and Option 3 need the construction of new treatment plants. As such, it is considered that the community would be more satisfied with respect to Option 1 than the other two options.

Sustainability indicator of ‘minerals conservation’: The information for the pairwise comparison of the ELV reclamations options was obtained from different sources, particularly from the study conducted by (Cossu and Lai, 2015). The study provides the indicative minerals and the material recycling rate of different ASR treatment technologies (Table 5-8). The amounts of the minerals produced by Option 3 vary among its different technologies (GHK/Bios, 2006). Some of the mechanical separation technologies (e.g. the VW-Sicon process and the Gallo process) do not produce minerals and some of them (e.g. the Sult process and the R-Plus process) produce mineral in the range of around 25% of the total outputs.
### Table 5-8 Overview of post-shredder technologies (Cossu and Lai, 2015)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Type of technology</th>
<th>Plant scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argonne</td>
<td>Dry mechanical separation system</td>
<td>Pilot plant, treatment of 2 tonnes per hour</td>
<td>Recovery of 90% of polymers (&gt;6 mm) and 90% of residual ferrous and nonferrous materials (&gt;6 mm)</td>
</tr>
<tr>
<td>Salyp</td>
<td>Mechanical separation</td>
<td>Trial plant</td>
<td>Recovery of ferrous and nonferrous materials and a clean plastic concentrate without wood and glass impurity</td>
</tr>
<tr>
<td>WESA SLF process</td>
<td>Mechanical separation</td>
<td>Full scale plant, treatment of 4 t/year</td>
<td>Recovery of ferrous metals, copper, minerals and mixed metals, and organic materials</td>
</tr>
<tr>
<td>Witten</td>
<td>Mechanical separation</td>
<td>Full scale plant, treatment of 30,000 t/year</td>
<td>Outputs of the process: 3–8% ferrous materials containing 80–95% of iron, 8–23% of a mixed Fe/Cu/Al fraction, 25–35% of high-ash fraction</td>
</tr>
<tr>
<td>Sortec process</td>
<td>Mechanical separation</td>
<td>Full scale plant, treatment of 40,000 t/year</td>
<td>Recovery of metals and organic fraction</td>
</tr>
<tr>
<td>VW – Sicon</td>
<td>Mechanical separation</td>
<td>Full scale plant, 100,000 t/year</td>
<td>Outputs of the process: shredder granules 36%, shredder fibres 31%, metals 8%, wastes 26%</td>
</tr>
<tr>
<td>Galloo</td>
<td>Mechanical separation</td>
<td>Operating plants</td>
<td>Outputs of the process: recycled plastics 9%, metals 30%, refuse derived fuel 13%, wastes 48%</td>
</tr>
<tr>
<td>Suit</td>
<td>Mechanical separation</td>
<td>Operating plants</td>
<td>Outputs of the process: organic plastic 50%, mineral 20%, metals 10%, water 20%</td>
</tr>
<tr>
<td>R-Plus</td>
<td>Mechanical separation</td>
<td>Operating plants</td>
<td>Outputs of the process: organic fraction 60%, minerals 35%, metals 5%</td>
</tr>
<tr>
<td>Toyota process</td>
<td>Mechanical separation</td>
<td>Pilot plant: capacity of 15,000 ELVs per month</td>
<td>Outputs of the process: foam and fabric sorted and recycled into soundproofing material, recycling copper from wire harnesses</td>
</tr>
<tr>
<td>Nissan process</td>
<td>Thermal treatment to energy recovery</td>
<td>Full-scale operating plant, treatment of 400 t/month</td>
<td>Thermal energy generated during incineration is converted into steam</td>
</tr>
<tr>
<td>Technology</td>
<td>Type of technology</td>
<td>Plant scale</td>
<td>Description</td>
</tr>
<tr>
<td>----------------</td>
<td>--------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Siemens-KWU</td>
<td>Pyrolysis</td>
<td>Trial plant (one trial using 30 tonnes of shredder residue)</td>
<td>Indirect heated rotary kiln operating at 450°C to convert the feed material to a pyrolysis gas and coke. Solids (including the char) are discharged from the kiln for recovery of metals. The pyrolysis gas and solid char are then combusted in an incinerator for steam production</td>
</tr>
<tr>
<td>process</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batrec process</td>
<td>Pyrolysis combined with mechanical separation</td>
<td>Trial plant (400 kg/h)</td>
<td>Pyrolysis of the ASR organic fraction followed by mechanical separation of metals (iron and copper) from the residual solids</td>
</tr>
<tr>
<td>Takuma process</td>
<td>Pyrolysis combined with sorting process</td>
<td>Plant with a capacity of 90 t/day</td>
<td>Pyrolysis of the ASR following by sorting of the residual solids to recover metals (1% of copper, 10% of mixed metals)</td>
</tr>
<tr>
<td>Citron Oxy-reducer process</td>
<td>Pyrolysis at high temperatures</td>
<td>Trial plant with a capacity of 130,000 t/year of waste (12,000 tonnes of ASR)</td>
<td>Outputs of the process: Ca Fe concentrate 45%, zinc concentrate 4.3%, mercury 0.7%, wastes 50%</td>
</tr>
<tr>
<td>VOEST-ALPINE Process</td>
<td>High-gasification process temperature</td>
<td>Trial plant</td>
<td>Tests were conducted in which the shredder residue was blended with mixed plastics, waste oils, and fuel oil</td>
</tr>
<tr>
<td>TwinRec Process</td>
<td>Fluidized-bed gasification with ash melting</td>
<td>Operating plants 8 tonnes per hour</td>
<td>Outputs of the process: metals 8%, glass granulate 25%, recovery 52%, wastes 15%</td>
</tr>
<tr>
<td>SVC process</td>
<td>Gasification process</td>
<td>Trial plant, using a ratio of 30% shredder residue 70% other solid and liquid wastes</td>
<td>Outputs of the process: synthetic gas 75%, metals 8%, wastes 17%</td>
</tr>
</tbody>
</table>
The mineral outputs from Option 2 also vary among its different technologies. One of the gasification technologies (i.e. TwinRec) produces around 25% glass granulates (GHK/Bios, 2006). The glass granulates from that ASR gasification technology is used as an aggregate in the construction industry and replaces natural minerals (e.g. sand). The high temperature of the gasification process immobilises most of the contaminants associated with ASR as such; there is less concern regarding the application of glass granulate produced from the ASR gasification processes than the minerals produced by the mechanical separation options. This implies that some minerals produced by the mechanical separation options might not be fully reused as a substitute for some minerals. No mineral was considered to be saved through the implementation of the plastic injection option.

**Sustainability indicator of ‘fossil fuel conservation’:** Option 2 generates electricity, heat, and aggregate. The generated electricity and heat replaces the electricity and heat which would be otherwise generated from burning fossil fuels. In contrast, Option 3 only consumes electricity and heat for its operation. The used electricity and heat have to be supplied from burning the fossil fuel of coal in the Australian power plants. However, the secondary materials produced from the mechanical separation option replace some virgin materials. The production of these virgin materials need energy and heat which are mainly supplied by burning fossil fuels.

Option 1 replaces some conventional reducing agents including coke and coal that are fossil fuels as well. As such, some fossil fuel savings can be achieved by Option 1. However, the savings are not considered to be the same as the fossil fuel savings by Option 2. The fossil fuel savings from Option 1 through the replacements of the conventional reducing agents of coke and coal is considered to be slightly more than the fossil fuel savings resulted from Option 3.

**Sustainability indicator of ‘landfill space conservation’:** The overall recycling and recovery rates of the options were considered as the main basis for the pairwise comparisons of the options against the assessment indicator. According to the study conducted by GHK/Bios (2006), the most commonly used ASR gasification processes (i.e. TwinRec and SVZ Schwarse Pumpe) and the most commonly used mechanical separation processes (VW-Sicon, Gallo, Sult, and R-Plus) have the overall recycling and recovery rate above 90%. Therefore, Option 2 and Option 3 equally meet the requirement of the assessment indicator (i.e. landfill space savings).
With respect to Option 1, the option only diverts plastics from landfill. Given the approximate weight percentage of plastics in modern cars (which is between 10% and 13%), recovery of the easily accessible plastics (around half of the available plastics) can improve the overall recycling and recovery of ELVs from the current level of around 70% to around 78%. Therefore, with respect to other two options, Option 1 has lesser ability to divert waste from landfill.
Table 5-9 Pairwise comparison matrix of the sustainability assessment of the ELV reclamation options

<table>
<thead>
<tr>
<th>Sustainability indicator</th>
<th>ELV reclamation option</th>
<th>Thermo-chemical process</th>
<th>Mechanical-physical separation</th>
<th>Plastic injection to blast furnaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change mitigation</td>
<td>Thermo-chemical process</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Mechanical-physical separation</td>
<td>1/3</td>
<td>1</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td>Plastic injection to blast furnaces</td>
<td>1/3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Water conservation</td>
<td>Thermo-chemical process</td>
<td>1</td>
<td>3</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td>Mechanical-physical separation</td>
<td>1/3</td>
<td>1</td>
<td>1/4</td>
</tr>
<tr>
<td></td>
<td>Plastic injection to blast furnaces</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Job creation</td>
<td>Thermo-chemical process</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Mechanical-physical separation</td>
<td>1/3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Plastic injection to blast furnaces</td>
<td>1/5</td>
<td>1/4</td>
<td>1</td>
</tr>
<tr>
<td>Capital conservation</td>
<td>Thermo-chemical process</td>
<td>1</td>
<td>1/3</td>
<td>1/6</td>
</tr>
<tr>
<td></td>
<td>Mechanical-physical separation</td>
<td>3</td>
<td>1</td>
<td>1/5</td>
</tr>
<tr>
<td></td>
<td>Plastic injection to blast furnaces</td>
<td>6</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Safety and public health</td>
<td>Thermo-chemical process</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Mechanical-physical separation</td>
<td>1/2</td>
<td>1</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td>Plastic injection to blast furnaces</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Fossil fuel conservation</td>
<td>Thermo-chemical process</td>
<td>1</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Mechanical-physical separation</td>
<td>1/4</td>
<td>1</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td>Plastic injection to blast furnaces</td>
<td>1/3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Social acceptability</td>
<td>Thermo-chemical process</td>
<td>1</td>
<td>1</td>
<td>1/5</td>
</tr>
<tr>
<td></td>
<td>Mechanical-physical separation</td>
<td>1</td>
<td>1</td>
<td>1/5</td>
</tr>
<tr>
<td></td>
<td>Plastic injection to blast furnaces</td>
<td>5</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Minerals conservation</td>
<td>Thermo-chemical process</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Mechanical-physical separation</td>
<td>1</td>
<td>1/4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Plastic injection to blast furnaces</td>
<td>1/4</td>
<td>1/2</td>
<td>1</td>
</tr>
<tr>
<td>Landfill space conservation</td>
<td>Thermo-chemical process</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Mechanical-physical separation</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Plastic injection to blast furnaces</td>
<td>1/3</td>
<td>1/3</td>
<td>1</td>
</tr>
</tbody>
</table>
5.3.6 Results with respect to the individual sustainability indicator

The performance ranking of the ELV reclamation options with respect to the individual sustainability indicator for the best case scenario and the worst case scenario are presented in Figure 5-6 and Figure 5-7 respectively. These figures have been generated through application of Expert Choice as per the mathematical processes described in Appendix C.
Figure 5-7 Performance ranking of the ELV reclamation options with respect to the individual sustainability indicator for the worst case scenario
5.3.7 Results with respect to the goal of the sustainability assessment

The performance ranking of the ELV reclamation options with respect to the goal of the assessment for the best case scenario and the worst case scenario are presented in Figure 5-8 and Figure 5-9. These figures have been generated through application of the Expert Choice software as per the mathematical processes described in Appendix C.

### Figure 5-8 Performance ranking of the ELV reclamation options with respect to the goal of the sustainability assessment for the best case scenario

<table>
<thead>
<tr>
<th>Synthesis with respect to:</th>
<th>Goal: Selecting the most sustainable ELV reclamation option for Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo-chemical treatment of ASR (pyrolysis, and gasification)</td>
<td>1.000</td>
</tr>
<tr>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>.702</td>
</tr>
<tr>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>.386</td>
</tr>
</tbody>
</table>

Overall Inconsistency $= .02$

### Figure 5-9 Performance ranking of the ELV reclamation options with respect to the goal of the sustainability assessment for the worst case scenario

<table>
<thead>
<tr>
<th>Synthesis with respect to:</th>
<th>Goal: Selecting the most sustainable ELV reclamation option in Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo-chemical treatment of ASR (pyrolysis and gasification)</td>
<td>1.000</td>
</tr>
<tr>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>.830</td>
</tr>
<tr>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>.471</td>
</tr>
</tbody>
</table>

Overall Inconsistency $= .01$

As indicated in Figure 5-8 and Figure 5-9, the difference between the amounts of the global priority of the first and second ranked ELV reclamation options is more than 10% for the best case scenario and the worst case scenario. As such, there is no need to expand the number of the sustainability indicators and repeat the assessment based on a new set of sustainability indicators (see Section 5.2).

5.3.8 Sensitivity analysis of the sustainability assessment

Four sensitivity tests were conducted in which different amounts of weighting factors were assigned to the sustainability indicator groups. The assigned weighting factors for each sensitivity test are presented in Table 5-10. The normalised results of the sensitivity tests are presented in Figure 5-10 to Figure 5-13. These figures have been generated through application of Expert Choice per the mathematical processes described in Appendix C.
Chapter 5

Table 5-10 Weighting factors assigned in the sensitivity tests of the sustainability assessment

<table>
<thead>
<tr>
<th>Sensitivity test No.</th>
<th>Weighting factors of the sustainability assessment groups (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3D</td>
</tr>
<tr>
<td>1</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
</tr>
</tbody>
</table>

Synthesis with respect to:
Goal: Selecting the most sustainable ELV reclamation option in Australia

<table>
<thead>
<tr>
<th>Method</th>
<th>Weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo-chemical treatment of ASR (pyrolysis and gasification)</td>
<td>1.000</td>
</tr>
<tr>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>.838</td>
</tr>
<tr>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>.454</td>
</tr>
<tr>
<td>Overall Inconsistency = .01</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-10 Performance ranking of the ELV reclamation options with respect to the goal of the sustainability assessment based on the equal weighting factor of 0.35 for 3D and 2D indicator group and 0.3 for 1D indicator group

Synthesis with respect to:
Goal: Selecting the most sustainable ELV reclamation option in Australia

<table>
<thead>
<tr>
<th>Method</th>
<th>Weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo-chemical treatment of ASR (pyrolysis and gasification)</td>
<td>1.000</td>
</tr>
<tr>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>.838</td>
</tr>
<tr>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>.454</td>
</tr>
<tr>
<td>Overall Inconsistency = .01</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-11 Performance ranking of the ELV reclamation options with respect to the goal of the sustainability assessment based on the weighting factor of 0.4 for 3D and the equal weighting factor of 0.3 for 2D and 1D indicator groups

Synthesis with respect to:
Goal: Selecting the most sustainable ELV reclamation option for Australia

<table>
<thead>
<tr>
<th>Method</th>
<th>Weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo-chemical treatment of ASR (pyrolysis and gasification)</td>
<td>1.000</td>
</tr>
<tr>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>.838</td>
</tr>
<tr>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>.454</td>
</tr>
<tr>
<td>Overall Inconsistency = .02</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-12 Performance ranking of the ELV reclamation options with respect to the goal of the sustainability assessment based on the weighting factor of 0.4 for 3D, the equal weighting factor of 0.3 for 2D and the weighting factor of 0.25 for 1D indicator group

Synthesis with respect to:
Goal: Selecting the most sustainable ELV reclamation option for Australia

<table>
<thead>
<tr>
<th>Method</th>
<th>Weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo-chemical treatment of ASR (pyrolysis and gasification)</td>
<td>1.000</td>
</tr>
<tr>
<td>Use of ELV plastics as reducing agents in blast furnaces</td>
<td>.838</td>
</tr>
<tr>
<td>Mechanical-physical separation of ASR to recover its materials</td>
<td>.430</td>
</tr>
<tr>
<td>Overall Inconsistency = .01</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-13 Performance ranking of the ELV reclamation options with respect to the goal of the sustainability assessment based on the weighting factor of 0.5 for 3D and the equal weighting factor of 0.25 for 2D and 1D indicator groups
5.3.9 Interpretation of the results of the sustainability assessment

An effective approach to interpret the results of the sustainability assessment (with respect to the goal of the assessment) is the simultaneous consideration of the weighting factors of the sustainability indicators for both the ‘best case’ and ‘worst case’ scenarios (Table 5-4 and Table 5-5) and the results of the assessment for the scenarios with respect to each sustainability indicators (Figure 5-7 and Figure 5-8).

For the best case scenario, as indicated in Table 5-4, the sustainability indicator group of 3D has the highest weighting factor among the three sustainability indicator groups of 3D, 2D and 1D. The sustainability indicator group of 3D also has the least number of sustainability indicators (i.e. only two indicators of ‘climate change mitigation’ and ‘water conservation’). As such, the weighting factor per the individual sustainability indicator for the sustainability group of 3D is highest weighting factor (0.25) among all indicators of the sustainability assessment. This makes the overall ranking of the individual ELV reclamation options (with respect to the goal), to some considerable extent, dependent on the performance of that ELV reclamation option on two sustainability indicators located in the 3D group.

The individual sustainability assessment indicators included in the 1D group have a relatively low weighting factor (0.042 for each indicator). This is attributed to two factors. Firstly, the relative weighting factor of the 1D group is low (0.25) and the number of the sustainability indicators in the 1D group is relatively high (4 sustainability indicators). Given the low weighting factor of the individual sustainability indicator included in the 1D group, even if an ELV reclamation option is performed better than any of the 1D sustainability indicators, this would not significantly improve the overall ranking of that ELV reclamation with respect to the goal. An example is the excellent performance of the ELV reclamation option ‘use of ELV plastics as reducing agents in blast furnaces’ against the 1D sustainability indicator of ‘social acceptability’ (Figure 5-6).

As indicated in Table 5-5, the sustainability indicator groups of 3D, 2D and 1D have the same weighting factor (0.33). However, for the best case scenario, the number of sustainability indicators in each indicator group is different. As such, the sustainability group that has the lowest number of indicators (3D group) has the highest weighting factor per the individual sustainability indicator (0.166). However, the difference between the weighting factors of the individual
sustainability indicators are not significant as it was for the best case scenario. For instance, the individual sustainability indicator for the 2D group (0.110) is close to the individual sustainability indicator for the 1D group (0.083). Thus, the importance of a good performance against any of the sustainability indicators of 1D is almost the same as the importance of having a good performance against any of the sustainability indicators of 2D.

5.4 SUSTAINABILITY ASSESSMENT THROUGH THE TRIPLE BOTTOM LINE MODEL

5.4.1 Common MCDM steps in the both sustainability assessment models

As for the sustainability assessment conducted in Section 5.3, this section applies the MCDM process developed in Section 5.2 to assess the sustainability performance of the ELV reclamation options. However, most of the steps in the MCDM will be excluded in the TBL assessment as these steps are not specific to the applied sustainability assessment models. The only step in the MCDM that is different between the two sustainability assessment models is Step 5 in which the relative importance of each of the sustainability assessment indicators is estimated. This exercise is the subject of the next section.

5.4.2 Relative importance of the sustainability indicators based on the TBL model

As discussed in Section 2.5.9, the sustainability assessment indicators in the TBL model can only represent one dimension of sustainability. As such, the sustainability assessment indicators are categorised based on their representative sustainability dimension.

The relative importance (weighting factors) of the sustainability indicator groups of social, economic and environmental indicators and their weighting factor are presented in Table 5-11.
### Table 5-11 Relative importance (weighting factors) of the sustainability indicators based on the TBL model

<table>
<thead>
<tr>
<th>Sustainability indicator</th>
<th>Relevant indicator category</th>
<th>Weighting factor of the relevant indicator category</th>
<th>Weighting factor of the individual sustainability indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital conservation</td>
<td>Economic</td>
<td>0.400</td>
<td>0.400</td>
</tr>
<tr>
<td>Climate change mitigation</td>
<td>Environmental</td>
<td>0.400</td>
<td>0.080</td>
</tr>
<tr>
<td>Water conservation</td>
<td>Environmental</td>
<td>0.400</td>
<td>0.080</td>
</tr>
<tr>
<td>Minerals conservation</td>
<td>Environmental</td>
<td>0.400</td>
<td>0.080</td>
</tr>
<tr>
<td>Fossil fuel conservation</td>
<td>Environmental</td>
<td>0.400</td>
<td>0.080</td>
</tr>
<tr>
<td>Landfill space conservation</td>
<td>Environmental</td>
<td>0.400</td>
<td>0.080</td>
</tr>
<tr>
<td>Job creation</td>
<td>Social</td>
<td>0.200</td>
<td>0.067</td>
</tr>
<tr>
<td>Safety and public health</td>
<td>Social</td>
<td>0.200</td>
<td>0.067</td>
</tr>
<tr>
<td>Social acceptability</td>
<td>Social</td>
<td>0.200</td>
<td>0.067</td>
</tr>
</tbody>
</table>

*The sum of the column is slightly less than one due to rounding precision.

The weighting factors for the sustainability assessment groups are sourced from an ELV comparative assessment study conducted in Cyprus (Mergias et al., 2007). In that study, an equal weighting factor (0.4) was assigned to the economic and environmental sustainability indicator groups. The weighting factor of the social group was assigned half of the weighting factor assigned to the economic group and to the environmental group. The rational for the assignment of such weighting factors is not provided in that study.

A comprehensive sensitivity analysis will be conducted in the following sections to assess the sensitivity of the results of the assessment (i.e. the preference ranking of the ELV reclamation options) with respect to the assigned weighting factors inside the sustainability assessment groups of social, economic and environmental.

#### 5.4.3 Results with respect to the individual indicator based on the TBL model

The preference ranking of the ELV reclamation options with respect to the individual sustainability assessment indicators are shown in Figure 5-14. The figure has been generated through the application of the Expert Choice software as per the mathematical processes described in Appendix C.
Figure 5-14 Performance ranking of the ELV reclamation options with respect the individual sustainability indicator based on the TBL model
5.4.4 Results with respect to the goal of the assessment based on the TBL model

The performance ranking of the ELV reclamation options with respect to the goal of the sustainability assessment are shown in Figure 5-15. The figure has been generated through application of Expert Choice per the mathematical processes described in Appendix C.

![Synthesis with respect to:
Goal: Selecting the most sustainable ELV reclamation option for Australia
Use of ELV plastics as reducing agents in blast furnaces 1.000
Thermo-chemical treatment of ASR (pyrolysis and gasification) .769
Mechanical-physical separation of ASR to recover its materials .474
Overall Inconsistency = .02

Figure 5-15 Performance ranking of the ELV reclamation options with respect to the assessment goal (based on the triple bottom line approach)

As indicated in Figure 5-15, the difference between the amounts of the global priority of the first and second best ranked ELV reclamation options is more than 10% (see Section 5.2). As such, there is no need to extend the number of the sustainability assessment indicators and repeat the sustainability assessment based on the new set of the sustainability indicators.

5.4.5 Sensitivity analysis of the sustainability assessment based on the TBL model

As for the sensitivity analysis conducted for the multi-dimensionality model, the sensitivity analysis of the results in the TBL model includes testing the robustness of the performance ranking of the ELV reclamation options under different weighting factors. Four sensitivity tests were conducted. In the first test, an equal weighting factor (0.33) was assigned to all of the sustainability assessment groups. The results of the sensitivity test are shown in Figure 5-16.

![Synthesis with respect to:
Goal: Selecting the most sustainable ELV reclamation option for Australia
Use of ELV plastics as reducing agents in blast furnaces 1.000
Thermo-chemical treatment of ASR (pyrolysis and gasification) .811
Mechanical-physical separation of ASR to recover its materials .484
Overall Inconsistency = .02

Figure 5-16 Performance ranking of the ELV reclamation options based on the equal weighting factor of 0.33 for social, economic and environmental indicator groups
The default weighting factors applied in the sustainability assessment (Table 5-11) are based on the consideration of the similar weighting factors for the economic and environmental groups (0.4 each). In the second sensitivity test, an equal weighting factor (0.4) was assumed for the social and environmental groups and the weighting factor of the economic group was assumed to be 0.2. The results of the second sensitivity test are shown in Figure 5-17.

In the third sensitivity test, the weighting factor of 0.5 was assigned to the environmental group and an equal weighting factor of 0.25 was assumed for both social and economic groups. This sensitivity test is similar to the fourth sensitivity test that was conducted in the multi-dimensionality model (Table 5-10) in which the weighting factor of one of the sustainability indicator group (3D) was considered twice of the weighting factors of the two other sustainability indicator groups (2D and 1D). The results of the third sensitivity test are shown in Figure 5-18.

In the fourth sensitivity tests, an equal weighting factor of 0.11 was assigned to each sustainability assessment indicator. The tests assumed that all of the sustainability assessment indicators — regardless of being social, economic or environmental — have relative importance in the sustainability assessment. The results are shown in Figure 5-19.
Figure 5-19 Performance ranking of the ELV reclamation options based on the equal weighting factor of 0.11 for all of the sustainability indicators

5.4.6 Interpretation of the results of the assessment based on the TBL model

An effective approach to interpret the results of the sustainability assessment based on the TBL model is to simultaneously consider the weighting factors of the sustainability indicator groups (Table 5-11) and the normalised results of the assessment with respect to the individual sustainability indicators (Figure 5-14). As indicated in Table 5-11, the relative importance (weighting factor) of the sustainability indicator groups of economic and environmental in the sustainability assessment is equal (each 0.4). However, the economic group includes only one sustainability indicator and five environmental assessment indicators. As such, the response of the individual ELV reclamation options against the single sustainability indicator of economic (i.e. capital conservation) is highly important in the assessment.

Whilst the weighting factor of the environmental group (0.4) is twice that of the social group (0.2), the weighting factor of the individual environmental indicator (0.080) is not significantly greater than the individual social indicator (0.067). This is attributed to the higher number of the environmental indicators (five) to the number of the social indicators (three). As such, a good performance against any of the environmental indicators is almost equal to a good performance against any of the social indicators.

The ELV reclamation option of ‘thermo-chemical treatment of ASR (pyrolysis and gasification)’ was the best performed ELV reclamation option in six of the nine assessments that were conducted with respect to the individual sustainability indicators (Figure 5-14). Despite this, the reclamation option ranked as the second best performed ELV reclamation option in the assessment against the goal of the sustainability assessment (Figure 5-15). This could be mainly attributed to the poor performance of the reclamation option against
the sustainability indicator of ‘capital conservation’ that had the highest weighting factor (see Attachment B for further details).

The sensitivity analysis provided mixed results. The results of one of the sensitivity tests (Figure 5-16) were consistent with the results of the main sustainability assessment (Figure 5-15). However, the results of three sensitivity tests (Figure 5-17 to Figure 5-19) were inconsistent with the results of the main sustainability assessment. This provides little confidence in the results of the sustainability assessment based on the TBL model.

5.5 MOST SUSTAINABLE END-OF-LIFE VEHICLE RECLAMATION OPTION IN THE AUSTRALIAN CONTEXT

This research identifies the ELV reclamation option of ‘thermo-chemical treatment of ASR (pyrolysis and gasification)’ as the most sustainable ELV reclamation option in the Australian context. This is supported by the results of the sustainability assessment that was conducted which was based on the multi-dimensionality model. The results of the sustainability assessment were confirmed through a comprehensive sensitivity analysis in which different weighting factors were assigned to the sustainability indicators.

The results of the sustainability assessment based on the TBL model are considered to be very sensitive to the applied weighting factors of the social, economic and environmental indicators. This creates little confidence in identifying the best performed ELV reclamation option based on the TBL model as the most sustainable ELV reclamation option in the Australian context.

5.6 PROPOSED AUSTRALIAN ELV RECYCLING NETWORK

The figure representing the current Australian recycling network (Figure 1-4) was modified through the replacement of the ASR landfill disposal with the ELV reclamation option that was identified in Section 5.5 as the most sustainable ELV reclamation option for Australia. The modified figure (Figure 5-20) represents the proposed Australian recycling network.
As indicated in Figure 5-20, in the proposed Australian ELV recycling network, the ASR generated at the ELV shredding plants is treated in thermo-chemical plants. The ASR thermo-chemical plants produce a residue that is often sent to landfill. The amount of the residue reported from the existing ASR thermo-chemical plants is less than 5% of the total mass of an ELV (see Table 5-8).

5.7 DISCUSSION AND CONCLUSIONS

A comprehensive discussion is made in this section from two main perspectives: the methodological perspective and the results perspective. From the former perspective, the chapter
assessed the sustainability performance of a set of waste treatment practices (i.e. ELV reclamation options) through two different sustainability assessment models. This exercise is new to the present research.

One of the applied sustainability assessment models (i.e. the TBL model) has a well-established methodology. However, there are some methodological aspects to be developed for another applied sustainability assessment model (i.e. the multi-dimensional model). The chapter applied some proposed methods (e.g. the best case-worst case scenarios) that helped conclusions to be formulated in the decision-making process regarding the identification of the most sustainable ELV reclamation for Australia. The proposed methods in the chapter could be applied in the future research studies focused on a sustainability assessment of a set of waste treatment practices both in Australia and elsewhere.

Other contributions of the chapter to the multi-dimensional sustainability assessment model are the identification of a set of Australian-specific sustainability assessment indicators and the identification of the dimensionality of each sustainability indicator. These findings could be used in the future research studies focused on the sustainability assessment of a set of waste treatment practices in the Australian context.

It can be argued that the sustainability assessment indicators developed in the research meet the required specifications defined by the Australian Government (Australian Government, 2015). As presented in Section 1.4.1, the sustainability assessment indicators are the indicators that allow decision-makers to focus their efforts on specific areas of sustainability and to measure performance and improvements (Australian Government, 2015). The identified sustainability assessment indicators in the research are nine indicators that cover almost every important aspect of sustainability including natural resources (e.g. water), capital resources, human resources (e.g. job creation), and Australian national resources (e.g. minerals). The identified sustainability indicators in the research are suitable for the measurement of the improvements in the Australian ELV recycling industry through the adoption of a sustainable ELV reclamation option.

One of the key outcomes of the chapter is the identification of the most sustainable ELV reclamation option (i.e. thermo-chemical treatment of ASR) in the Australian context. As stated in Section 1.4.1, the literature has defined a sustainable waste management option as an
environmentally effective, economically affordable and socially acceptable waste management option (Nilsson-Djerf, 2000). It can be argued that the identified ELV reclamation option in the research satisfactorily meets the key requirements of a sustainable waste management option. This is supported by the results of the comprehensive sustainability assessment that was conducted in the chapter.

An important conclusion of the chapter is that the results of a conducted sustainability assessment research could be highly sensitive to the applied sustainability assessment model. As observed in the chapter, the two different applied sustainability assessment models (i.e. TBL model and the multi-dimensionality model) identified two different ELV reclamation options as the most sustainable ELV reclamation options for Australia. The chapter concluded, based on the results of the conducted sensitivity tests, that the results of the multi-dimensionality model are more vigorous than the results of the TBL model.

Whilst the findings of the chapter indicate the superiority of the multi-dimensional model over the TBL model for the sustainability assessment of a set of waste treatment practices, the present research suggests further research, focusing on the comparative assessment of the two sustainability assessment models.

5.8 SUMMARY

In this chapter, the multi-criteria analysis (MCA) method has been applied to assess the sustainability performance of the three technically viable ELV reclamation options in the Australian context. The initial section of the chapter developed a customised multi-criteria decision-making (MCDM) process to facilitate the application of the MCA method in the chapter.

An important step of the MCDM process was the identification of a set of Australian-specific sustainability assessment indicators. A comprehensive literature review identified a list of the most frequently applied technical, social, economic, and environmental assessment indicators in existing waste management studies. The chapter analysed the list and identified nine social, economic and environmental indicators as the most relevant indicators to the present research and to the Australian context.
The chapter then continued with the sustainability assessment of the ELV reclamation options through two sustainability assessment models namely the multi-dimensionality model and the triple bottom line (TBL) model. In the multi-dimensionality model, as opposed to the TBL model, a sustainability assessment indicator can represent more than one dimension of sustainability (i.e. social, economic and environmental).

The results of the sustainability assessment models were analysed in the chapter. The analysis found that the preference ranking of the ELV reclamation options based on the multi-dimensionality model, in comparison to the preference ranking based on the TBL model, are less sensitive to the key assumptions of the sustainability assessment (i.e. the weighting factors of the sustainability indicators). As such, the preference ranking of the ELV reclamation options, based on the multi-dimensionality model, was selected as the basis for the identification of the most sustainable ELV reclamation option for Australia.

The ELV reclamation option of ‘thermo-chemical treatment of ASR (pyrolysis and gasification)’ was the highest ranked ELV reclamation option in the preference ranking developed through the application of the multi-dimensionality model. As such, the chapter identified the ELV reclamation option of ‘thermo-chemical treatment of ASR (pyrolysis and gasification)’ as the most sustainable ELV reclamation for Australia.

The final section of the chapter focused on the development of a proposed ELV recycling network for Australia based on key findings from within the chapter. In the proposed network, the ELV reclamation option of ‘thermo-chemical treatment of ASR (pyrolysis and gasification)’ replaces the existing ASR landfill treatment practice in the Australian recycling network. The chapter concluded with providing the proposed ELV recycling network in other countries including Malaysia and India.
6 A sustainable business model for end-of-life vehicle reclamation in Australia

6.1 INTRODUCTION

This chapter identifies a sustainable business model for ELV reclamation in Australia. The business model is expected to define the most sustainable implementation of the ELV reclamation option of ‘thermo-chemical treatment of ASR’ that was identified in Section 5.5 as the most sustainable option for Australia.

A comprehensive literature review is conducted in the initial section of the chapter focused on the identification of the existing business models related to the considered ELV reclamation option. The multi-criteria analysis (MCA) method is applied to identify the most effective business model for ELV reclamation in Australia. As the MCA method involves many steps, initially a customised multi-criteria decision-making (MCDM) process is developed. The MCDM process involves many steps, including the identification of the assessment goal and the assessment indicators, the estimation of the relative importance of the assessment indicators, and the assessment of the alternatives (i.e. the business models) against the decision criteria. The assessment of the business models against the assessment indicators (e.g. robustness) is based on the best available information in the literature. As such, no attempt is made in the chapter to measure quantitatively a specific assessment indicator (e.g. measuring the robustness of a specific business model). The best available information in the literature is used for the pairwise comparison of the business models against the assessment indicators, according to the procedure described in Section 3.2.4.

The chapter applies two different but linked methods to assess the sustainability performance of the selected business model. The first method, conceptual modelling, creates an abstract of the selected business model (i.e. a summarised form of the business model that aids in visualising how different variables in the selected business model are interrelated) and identifies the reinforcing and balancing feedback loops between the business model and the other business models within the proposed Australian ELV recycling network (see Figure 5-20). The results of the modelling, a causal loop diagram, is then analysed to comment on the sustainability performance of the selected business model.
The second method applied to assess the sustainability performance of the selected business model is system dynamics. The developed abstract of the business model is used as a basis to develop the stocks and flows diagram (SFD) of the model. A computer simulation of the SFD, based on a set of Australian-based quantitative information, identifies the behaviour-over-time (BOT) pattern mode of the selected business model. A growing BOT pattern mode confirms that the selected business model is sustainable— as the selected business can create value (in the form of energy or material) from the non-metallic materials of ELVs in Australia.

6.2 MULTI-CRITERIA ANALYSIS OF THE EXISTING BUSINESS MODELS

6.2.1 A customised MCDM process for the assessment of the business models

The multi-criteria analysis (MCA) method is now applied to identify the most effective and preferred business model for ELV reclamation in Australia employing thermo-chemical technology. As the MCA method involves many different steps (see section 3.2.3.1), a multi-criteria decision-making (MCDM) process has been developed (Figure 6-1) to facilitate the application of the MCA.

As indicated in Figure 6-1, the MCDM process has ten steps, commencing from the definition of the assessment goal (i.e. the identification of the most preferred business model to implement thermo-chemical treatment of Automobile Shredder Residues (ASR) in Australia). Step 2 focuses on the formulation of the alternatives (i.e. the business models). A literature review will identify the existing business models related to ASR treatment by the thermo-chemical technology.

Step 3 identifies the indicators to assess the performance of the business models. The key characteristics of a successful business model will be used as assessment indicators. Step 4 constructs the decision hierarchy of the applied MCA method (i.e. the analytical hierarchy process (AHP) technique). The relative importance (weighting factors) of the assessment indicators will be determined in Step 5.
Chapter 6

Figure 6-1 MCDM process developed in this research for the comparative assessment of a set of business models for ELV reclamation in Australia

Step 1
Goal: identification of the most effective business model for ELV reclamation in Australia through the thermo-chemical treatment of ASR

Step 2
Formulate the alternatives (business models) based on the international applications of the thermo-chemical technology for ASR treatment

Step 3
Identify the key characteristics of a successful business model and regard them as the assessment indicators

Step 4
Structure the relevant decision hierarchy of the AHP technique

Step 5
Determine the relative importance (weighting factor) of the assessment indicators with respect to the goal of the assessment

Step 6
Develop the pairwise comparison matrix of the MCDM process based on the relative capability of the business models to meet the conditions of the criteria

Step 7
Identify the performance ranking of the business models with respect to the goal of the assessment

Step 8
Is there more than 10% difference between the amounts of the global priority of the first and second ranked business model?

- No
  Increase the number of the criteria and repeat the multi-criteria assessment from Step 5

- Yes

Step 9
Test the robustness of the identified performance ranking of the business models with respect to the goal of the assessment through a sensitivity analysis

Step 10
Interpret the results of the sensitivity analysis and conclude the assessment
The pairwise comparison matrix of the AHP assessment is developed in step 6. Step 7 presents
the results of the AHP assessment that includes both the performance ranking of the business
models with respect to the individual assessment indicators and to the assessment goal. Step 8
checks if there is a noticeable gap (more than 10%) that exists between the amounts of the global
priority for the best, and for the second ranked business models. If so, the MCDM process will
be advanced to Step 9. In Step 9 a series of sensitivity tests will examine the robustness of the
identified performance ranking of the business models with respect to the goal of the assessment.
Otherwise, the number of the assessment indicators will be increased and the MCDM processes
will be started from Step 5. Step 10 interprets the results of the sensitivity tests and concludes the
assessment.

6.2.2 Formulation of the alternative business models

According to the information provided in Table 5-8, the existing business models for thermo-
chemical treatment of ASR have either been established and operated by car manufacturers (e.g.
the ASR pyrolysis plant operated by Citroen) or by the waste management companies (e.g. the
existing ASR thermo-chemical plants in Japan). There is also an emerging business model for the
establishment and operation of ASR thermo-chemical plants. This business model is based on the
establishment and operation of ASR thermo-chemical plants by automobile shredding companies.
An example is the proposed ASR gasification plants established and operated by European Metals
Recycling (EMR) that is the largest ELV shredding company in the UK (Brown, 2014).

The following business models for ELV reclamation in Australia through the thermo-chemical
technology are investigated:

1. The ASR thermo-chemical plants established and operated by vehicle manufacturers.
2. The ASR thermo-chemical plants established and operated by waste management companies.
3. The ASR thermo-chemical plants established and operated by ELV shredding facilities.

6.2.3 Assessment indicators

This research adopts the key characteristics of a successful business model, developed in the
research by Casadesus-Masanell and Ricart (2011), as the indicators for the comparative
assessment of the identified business models. These indicators are defined in Table 6-1.
Table 6-1 Indicators for the assessment of the business models (Casadesus-Masanell and Ricart, 2011)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal-alignment</td>
<td>Ability to deliver consequences that enable an organisation to achieve its goals</td>
</tr>
<tr>
<td>Self-reinforcement</td>
<td>Ability to generate virtuous cycles, or feedback loops, that are self-reinforcing</td>
</tr>
<tr>
<td>Robustness</td>
<td>Ability to sustain its effectiveness over time</td>
</tr>
</tbody>
</table>

As detailed in Section 2.5.10, the research by Casadesus-Masanell and Ricart (2011) has identified the characteristics presented in Table 6-1 through a system-based (feedback loop analysis) analysis of a number of successful business models. This is considered to be relevant to the objective of the present research — that is to identify a sustainable business model for ELV reclamation in Australia based on the system-based analysis.

6.2.4 Decision hierarchy of the assessment

A decision hierarchy in the AHP method breaks down or structures the assessment decision into a hierarchy in order to capture the essential variables (goal, criteria, alternatives) of the problem (Staikos and Rahimifard, 2007a). A decision hierarchy was developed in the research (Figure 4-2) consisting three levels. The top level represents the overall objective or goal of the problem. The criteria (the assessment indicators) upon which this goal is dependent are assigned in the second level. The lower level of the hierarchy contains the alternatives (i.e. the business models) through which the goal may be achieved.
Figure 6-2 Decision hierarchy for the comparative assessment of the identified business models
6.2.5 Relative importance of the assessment indicators

No research study has yet determined the relative importance (weighting factors) of a set of criteria for the assessment of a set of business models for waste management. Hence the present research assumes an equivalent weighting factor for all of the assessment indicators. The effect of this assumption on the performance ranking of the business models will be tested through a comprehensive sensitivity analysis. The relative weighting factors of the assessment indicators are presented in Table 6-2.

<table>
<thead>
<tr>
<th>Assessment indicator</th>
<th>Weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal alignment</td>
<td>0.33</td>
</tr>
<tr>
<td>Self-reinforcement</td>
<td>0.33</td>
</tr>
<tr>
<td>Robustness</td>
<td>0.33</td>
</tr>
</tbody>
</table>

6.2.6 Pairwise comparison matrix of the multi-criteria assessment

The numerical scale presented in Table 3-5 was used to develop the pairwise comparison matrix of the AHP process relevant to the assessment (Table 6-3). The rationale for each assigned numerical value is provided in Appendix A.
### Table 6-3 Pairwise comparison matrix of the comparative assessment of the business models

<table>
<thead>
<tr>
<th>Assessment criteria</th>
<th>Business model</th>
<th>Business established by automobile manufacturers</th>
<th>Business established by waste management companies</th>
<th>Business established by ELV shredding facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal alignment</td>
<td>Business established by automobile manufacturers</td>
<td>1</td>
<td>1/5</td>
<td>1/7</td>
</tr>
<tr>
<td></td>
<td>Business established by waste management companies</td>
<td>5</td>
<td>1</td>
<td>1/3</td>
</tr>
<tr>
<td></td>
<td>Business established by ELV shredding facilities</td>
<td>7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Self-reinforcement</td>
<td>Business established by automobile manufacturers</td>
<td>1</td>
<td>1/3</td>
<td>1/5</td>
</tr>
<tr>
<td></td>
<td>Business established by waste management companies</td>
<td>3</td>
<td>1</td>
<td>1/3</td>
</tr>
<tr>
<td></td>
<td>Business established by ELV shredding facilities</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Robustness</td>
<td>Business established by automobile manufacturers</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Business established by waste management companies</td>
<td>1/3</td>
<td>1</td>
<td>1/3</td>
</tr>
<tr>
<td></td>
<td>Business established by ELV shredding facilities</td>
<td>1/2</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

#### 6.2.7 Results with respect to the individual assessment indicators

The performance ranking of the business models with respect to the individual assessment indicators are shown in Figure 6-3. The figure has been generated through application of Expert Choice per the mathematical processes described in Appendix C.
6.2.8 Results with respect to the goal of the assessment

The performance ranking of the business models with respect to the goal of the assessment are shown in Figure 6-4. The figure has been generated through application of Expert Choice per the mathematical processes described in Appendix C.

As indicated in Figure 6-4, there is more than 10% difference between the amounts of the global priority of the first and second ranked business models; as such, there is no need to extend the number of assessment indicators and repeat the assessment.
6.2.9 Sensitivity analysis of the assessment

Three sensitivity tests were conducted. In the first test, the assessment indicator of 'goal alignment' was assigned a weighting factor of 0.6 and an equal weighting factor of 0.2 was assigned for each of the other two assessment indicators. The results of the test are shown in Figure 6-5.

Figure 6-5 Performance ranking of the business models based on the weighting factor of 0.6 for the assessment indicator of 'goal alignment' and the weighting factor of 0.2 for the other assessment indicators

In the second sensitivity test the assessment indicator of 'reinforcement' was assigned a weighting factor of 0.6 and an equal weighting factor of 0.2 was assigned for each of the other two assessment indicators. The results of the test are shown in Figure 6-6.

Figure 6-6 Performance ranking of the business models based on the weighting factor of 0.6 for the assessment indicator of 'reinforcement' and the weighting factor of 0.2 for the other assessment indicators

In the third sensitivity test the assessment indicator of 'robustness' was assigned a weighting factor of 0.6 and an equal weighting factor of 0.2 was assigned for each of the other two assessment indicators. The results of the test are shown in Figure 6-7.

Figure 6-7 Performance ranking of the business models based on the weighting factor of 0.6 for the assessment indicator of 'robustness' and the weighting factor of 0.2 for the other assessment indicators
6.2.10 Interpretation of the results of the multi-criteria analysis

An effective approach to interpret the normalised results of the assessment of business models with respect to the goal of the assessment (Figure 6-4) is to simultaneously consider the relative importance of the assessment indicators (Table 6-2) and the normalised results of the assessment with respect to the individual assessment indicators (Figure 6-3).

As indicated in Table 6-2, the assessment indicators have the same weighting factor (0.33 each). As such, for any of the business models, the performances against the assessment indicators are equally important. This could partially justify why the business model of ‘business established by ELV shredding facilities’ was the best performed business model with respect to the goal despite of not being the best performed business model with respect to the assessment indicator of ‘robustness’ (Figure 6-4). That business model was the best performed business model with respect to the assessment indicator of ‘goal alignment’ (Figure 6-5) and with respect to the assessment indicator of ‘reinforcement’ (Figure 6-6).

The results of the sensitivity analysis are consistent with the results of the main assessment. This indicates that the identified performance ranking of the business models, with respect to the goal of the assessment (Figure 6-4), is not sensitive (to an acceptable extent) to the applied weighting factor. The performance ranking could be changed with extreme changes in the weighting factors – such as the assignment of a very high quantity of weighting factor to the assessment indicator of ‘robustness’. For that assessment indicator, the business model of ‘business established by ELV shredding facilities’ was not the best performed business model.

6.3 SELECTED BUSINESS MODEL FOR THE THERMO-CHEMICAL TREATMENT OF ASR IN AUSTRALIA

The results of the sensitivity tests provided enough confidence to conclude that the business model established and operated by ELV shredding plants is the most effective business model for ELV reclamation in Australia through thermo-chemical technology.
6.4 SUSTAINABILITY ASSESSMENT THROUGH THE CONCEPTUAL MODELLING METHOD

The main purpose of the conceptual modelling in this research is to create an abstract of the selected business model, the business model by which the ASR thermo-chemical plants in Australia will be established and operated by the Australian ELV shredding plants. The abstract allows a thorough investigation of the possible interactions (or feedback loops) that could occur between the selected business model and other business models within the Australian ELV recycling network. The analysis of the feedback loops determines the sustainability performance of the selected business model.

Some existing studies (Zamudio-Ramirez, 1994, Farel et al., 2013, Ferrão and Amaral, 2006, Halabi and Doolan, 2013, Halabi et al., 2012, Stasinopoulos et al., 2012) have identified the feedback loops that could be created within an ELV recycling network. One of the most comprehensive conceptual modelling studies focused on the ELV recycling industry is the research by Zamudio-Ramirez (1994). The present research utilised the conceptual models developed by Zamudio-Ramirez (1994) as the platforms for the development of the conceptual model of the selected business model.

The key outcome of a conducted conceptual modelling is a diagram called the ‘causal loop diagram (CLD)’ (Maani and Cavana, 2007). The CLD diagrams can include feedback loops if information resulting from some action travels through one variable and eventually returns in some form to its point of origin potentially influencing future action (Richardson, 2009). The feedback loops are broadly classified into two categories of reinforcing loops (usually shown with letter R inside the loops) and balancing loops (usually designated with letter B inside the loop). If the tendency in the loop is to reinforce the initial action, the loop is called a positive or reinforcing feedback loop and if the tendency is to oppose the initial action, the loop is called a negative, counteracting, or balancing feedback loop (Richardson, 2009)

The main element of the CLDs is causal links (or arrows) connecting variables (Maani and Cavana, 2003). The polarity of the causal links, i.e. the positive or the negative sign, represents the nature of the causal links between any pair of variables. The positive sign (+) indicates that any increase (or decrease) in the variable at the tail of an arrow causes a corresponding increase (or decrease) in the variable at the head of the arrow.
6.4.1 Results of the conceptual modelling

The CLD diagram of the selected business model is shown in Figure 6-8. The CLD contains the feedback loops that represent the possible interactions between the selected business model (i.e. ASR gasification in the ELV shredding plants) and the other business models (e.g. the business model of car dismantling facilities) within the Australian ELV recycling network.

![Causal loop diagram of the selected business model](image)

Figure 6-8 Causal loop diagram of the selected business model

The CLD diagram shown in Figure 6-8 has only captured the most influential feedback loops as recommended by (Sterman, 2000). The inclusion of all possible feedback loops in a CLD could undermine the effective communication of that CLD.
6.4.2 Interpretation of the individual feedback loops of the causal loop diagram

The CLD contains one reinforcing feedback loop and four balancing feedback loops (B1 to B4) (see Figure 6-8). The only reinforcing loop of the CLD diagram (R) advances the growth of the selected business model and the balancing loops of B1 to B4 contract (offset or dilute) the growth of the selected business model.

The R loop represents the feedback between the ASR gasification plants, car dismantlers, and the car’s last owner. As indicated in Figure 6-8, the variable of ‘junk car price’ (i.e. the ELV price) is linked to another variable of the loop called ‘willingness to bring cars to recycling’. The causal link (or the arrow) connecting these two variables has positive polarity meaning that any increase in ‘junk car price’ leads to an increase in the variable of ‘willingness to bring cars to recycling’. This causal link implies that an increase in the price paid by an ELV dismantler to the ELV last would create further incentive for the ELV’s last owner to enter the ELV into the Australian ELV recycling network. This would increase the number of ELVs that are dismantled and shredded by the Australian ELV recycling network. These consequences have been presented in the loop in the forms of the positive causal link between the variables of ‘willingness to bring cars to recycling’ and ‘car dismantling’, and the positive causal link between ‘car dismantling’ and ‘car shredding’.

Another important variable related to the reinforcing loop R is ‘fraction of non-metallic materials in car’. This would increase the carbon content of ASR that is presented in the R loop as the variable of ‘carbonaceous in ASR’. With an increase in ‘carbonaceous in ASR’, more energy can be recovered from ASR. This is presented in the R loop as ‘energy recovering’. When the amount of recoverable energy in ASR is increased, the profit gained from the ASR gasification plant would be increased, and consequently the gasification plant would be in an improved financial situation, enabling it to offer a higher price to an ELV dismantler for an ELV hulk. This is presented in the loop through the positive causal loop between ‘gasification profit’ and ‘price of hulks’. With an increase in the price paid by the ASR gasification plants for ELV hulks, the profit of the car dismantling business would be increased. This is represented by the positive causal link between ‘dismantlers profits’ and ‘junk car price’. The next causal link from the variable of ‘junk car price’ has already described in this section.
The balancing feedback loop of B1 presents the causal links related to the profitability of the ASR gasification plants. As the gasification profit increases, the attractiveness of ASR gasification is increased and, consequently, the ELV shredding plants would have more motivation to expand their gasification capacity. This would increase the fixed costs of gasification and ultimately reduce the profit of the gasification. Consequently, this would increase the fixed costs of the business and ultimately reduce its profits. The feedback loop of B1 partially trades-off the effects of the reinforcing loop of R.

The balancing feedback loop of B2 contains two variables that are linked together through both positive and negative causal links. The positive causal link implies that an increase in the profit of the ASR gasification plants would increase the tendency of the gasification plant to offer further price for ELV hulks. By way of contrast, the negative causal link implies that an increase in the hulk’s price would reduce the profit gained by the ASR gasification plants. The balancing feedback loop of B2 partially controls the paid price for ELV hulks, and as such it partially contributes to the contraction of the feedback loop of R.

The balancing feedback loop of B3 is similar to the feedback loop of B1 but it is related to the profitability of the car dismantling business. An increase in the price of ELV hulks would increase the profit for car dismantlers and therefore increase the attractiveness of car dismantling. When the attractiveness of the business is increased, the dismantlers would have more motivation to further invest in the business. This, consequently, would increase the fixed costs of the business and it would ultimately reduce the business’ profit. The feedback loop of B3 partially trades-off the effects of the reinforcing loop of R.

The balancing feedback loop of B4 is similar to the feedback loop of B2 but it is related to the ELV price. When the profit of dismantling business is increased, it would likely increase the price offered by car dismantlers to the car last owner. However, an increase in the junk car price would decrease the profit gained by car dismantlers. Similar to other balancing feedback loops of B1 to B3, the feedback loop of B4 partially trades-off the effect of the reinforcing loop of R.
6.4.3 Interpretation of the results with respect to the goal of the conceptual modelling

A sustainable business model for ELV reclamation is a business model that creates competitive advantage through superior customer value, and contributes to a sustainable development of the company and society through creating value (materials or energy) from non-metallic materials of the ELVs generated in Australia (see Section 1.4.1). As such, the selected business model could be regarded as a sustainable business model if the reinforcing loop of R (i.e. the value/energy creating loop) is the most dominant feedback loop in the developed. The balancing loops of B1 to B4, if they become extremely influential, could reduce the value (energy) creation of the selected business model and negatively impact the sustainability performance of the business model.

There is some evidence which indicates that the balancing loop cannot become extremely influential in the CLD. The balancing loop of B1, as described in Section 6.4.2, represents the effects of the investment within the ASR gasification plants on the reinforcing loop of R. The extreme strength of the B1 loop, through a massive investment for the expansion of the gasification plant, would weaken the strength of the R loop through the offering of very low prices to car dismantlers for ELV hulks. However, given that the ASR gasification plants will be managed by the ELV shredding plants, a massive reduction in the price of ELV hulks would not only affect the ASR gasification plants, but would also affect the metal recycling business of the ELV shredding facilities. It would significantly reduce the number of the incoming ELVs to the ELV shredding plants.

A similar argument can be presented for the B3 loop that represents the effects of the investment within car dismantling plants on the reinforcing loop of R. The extreme strength of the B3 loop, through a massive investment for the expansion of car dismantling facilities, would reduce the strength of the R loop. The reduction would happen when a very low price for ELVs is offered by car dismantlers to the car last owner. This would significantly reduce the willingness of the car’s last owner to enter their cars into the Australian recycling network. If this occurs, less ELV would be available for dismantling. The financial risks of offering a very low price for ELVs can be significant for the car dismantling facilities.

The B2 and B4 loops are not expected to dominate the R loop, based on the discussions presented above for the B1 and B3 loops. The strengthening of the B2 would be only possible through
offering a very low price for ELV hulks by ELV shredding facilities and the strengthening of the B4 would be only possible through offering a very low price for ELVs by car dismantlers. As discussed before in this section, these decisions would weaken the R loop but at the same time would cause significant risks (as explained above) to the financial viability of the ELV shredding plants and the car dismantling facilities.

Based on the above discussions, it would be unlikely that the balancing loops of the CLD would become the most influential feedback loops in the CLD of the selected business model. In the absence of strong weakening effects from the balancing loops, the reinforcing loop of R can maintain its value (energy) creation. As such, the selected business model can be regarded as a sustainable business model for ELV reclamation in Australia.

6.5 SUSTAINABILITY ASSESSMENT THROUGH THE SYSTEM DYNAMICS METHOD

6.5.1 Stocks and flows diagram of the system dynamics modelling

The system dynamics modelling often commences with the development of a diagram called ‘stocks and flows’ (SFD). A SFD represents the structure of the system that is modelled in a system dynamics study (Abu-Taieh, 2009). It provides a bridge to system dynamics, modelling and simulation, through the provision of specific symbols and components required for the modelling. A SFD contains all significant processes and phenomena of a modelled system so it can be regarded as a conceptual model for visualising various independent and interdependent processes (Muthuprakash and Damani, 2014).

The main elements of a SFD are stocks, flows, valves, converters, connectors, auxiliary variables, and clouds. Stocks, or the rectangular shapes in the SFDs, represent a part of a system whose value at any given instant in time depends on the systems past behaviour (TM Consulting, 2012). Flows, or the pipes in the SFDs, represent the rate at which the stock is changing at any given instant they either flow into a stock (causing it to increase) or flow out of a stock (causing it to decrease) (TM Consulting, 2012). Valves control flows and converters represent parts of a system whose value can be derived from other parts of the system at any time through some computational procedure. Connectors, or arrows, show how parts of a system influence each other. Auxiliary variables are the constant, or the other parameters, that are used for the quantification of flows and
stocks. Clouds represent the sources and sinks that lie outside of the model’s boundary: they are used to show that a stock is flowing from a source, or into a sink that lies outside of the model’s boundary (TM Consulting, 2012). Some SFD might include dashed lines that denote information.

Construction of a SFD begins with identification of relevant processes followed by the identification of stocks in an individual process (Wolstenholme, 1983). The modelling is an iterative process with description of each process resulting in introduction of new stocks, flows, and auxiliary variables. This in turn brings focus on yet unconsidered processes involving more variables (Muthuprakash and Damani, 2014). This methodology has been applied in the present research to develop the SFD of the selected business model.

The SFD of the selected business model is shown in Figure 6-9. It includes all significant processes and phenomena related to the selected business model, from the inputs of new vehicles to the Australian fleet, to the retirement of those vehicles and their respective end-of-life treatments. The SFD also covers some important aspects of the ELV recycling system which affects the rate of the energy recovery of the business model. These include the issue of ELV abandoning in Australia and the issue of changing material composition of vehicles.
Figure 6-9 Stocks and flows diagram of the selected business model

Note: ‘Aband Cars’ in the figure represents ‘Abandoned Cars’.


6.5.2 Key assumptions of the system dynamics modelling

The system dynamics modelling of the selected business model is based on some assumptions. The sustainability performance of the business model is modelled for 25 years, commencing in 2015 and concluding in 2040. A prediction about the key modelling inputs including the average ELV age, the average ELV material compositions, and the average ELV weight would be highly uncertain for the modelling period beyond 25 years.

It is assumed that the implementation of the proposed ELV reclamation in Australia (i.e. thermo-chemical treatment of ASR) will reduce the number of abandoned ELVs in the country. The assumption is supported by some international experiences. A study that reviewed the effects of the ELV recycling law in Japan three years after its implementation (Togawa, 2008) reported that the number of illegal ELVs dumped in the remote areas in Japan sharply reduced from 126,000 units in August 2001 to 35,064 units in March 2007. That study mainly attributed this reduction to the implementation of the ELV recycling law in Japan. The research by Ferrão et al. (2008) has reported that the implementation of the waste tyre recycling initiatives in Portugal has reduced the abandonment rate of waste tyres in that country also.

The above assumption is reflected in the SFD shown in Figure 6-9 in the form of a reinforcing feedback loop. The research considers that an increase in the energy recovery of the ASR thermo-chemical plants would increase the demand for ELVs, and this in turn would reduce the number of abandoned ELVs. This assumption will be tested through a sensitivity analysis in which the ELV reclamation in Australia would not cause any effect on the number of the abandoned ELVs in the country.

The precise number of the abandoned ELVs in Australia is unknown. An early study reported that approximately 8% of the total ELVs generated in Australia are abandoned in farms, lakes, and other places (Australian Government, 2002). This research assumes that no reduction in the ELV abandonment rate would be observed in Australia during the first ten years of the operation of the ASR gasification plants but the rate would be gradually reduced. This trend is shown in Figure 6-9.
Annually, around 4% of the second-hand cars in Australia are exported to other countries (ABS, 2008). This causes a 4% reduction in the number of ELVs that annually enter the Australian ELV recycling systems. The model assumes a constant value (4%) for the exported cars. This assumption is challenged later in this chapter where a greater fraction for the export of second-hand ELVs from Australia is applied.

The model assumes that plastics are the main substitutes for the fraction of steel that is reduced from cars for different purposes – including increasing the fuel efficiency of cars (Park et al., 2013, Hope, 2013, Giannouli et al., 2007). As such, the model assumes an increase in the plastics content of ELVs during the modelling period. This increases the amount of energy recovery from ASR gasification plants. This assumption will be challenged later in this chapter when both plastics, and lightweight metal alloys (e.g. alloys contain magnesium), replace a fraction of steel in cars.

The model assumes that the ASR gasification practice is the only method to recover non-metallic materials of ELVs in Australia during the modelling period (2015 to 2040). This assumption will be tested later in this chapter when a significant fraction of non-metallic materials is assumed to be recovered by other treatment practices.
6.5.3 Inventory of the system dynamics modelling

The system dynamics method depends upon quantitative data (Luna-Reyes and Andersen, 2003). This research collected a broad range of data to produce a computer simulation of the selected business model (i.e. the gasification treatment of ASR). The average data for the variables and constants of the system dynamics modelling are presented in Table 6-4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial amount</th>
<th>Unit</th>
<th>Trend</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>New purchasing cars per year</td>
<td>1.1</td>
<td>millions</td>
<td>increasing</td>
<td>(DoIISRTE, 2012)</td>
</tr>
<tr>
<td>Australian fleet size</td>
<td>13.4</td>
<td>millions</td>
<td>increasing</td>
<td>(ABS, 2012)</td>
</tr>
<tr>
<td>ELV abandonment rate</td>
<td>8</td>
<td>% of total ELVs</td>
<td>decreasing</td>
<td>(Australian Government, 2002)</td>
</tr>
<tr>
<td>ELVs exporting rate</td>
<td>4</td>
<td>% of total ELVs</td>
<td>unchanging</td>
<td>(ABS, 2008)</td>
</tr>
<tr>
<td>Average age of ELVs</td>
<td>15.4</td>
<td>year</td>
<td>increasing</td>
<td>(Staudinger and Keoleian, 2001)</td>
</tr>
<tr>
<td>Average weight of ELVs</td>
<td>1250.0</td>
<td>kg</td>
<td>increasing</td>
<td>(CamanoeAssociates, 2003)</td>
</tr>
<tr>
<td>Weight percentage of non-metallic materials in ELVs</td>
<td>25.0</td>
<td>% of an ELV mass</td>
<td>increasing</td>
<td>(Giannouli et al., 2007)</td>
</tr>
<tr>
<td>Weight percentage of non-metallic materials removed by dismantlers</td>
<td>4%</td>
<td>% of an ELV mass</td>
<td>unchanging</td>
<td>(DoTI, 2005)</td>
</tr>
<tr>
<td>Net energy recovery per kg of ASR</td>
<td>4.3</td>
<td>MJ/kg ASR</td>
<td>unchanging</td>
<td>(Viganò et al., 2010)</td>
</tr>
</tbody>
</table>

Those modelling parameters in Table 6-4 that have either an ‘increasing trend’ or a ‘decreasing trend’ are changed throughout the modelling period. The quantities of these parameters for the different years are presented in Table 6-5. The applied time-scale of the system dynamics modelling is 25 years—as after this period another ELV reclamation option could be identified and applied as the most sustainable ELV reclamation for Australia.
Table 6-5 Parametric values used in the system dynamics modelling

<table>
<thead>
<tr>
<th>Year</th>
<th>Purchasing cars</th>
<th>Average ELV age</th>
<th>Abandonment rate</th>
<th>Average ELV weight</th>
<th>Weight percentage of non-metallic in ELV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousand cars</td>
<td>Year</td>
<td>% of the total number of ELVs</td>
<td>Kg</td>
<td>% of the total mass of an ELV</td>
</tr>
<tr>
<td>2015</td>
<td>1015.00</td>
<td>15.41</td>
<td>8.00</td>
<td>1250.00</td>
<td>25.00</td>
</tr>
<tr>
<td>2107</td>
<td>1047.00</td>
<td>15.48</td>
<td>8.00</td>
<td>1232.00</td>
<td>25.50</td>
</tr>
<tr>
<td>2019</td>
<td>1076.00</td>
<td>15.55</td>
<td>8.00</td>
<td>1219.00</td>
<td>26.20</td>
</tr>
<tr>
<td>2021</td>
<td>1114.00</td>
<td>15.68</td>
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6.5.4 Results of the system dynamics modelling

The computer program of STELLA (Isee Systems, 2009) is used to perform the system dynamics modelling and produce the behaviour over time (BOT) pattern mode of the business model (see Section 3.2.3.3). Further information about the STELLA software is provided in Appendix D. The annual electricity production of the ASR gasification plants presented in Megajoule (MJ) was selected as the variable of interest for the BOT pattern mode. The computer programming of the system dynamics modelling for the base case, for the associated sensitivity test, and for the validation tests are provided in Appendix B.
6.5.5 Interpretation of the results of the system dynamics modelling

As stated in Section 3.2.3.3, a relatively small number of the BOT pattern modes is common to a large variety of systems (Sterman, 2000). These pattern modes (Figure 3-3) include: (i) Exponential Growth, (ii) Goal Seeking, (iii) S-shaped Growth, (iv) Oscillation, (v) Growth with Overshoot, and (vi) Overshoot and Collapse. It was discussed in Section 3.2.3.3 why a desirable BOT pattern mode for the selected business model is a pattern mode that is similar to the pattern models of ‘Exponential Growth’ and ‘S-shaped Growth’.

The results of the system dynamics modelling (Figure 6-11) indicate the annual electricity production of the ASR gasification plants over the modelling time (i.e. the BOT pattern mode of the business model) is similar to the desirable pattern mode of ‘Exponential Growth’. This indicates that the selected business model can create value (energy in the form of electricity) from the non-metallic materials of ELVs. As such, the business model can be regarded, subject to the confirmation in the sensitivity analysis, as the most sustainable business model for ELV reclamation in Australia through the thermo-chemical technology.
6.5.6 Validation and verification of the model

The main differences between the validation process and the verification process of a numerical model are described by Thacker et al. (2004) as:

“Model verification and validation are the primary processes for quantifying and building credibility in numerical models. Verification is the process of determining that a model implementation accurately represents the developer’s conceptual description of the model and its solution. Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. Both verification and validation are processes that accumulate evidence of a model’s correctness or accuracy for a specific scenario; thus, V&V cannot prove that a model is correct and accurate for all possible scenarios, but, rather, it can provide evidence that the model is sufficiently accurate for its intended use.”

Three validation techniques – (i) structure confirmation test, (ii) sensitivity test, and (iii) behaviour pattern tests – have been recommended in the literature (Barlas, 1996, Zhang et al., 2013) for system dynamics modelling. The sequence of the techniques is shown in Figure 6-12.

![Figure 6-12 Recommended validation techniques in system dynamics modelling (Barlas, 1996) (adopted from research by Zhang et al. (2013))](image)

This research tested the structure of the DSF through testing the consistency of the units of the elements of the SFD (e.g. stocks, flows, converters) and through testing the energy and mass balance of the SFD elements. Furthermore, the research applied the triangulation technique to verify the data used in the SFD. In this exercise, where it was possible, the data utilised was compared with the corresponding data reported in other sources (e.g. verification of the data related to the age and weight of an ELV).
In the sensitivity test, as opposed to the base assessment, the ELV abandonment rate is assumed to be constant (around 8% of the total generated ELVs). As such, in comparison to the base assessment, a lower number of ELVs enter the Australian recycling network; as such, less ASR will be available for the gasification plants. The results of the sensitivity test are shown in Figure 6-13.

As indicated in Figure 6-13, the BOT modes of the business model (i.e. the annual electricity production of the ASR gasification plants) for the base case and for the sensitivity test are the same. However, less electricity is produced in the sensitivity test than in the base case as a smaller number of ELVs are treated by the Australian ELV recycling network in the sensitivity test.

The BOT mode of the selected business model was tested through three scenarios in which extreme conditions were imposed by other business models on the selected business model. The scenarios were developed based on the key assumptions of the modelling (see Section 6.5.2). To provide a better visual effect of the scenarios on the BOT mode of the selected business model, the relative annual electricity production of the ASR gasification plants (in %) will be used instead of the net annual electricity production of the ASR gasification plants. The relative electricity production of the ASR gasification plants is defined as:
Relative electricity production \( \% = \left( E_n - E_1 \right) \times \frac{100}{E_1} \) (1)

Where \( E_n \) is electricity production in year \( n \) (\( n = 1 \) to 25) and \( E_1 \) is electricity production in the first year (the year 2015).

Scenario 1 assumes that ten years after the establishment of the ASR gasification plants in Australia, the fraction of the annual export of ELVs from Australia will increase from 4% to 18% (Figure 6-14). This is a significant increase in the number of the exported cars from Australia and such an increase might not occur. However, the analysis aims to test the robustness of the business model under extreme conditions.

![Figure 6-14 Trends of the ELV export/take back in Scenario 1 and in Base Case](image)

An increase in the number of the exported ELVs from Australia could happen for different reasons. For instance, some of the European car makers might decide to ‘take back’ the discarded vehicles that they have already sold in Australia, as part of their ‘product stewardship’ policy (see Section 2.4.1.1). At present though there is no evidence that any of the international car makers has an intention to take back their sold cars in Australia.

The BOT mode of Scenario 1 is shown in Figure 6-15. As indicated in Figure 6-15, the relative electricity production of the ASR gasification plants is reduced by around 5% in 2025 but three
years later (2028) the ASR gasification plants again reach the electricity production rate that they had achieved in the first year.

The relative electricity production rate of the ASR gasification plants is gradually increases after 2018. This could be related to the annual increase in the quantity of non-metallic materials of ELVs in the modelling (see Table 6-5), which consequently increases the energy production of the gasification plants.

Scenario 2 tests the BOT of the business model when a fraction of non-metallic materials of ELVs are assumed to be used in other resource recovery plants. This scenario largely depends on the willingness of car dismantling facilities to further remove non-metallic materials of ELVs (e.g. plastics and rubbers) and sell them to dedicated plastics or rubber recycling plants. Such dedicated material recycling plants are not available in every Australian state or territory (Australian Government, 2014c) but this research assumes that there will be an increased presence of such recycling plants across Australia after 2025.

At present, car dismantlers are required to remove fluids (e.g. fuel), refrigerants, batteries, and the explosive parts (e.g. air bags) of the ELVs. These are estimated to account to around 4% of the total ELV mass. Scenario 2 assumes that car dismantlers, with a delay of 10 years from the
establishment year of the ASR gasification plants, remove 12% of the total mass of an ELV (Figure 6-16) to sell them to other resource recovery plants.

Based on the findings of some international studies (Coates and Rahimifard, 2007, Duval and MacLean, 2007, Ferrão and Amaral, 2006), the removal of 12% of ELV total mass would be an ambitious target for the typical car dismantler. This finding is attributed to high labour costs for the removal of the ELV mass for the ordinary car dismantlers which are characterised as small business entities with only basic removal tools available. However, Scenario 2 intends to test the robustness of the selected business model under severe conditions.

The BOT mode of Scenario 2 is shown in Figure 6-17. Based on Figure 6-17, in 2025 when a partial diversion of non-metallic materials of ELVs occurs in the modelling, the relative electricity production of the ASR gasification plants will reduce by around 30%. However, nine years later (2034), the ASR gasification plants produce the same amount of the electricity that they produced in the first year (2015). After this, the ASR gasification plants have an increasing trend of electricity production.
Scenario 3 tests the BOT mode of the selected business model when an unexpected change has assumed to have occurred in the material composition of cars. As opposed to the base case analysis in which the non-metallic materials (e.g. plastics) are assumed to be the main substitute for the fraction of steel that is eliminated from cars to make the cars lighter, Scenario 3 assumes that the substitution materials are a mix of non-metallic materials and lightweight metal alloys (e.g. magnesium alloys). This is based on the prediction of the further applications of lightweight metal alloys in future cars (Farag, 2008, Hirsch and Al-Samman, 2013, Kulekci, 2008).

Scenario 3 assumes that ten years after the establishment of the ASR gasification plants in Australia (2025), the fraction of non-metallic materials in cars is reduced by 20% — because of the further application of lightweight metal alloys in cars — and also because the fraction of non-metallic materials stays constant in the remaining years of the modelling period, as shown in Figure 6-18.
As indicated in Figure 6-19, the relative electricity production of the ASR gasification plants in 2025 is reduced by 5% when the fraction of non-metallic materials is reduced by 20% in 2025. However, around 13 years later (2038), the ASR gasification plants produce the same electricity that they produced in the first year (2015). This could be related to the annual increase in the number of ELVs generated in Australia that subsequently increases the ASR that fed into the gasification plants.
6.6 MOST SUSTAINABLE BUSINESS MODEL FOR ELV RECLAMATION IN THE AUSTRALIAN CONTEXT

The present research identifies the business model in which non-metallic materials of ELVs are reclaimed through thermo-chemical treatment of ASR at Australian ELV shredding plants as the most sustainable business model for ELV reclamation in the Australian context. This is supported with the results of the sustainability assessment of the business model through the applications of the conceptual modelling method and the system dynamics method.

6.7 DISCUSSION AND CONCLUSIONS

The chapter applied three assessment methods of: (i) multi-criteria analysis (MCA), (ii) conceptual modelling, and (iii) system dynamics, to identify the most sustainable ELV reclamation for Australia. Such combination of assessment methods has not been practiced in any waste management research to date.

The MCA method demonstrated again its strong ability to compare a set of alternatives, a set of business models for ELV reclamation, against a set of decision-criteria and subsequently identify one alternative as the best option. However, the MCA method was not used in the chapter as a tool to assess the sustainability performance of the considered business models. The sustainability assessment of the business models for ELV reclamation in Australia is a system-based assessment requiring a thorough analysis of the possible interactions (feedback loops) between the business models and other business models. Such analysis is beyond the capacity of the MCA method.

Both the conceptual modelling method and the system dynamics method demonstrated their strong ability to conduct a system-based analysis. The applied conceptual modelling in the chapter assessed the sustainability performance of the selected business model through a qualitative analysis; whereas, the applied system dynamics modelling delivered the same task through a quantitative analysis. It can be argued that both qualitative and quantitative analysis benefited the research. However, the conducted system dynamics analysis provided a greater level of confidence about the sustainability performance of the selected business model.

The chapter validated and verified the results of the system dynamics modelling through a set of three techniques that are recommended in the literature. The application of one of the validation
techniques, the behaviour pattern test, involved developing three ‘what-if’ scenarios. The scenarios covered some undesirable conditions that the selected business model might encounter during its lifetime.

The first scenario tested the robustness of the business model if car makers decide to take-back some ELVs, or the used car dealers decide to expand the exportation of used cars from Australia. The second scenario tested the robustness of the business model if car dismantlers decide to further remove auto parts made from non-metallic materials and sell them to relevant material recycling plants. The third scenario tested the business model when the material composition of cars was changed in the favour of lightweight metal alloys.

It can be argued that the scenarios tested the business model against the most possible business risks, and the business model performed well against all of the three scenarios. The results of the scenarios, the relative energy production of the ASR gasification plants, indicate that the third scenario could create more severe risks to the business model than the other two scenarios. Scenario 3 is based on the extensive application of lightweight metal alloys in future cars. In the event of such conditions, the ASR gasification plants might not have any opportunity to expand and their annual electricity production could be less than the electricity production that they had in the first year.

Whilst the approach developed in the chapter has been applied to identify the most sustainable business model for ELV reclamation in Australia, the proposed approach can be used to identify the most sustainable business model for other waste streams ─ both in Australia and internationally. The research in the chapter has extended the frontier of business model development areas by introducing a new combination of three sustainability assessment methods (i.e. multi-criteria assessment, conceptual modelling, and system dynamics). This new methodology when applied will enable the identification of the most sustainable business model for management of a specific waste stream to be determined.

6.8 SUMMARY

In this chapter, a sustainable business model for ELV reclamation in Australia via the implementation of the ELV reclamation option of ‘thermo-chemical treatment of ASR’ identified. In the initial section of the chapter, the existing business models relevant to the ELV reclamation
option are identified. These business models were that (i) the business was established and operated by vehicle manufacturers, (ii) the business was established and operated by waste management companies, and (iii) the business was developed and established by ELV shredding facilities.

The chapter then applied the Analytical Hierarchy Process (AHP) technique to compare the identified business models with respect to the key characteristics of a successful business model. The assessment identified the business model in which the ASR thermo-chemical plants are established and operated by ELV shredding facilities as the most preferred business model in the Australian context.

The chapter continued with the sustainability assessment of the selected business model. The sustainability assessment was carried out through both the conceptual modelling method and the system dynamics method. The first method created an abstract of the business model, allowing the identification of the reinforcing and the balancing feedback loops between the business model and the other business models within the Australian ELV recycling network.

The conceptual modelling produced the causal loop diagram (CLD) of the business model. One reinforcing feedback loop and four balancing feedback loops were identified in the CLD. The reinforcing feedback loop was identified as the feedback loop that created value (energy) for the business model and the balancing feedback loops were identified as the feedback loops that reduced the value creation of the business model. A comprehensive analysis of the CLD indicated that the reinforcing loop of the CLD is the most influential feedback loop in the CLD, and it also indicated that it would be unlikely in the future, in a business’ ‘usual case scenario’, that the balancing loops of the CLD would become the most influential feedback loops of the CLD, offsetting the value creation of the reinforcing loop.

The second method used the abstract developed by the conceptual modelling method as a basis to develop the stocks and flows diagram (SFD) of the business model. The annual electricity production of the ASR gasification plants across Australia was considered as the key indicator of behaviour of the selected business model. A computer simulation of the SFD based on a set of Australian-based quantitative information identified the behaviour-over-time (BOT) mode of the selected business model as an ‘Exponential Growth’ pattern mode. The identified BOT mode was
regarded as evidence that the business model is a sustainable business model as it creates value (energy) in a growing trend from non-metallic materials of ELV that otherwise would be sent to landfill.

The chapter validated and verified the results of the system dynamics modelling through a set of three techniques recommended in the literature. The application of one of the validation techniques, the behaviour pattern test, involved developing three ‘what-if’ scenarios. The scenarios covered some undesirable conditions that the selected business model might encounter during its lifetime.

The first scenario tested the robustness of the business model if the car makers decided to ‘take-back’ some ELVs, or if the used car dealers decided to expand the exportation of the used cars from Australia. The second scenario tested the robustness of the business model if car dismantlers decided to further remove the auto parts made from non-metallic materials and sell them to the relevant material recycling plants. The third scenario tested the business model when the material composition of cars is changed in favour of lightweight metal alloys.

The selected business model performed successfully in all of the applied validation and verification tests. This provided enough confidence to regard the business model of ELV reclamation through the treatment of ASR in thermo-chemical plants at ELV shredding facilities as the most sustainable business model for Australia.
7 Conclusions and recommendations

7.1 RESPONSE TO THE RESEARCH QUESTIONS

Which of the international best practice ELV reclamation options are technically viable in Australia?

To address the question, the research compared the international best practice ELV reclamation options against the four relevant technical indicators suggested in the literature: namely (1) functionality, (2) existing experience/reliability, (3) adaptability to local conditions, and (4) flexibility. The multi-criteria analysis (MCA) of the ELV reclamation options was conducted based on the principles of the Analytical Hierarchy Process (AHP) technique.

According to the first principle of the AHP technique, the assessment decision was broken down into a hierarchy of three levels namely: (1) goal, (2) assessment criteria (the technical indicators), and (3) alternatives (the ELV reclamation options). Based on the second principle of the AHP technique, the relative importance of the elements within each level of the hierarchy was evaluated with respect to the individual elements located in an upper level. The evaluation was conducted through the pairwise comparison approach.

Two sets of the pairwise comparisons were made. In the first set, the relative abilities of the ELV reclamation options to meet the requirements of the technical indicators were identified. This drove the ‘local’ priorities or the performance ranking of the ELV reclamation options with respect to the technical indicators. In the second set, the relative importance of the individual technical indicators with respect to the assessment goal was identified. This drove the ‘weighting factors’ of the technical indicators.

Based on the third principle of the AHP technique, the results were synthesised through the multiplication of the ‘local priority’ of a specific ELV reclamation, and the ‘weighting factor’ of the relevant technical indicator, and then adding together the multiplication results. The analysis produced the ‘global priorities’ of the ELV reclamation options. The calculated amounts of the
‘global priorities’ were used to develop the performance ranking of the ELV reclamation options with respect to the assessment goal.

The research considered the ELV reclamation options with the ‘global priorities’ between 0.5 to 1 as those that were technically viable ELV reclamation options in the Australian context. The research considered those with the ‘global priorities’ of less than 0.5 as the ELV reclamation options that are not currently technically viable in Australia. Three of the ELV reclamation options had the ‘global priorities’ between 0.5 to 1; and as such, were identified as the most technically viable ELV reclamation options in the Australian context. The technical viable ELV reclamation options were: (1) injection of ELV plastics as reducing agents in blast furnaces, (2) thermo-chemical treatment of automobile shredder residue (ASR), and (3) mechanical-physical separation of ASR.

**What are the most relevant indicators to assess the sustainability performance of the international best practice ELV reclamation options in the Australian context?**

To answer the second research question, the research reviewed the literature and identified a list of the most frequently applied social, economic, and environmental indicators for the identification of optimal waste management strategy available in existing publications. The research then screened the identified indicators based on the Australian conditions, and subsequently, developed a set of Australian specific sustainability indicators suitable for the assessment of technically viable ELV reclamation options. These sustainability indicators were: (1) climate change mitigation, (2) water conservation, (3) job creation, (4) safety and public health, (5) capital conservation, (6) social satisfaction, (7) mineral conservation, (8) fossil fuel conservation, (9) landfill space conservation.

**Which of the international best practice ELV reclamation options is the most sustainable ELV reclamation option for Australia?**

The third research question asked what the most sustainable ELV reclamation option is for Australia. To answer the third question, the research compared the sustainability performance of the ELV reclamation options through two different sustainability assessment models, based on the principles of the AHP technique. The applied sustainability assessment models were: an emerging
model, referred to in the research as ‘multidimensionality’, and an established sustainability assessment model often referred in the literature as the ‘triple bottom line (TBL)’ model. In the multi-dimensionality model, as opposed to the TBL model, a sustainability assessment indicator can represent more than one dimension of sustainability (i.e. social, economic and environmental).

Subsequently, the multi-dimensionality model identified the ELV reclamation option of ‘thermo-chemical treatment of ASR’ and the TBL identified the ELV reclamation option of ‘injection of ELV plastics as reducing agents in blast furnaces’ as the most sustainable ELV reclamation options for Australia. This is mainly attributed to the difference between the weighting factors of the sustainability assessment indicators assigned in the multi-dimensionality model and the assigned weighting factors in the TBL model (see Table 5-4 and Table 5-11).

A comprehensive sensitivity analysis was conducted in which the sensitivity of the assessment models, with respect to the weighting factors of the sustainability indicators, was assessed. The results indicated that the selected ELV reclamation option based on the TBL model, as opposed to the reclamation option based on the multi-dimensionality model, is highly sensitive to the applied weighting factors. Thus, there is little confidence on the selected ELV reclamation option based on the TBL model. The research identified that ELV reclamation option (i.e. thermo-chemical treatment of ASR) as the most sustainable ELV reclamation for Australia.

**What is the most sustainable business model to implement the selected most sustainable ELV reclamation option in Australia?**

The fourth research question asked what the most sustainable business model is to implement the selected most sustainable ELV reclamation option in Australia. To answer the question, a literature review was conducted to identify the existing business models relevant to the ELV reclamation option of ‘thermo-chemical treatment of ASR’. Three business models were identified namely: (1) the business model in which vehicle manufacturers build and operate ASR thermo-chemical treatment plants, (2) the business model in which waste management companies build and operate ASR thermo-chemical plants, and (3) the business model in which ELV shredding facilities build and operate ASR thermo-chemical plants.
To identify the most effective business model for Australia, the business models were compared, according to the principles of the AHP technique, against three relevant assessment indicators found in the literature namely (1) goal alignment, (2) self-reinforcement, and (3) robustness. The results indicated that the business model in which the proposed ASR thermo-chemical plants are established and operated by the ELV shredding facilities is the most effective business model for Australia. In comparison to other considered business models, that business model in which the proposed ASR thermo-chemical plants are established and operated by the ELV shredding facilities performed better in the applied multi-criteria assessment study. The selected business model maintained its position as the most effective business model in the conducted sensitivity analysis in which different weighting factors were assigned to the assessment indicators.

The sustainability assessment of the identified business model was conducted through two sustainability assessment methods of conceptual modelling and system dynamics. The conceptual modelling method created an abstract of the business model in the form of a produced causal loop diagram (CLD). The CLD represented the major interactions (feedback loops) between the proposed business model for ELV reclamation and the other business models within the Australian ELV recycling network.

Once reinforcing feedback, the loop creates value (energy) for the business model, and four balancing feedback loops, the loops that reduce the value creation of the business model, were identified in the CLD. A comprehensive analysis of the feedback loops indicated that the reinforcing loop of the CLD was the most influential feedback loop and that this would be unlikely to change in the future. This result provided enough confidence to conclude that this business model is a sustainable business model as it can create value (energy) from non-metallic materials of ELVs.

The sustainability assessment of the business model through the system dynamics method was conducted through the analysis of the behaviour-over-time (BOT) mode of the business model, based on the model lifetime of 25 years. The annual electricity production of the ASR gasification plants across Australia was considered as the behaviour of the business model. The abstract developed by the conceptual modelling method was used as a basis to produce the stocks and flows diagram (SFD) of the business model. A computer simulation of the SFD, based on the Australian specific data, identified the BOT mode of the business model as an ‘Exponential
Growth’ pattern mode. The identified BOT mode was regarded as evidence that the business model was a sustainable business model as it created value (energy) from non-metallic materials of ELV in an upwardly growing trend.

The BOT pattern mode of the business model was validated and verified through the recommended techniques in the literature. Three ‘what-if’ scenarios were developed based on the requirements of one of the validation techniques, the behaviour pattern test. The scenarios covered some extreme and undesirable conditions that the selected business model might encounter during its lifetime.

In the first scenario, ten years after the establishment of the business model, the fraction of the total ELVs generated in Australia that leave Australia as used cars suddenly increased from 4% to 18%. This would initially decrease the relative annual electricity production of the business (relative to the electricity production of the first year) by around 5%, but three years later the business model would create the same amount of electricity that would be produced in the first year. The business model will thus have a growing electricity production trend. This scenario could happen for a number of reasons including the adoption of a ‘beyond-Europe’ product stewardship policy by some European car makers.

In the second scenario, ten years after the establishment of the business model, car dismantlers decide to suddenly increase the mass of the removed non-metallic materials from 4% to 12% of the total mass of an ELV. This would reduce the relative electricity production of the business model (relative to the electricity production of the first year) by around 30% but nine years later, the business model would create the same amount of electricity that would be produced in the first year. The business model will thus have a growing electricity production trend. This scenario could happen for different reasons including further expansion of the plastic recycling facilities in Australia that would in turn create a strong demand for ELV plastics in Australia.

In the third scenario, ten years after the establishment of the business model, the mass fraction of non-metallic materials of ELVs is reduced by 20% and kept constant during the remaining lifetime of the business model. This would reduce the relative electricity production of the business model (relative to the electricity production of the first year) by 5% but 13 years later, the business model would create the same amount of electricity that would be produced in the first year. A possible
cause of the scenario would be the extensive application of lightweight metal alloys (e.g. magnesium based alloys) as the substitutes for some removed steel in cars.

While the ‘Exponential Growth’ pattern mode of the business model would be temporarily changed in the considered scenarios, the overall BOT pattern mode of the business model would remain consistent with the BOT pattern mode of ‘Exponential Growth’. This provides enough confidence to regard the investigated business model as the most sustainable business model for ELV reclamation in Australia.

7.2 POLICY IMPLICATIONS OF THE RESEARCH

The major policy implication of the research is on the Australian National Waste Policy, particularly its Product Stewardship Act 2011 (see Section 2.4.3). The Product Stewardship Act 2011 includes voluntary, coregulatory and mandatory product stewardship. Whilst vehicles has not been yet included in the Australian product stewardship schemes, the product stewardship scheme relating to vehicles could be proposed for Australia in coming years as similar schemes have already been proposed, and now are implemented, in Japan, South Korea, China, Taiwan, and the member states of the European Union.

The failed experience of the ELV legislation in Malaysia — because of the public perception that little ELV management research had been conducted prior to the introduction of the legislation — highlights the importance of the contextual research on ELV management. The present research, to some extent, reduces the risks of such public perception if any ELV legislation is proposed for Australia. The research provides a profound insight into the current treatment of non-metallic materials of ELV both in Australia and in the countries where the non-metallic materials are reclaimed. The research also contributes to the debate on the sustainable treatment of non-metallic materials of ELV in the Australian context through the identification of the most sustainable ELV reclamation for Australia, and the most sustainable business model for the implementation of the selected ELV reclamation option.

Another major contribution of the research to the Australian Product Stewardship Act 2011 is the identification of a set of sustainability assessment methods relevant to the research that is focused on the sustainable management of end-of-life products in Australia. The sustainability assessment methods used in the present research were selected through a rigorous assessment of more than 30
existing sustainability assessment methods. The applications of the selected assessment methods in the research demonstrated the abilities of the methods to identify a sustainable waste treatment practice, and a sustainable business model, for the selected waste treatment practice in the Australian context. The methodology applied in the present research is general enough to be applied in the research focused on the reclamation of non-metallic materials from end-of-life products including, but not limited to, end-of-life aircrafts, end-of-life ships, and end-of-life gymnasium products.

7.3 CONTRIBUTIONS OF THE RESEARCH

One of the major contributions of this research is the advancements made in relation to the emerging sustainability assessment model of multi-dimensionality. The conceptual structure of the multi-dimensionality model had already been developed in relevant early research studies. The present research contributed to the development of that conceptual model through developing some important methodological aspects of the model, including the allocation of the weighting factors of the sustainability indicators used in the model (i.e. best-case scenario/worst-case scenario analysis).

The research demonstrated the practical application of the multi-dimensionality model in a sustainability assessment analysis. The research compared the results based on the multidimensionality model and the results based on the established sustainability assessment model of the triple bottom line (TBL) model. The comparison concluded that the results based on the former model are less sensitive to the key modelling assumptions than the results based on the latter model. This could further promote the application of the multi-dimensionality model in any future research focused on the sustainability assessment of a set of options.

Another research implication of this research is related to the sustainability assessment of a set of business models for the implementation of a selected waste treatment practice for a given region. Whilst the sustainability assessment of a set of waste treatment practices for a region has been the subject of many research studies, none of the research studies has yet developed a sustainable business model for the implementation of the selected waste treatment practice in that geographical region. The system-based methodology developed in this research relating to the sustainability assessment of a set of business models could be applied in the future waste management research studies.
7.4 LIMITATIONS OF THE RESEARCH

The main limitations of the research are as follows:

1. The research is limited to the internationally best practice ELV reclamation options and is excluded the emerging ELV reclamation options listed in Table 1-7 as the information related to the social, economic and environmental aspects of the emerging ELV reclamation options are very limited.

2. The comparative sustainability assessment of the ELV reclamation options (the three most viable reclamation options) was conducted against nine sustainability assessment indicators relevant to the Australian context. The research has limited the applied sustainability assessment indicators to those assessment indicators that have been frequently used in waste management studies. As such, there could be some sustainability assessment indicators relevant to the treatment of waste generated in the Australian ELV recycling industry that have not been included in the research.

3. The system dynamics modelling of the business model was based on the best available indicative data (e.g. the indicative weight of an ELV) rather than the application of statistically average values for the used data. The key findings of the research are not considered to be sensitive to the use of indicative data rather than the actual data.

4. The research applied the AHP technique for the technical assessment and sustainability assessment of the ELV reclamation options and also for the comparative assessment of a set of business models in Chapter 6. The research aimed to obtain the information required for the development of the ‘pairwise comparison matrix’ relevant to each of the AHP assessments from the Australian-based research studies. However, the information from international studies was used when no information was found from the Australian-based studies. An example is the pairwise comparison between the ELV reclamation options of “thermo-chemical treatment” and “mechanical physical separation” against the sustainability indicator of “job creation”. Given the lack of relevant Australian-based research, a research conducted in the United States was used to compare the ELV reclamation options against the considered sustainability assessment indicator.

7.5 CONCLUSIONS

The main conclusions of the research are as follows:
1. In Australia, non-metallic materials of ELVs (~30% of an ELV total mass) are sent to landfill in form of a residue called automobile shredder residue (ASR). The current treatment of non-metallic materials of ELVs causes some considerable social, economic and environmental issues. In some countries, the energy and materials of ASR are commercially reclaimed mainly through seven different treatment practices.

2. Three of the seven international best practice ELV reclamation options are technically viable in Australia. Thermo-chemical treatment of ASR is the most sustainable ELV reclamation option in the Australian context.

3. The business model in which the proposed ASR thermo-chemical treatment plants are established and operated by ELV shredding facilities is the most sustainable business model for ELV reclamation in the Australian context. The proposed business model is strong enough to withstand against some assessed undesirable effects from other business models within the Australian ELV recycling network. The extensive application of lightweight metal alloys in the future cars is the most challenging scenario for the proposed business model.

4. The major policy implication of the research is on the Australian National Waste Policy, particularly its Product Stewardship Act 2011. The major research implication of the research is related to the emerging sustainability assessment model of multi-dimensionality.

5. The methodology used in the research is general enough to be used in the research studies focused on the identification of the most sustainable end-of-life treatment practice for a given product.

7.6 RECOMMENDATIONS

The key recommendations of the research are as follows:

1. The commencement of a national debate and discussion about the sustainable management of ELVs in Australia is recommended. The information provided in this thesis may assist in forming this debate.

2. The first Australian large-scale thermo-chemical (gasification) waste treatment plants will be operated soon in Port Hedland. It is recommended that the lessons learnt from the plant are shared with the research community and the industry, in particular the Australian ELV recycling industry.

3. It is recommended that the both sustainability assessment models of TBL and multi-dimensionality are applied in the research studies focused on the sustainability assessment of
a set of waste treatment practices. The performance ranking of the waste treatment practices could be sensitive to the applied sustainability assessment model.

4. An effective dialogue is recommended between the automotive industry and the Australian ELV recycling industry with respect to the most likely scenarios for the future material composition of cars. If the automotive industry decides to predominantly use lightweight metal alloys as a substitute for the reduced fraction of steel in cars, the decision could significantly reduce the annual energy recovered by the selected ELV reclamation option for Australia (i.e. thermo-chemical treatment of ASR).

7.7 FUTURE RESEARCH

This research proposes further research in the following areas:

1. A laboratory gasification treatment of the ASR collected from the various Australian ELV shredding facilities could provide valuable data for the detailed technical, economic, and environmental analysis of the treatment practice.

2. The expert-judgement approach was applied in the research—based on the recommendations provided in the literature—to develop the three pairwise comparison matrices of the research. A series of the future research studies could develop the matrices through stockholders’ consultation approaches, including the Delphi method.

3. The statistical data about current Australian car dismantlers businesses is incomplete and outdated. Research focusing on the characterisation of Australian car dismantlers businesses could provide valuable information for the sustainable management of ELVs in the Australian context.

4. The region-specific information about the key ELVs attributes (e.g. average weight, average age and others) is not currently available for every Australian States and Territories. Nationally based research focusing on the characterisation of the region-specific ELVs could provide important information for the sustainable management of ELVs in the Australian context.
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APPENDICES

APPENDIX A

Supporting information for the pairwise comparison matrix of the multi-criteria assessment of the business models

The research assessed the performance of three business models related to the ELV reclamation option of ‘thermo-chemical treatment of ASR’ against the essential characteristics of a successful business model namely: (1) goal alignment, (2) self-reinforcement, and (3) robustness. The assessed business models were:

Option 1: The business model in which vehicle manufacturers build and operate ASR thermo-chemical treatment plants
Option 2: The business model in which waste management companies build and operate ASR thermo-chemical plants
Option 3: The business model in which ELV shredding facilities build and operate ASR thermo-chemical plants.

This section provides an overview of the considerations related to the judgements made about the relative abilities of the business models to meet the requirements of the individual assessment indicators.

Assessment indicator of ‘goal alignment’: It can be argued that the main business goal for Option 1, Option 2 and Option 3 are vehicle manufacturing, waste treatment, and material reclamation respectively. As such, the reclamation of non-metallic materials of ELVs through the thermo-chemical technology is strongly aligned to the business goal of Option 3. The reclamation of the non-metallic materials is also aligned to the business goal of Option 2 but not to the extent that it is aligned with the business goal of Option 3.

Assessment indicator of ‘self-reinforcement’: the conceptual modelling method was applied to best compare the abilities of the options against the assessment indicator. The causal loop diagram
(CLD) for Option 1 and Option 2 is shown in Figure A. The CLD for Option 3 was previously shown in Figure 6-8.

A comparison between the CLDs shown in Figure C and Figure 6-8 indicates that whilst there is one reinforcing loop (R) in the CLDs of the three options, the number of balancing loops (B loops) are different from the CLD of Option 3 (four balancing loops) and the CLDs of Option 1 and Option 2 (six balancing loops). As discussed in Section 6.4.3, the balancing loops tend to offset
the reinforcing loop of R. Thus, it can be argued that Option 3 has more ability than the other two options to meet the requirement of the assessment indicator (i.e. self-reinforcing).

**Assessment indicator of ‘robustness’:** the robustness of the options is their ability to sustain their effectiveness over time (see Section 6.2.3). The relative robustness of the options is regarded almost the same for all three options. The relative robustness of Option 1 is considered to be slightly more than the other two options. This is mainly related to the role of vehicle manufacturers in the selection of material composition of vehicles.

The options are based on the treatment of ASR in thermo-chemical plants. A change leading to the reduction of non-metallic materials in cars such as the extensive application of lightweight metal alloys in cars can significantly reduce the effectiveness of the options (as demonstrated in Section 6.5.6). As such, it can be argued that the controlling material composition of cars by vehicle manufacturers can improve the ability of Option 1 to maintain its effectiveness more than Option 2 and Option 3.
APPENDIX B

Programming of the system dynamics modelling

Programming of the base case

□ Aband_Cars(t) = Aband_Cars(t - dt) + (Abandoning) * dt
 INIT Aband_Cars = 0
 INFLows:
   □ Abandoning = Discarding_cars*Abandonment_rate

□ Australian_Fleet(t) = Australian_Fleet(t - dt) + (Adding_cars - Discarding_cars) * dt
 INIT Australian_Fleet = 13400000
 INFLows:
   □ Adding_cars = Purchasing_new_cars
 OUTFLOWS:
   □ Discarding_cars = Australian_Fleet/Average_ELV_age

□ Exported_ELVs(t) = Exported_ELVs(t - dt) + (Exporting_or_taking_back) * dt
 INIT Exported_ELVs = 0
 INFLows:
   □ Exporting_or_taking_back = Discarding_cars*Exporting_rate

□ Recovered_Energy(t) = Recovered_Energy(t - dt) + (Electricity_production_in_MJ) * dt
 INIT Recovered_Energy = 0
 INFLows:
   □ Electricity_production_in_MJ = 
     Recycling_ELV*Net_energy_recovery_per_kg_of_ASR*Remaining_percentage_of_nonmetallic_materials/Average_ELV_weight

UNATTACHED:
□ Recycling_ELV = Discarding_cars*ELV_treating_rate
□ Base_year_production = INIT(Electricity_production_in_MJ)
□ ELV_treating_rate = 1-(Abandonment_rate+Exporting_rate)
□ Exporting_rate = 0.04+STEP(0,14,2025)
□ Net_energy_recovery_per_kg_of_ASR = 4.32
□ Profits = Recovered_Energy
□ Relative_Electricity_Production_in_% = 
  (Electricity_production_in_MJ/Base_year_production)*100/Base_year_production
□ Remaining_percentage_of_nonmetallic_materials = 
  Weight_percentage_of_nonmetallic_materials_in_ELV-Weight_percentage_of_nonmetallic_removed_by_dismantlers
□ Weight_percentage_of_nonmetallic_removed_by_dismantlers = 0.04
□ Abandonment_rate = GRAPH(TIME)
Programming of the sensitivity analysis

\[
\text{Aband\_Cars}(t) = \text{Aband\_Cars}(t-\text{dt}) + (\text{Abandoning}) \times \text{dt}
\]
INIT Aband\_Cars = 0
INFLOWS:
\[
\text{Abandoning} = \text{Discarding\_cars}\times\text{Abandonment\_rate}
\]
\[
\text{Aband\_Cars\_2}(t) = \text{Aband\_Cars\_2}(t-\text{dt}) + (\text{Abandoning\_2}) \times \text{dt}
\]
INIT Aband\_Cars\_2 = 0
INFLOWS:
\[
\text{Abandoning\_2} = \text{Discarding\_cars\_2}\times\text{Abandonment\_rate\_2}
\]
\[
\text{Australian\_Fleet}(t) = \text{Australian\_Fleet}(t-\text{dt}) + (\text{Adding\_cars} - \text{Discarding\_cars}) \times \text{dt}
\]
INIT Australian\_Fleet = 1340000
INFLOWS:
\[
\text{Adding\_cars} = \text{Purchasing\_new\_cars}
\]
OUTFLOW:
\[
\text{Discarding\_cars} = \text{Australian\_Fleet}/\text{Average\_ELV\_age}
\]
\[
\text{Australian\_Fleet\_2}(t) = \text{Australian\_Fleet\_2}(t-\text{dt}) + (\text{Adding\_cars\_2} - \text{Discarding\_cars\_2}) \times \text{dt}
\]
INIT Australian\_Fleet\_2 = 1340000
INFLOWS:
\[
\text{Adding\_cars\_2} = \text{Purchasing\_new\_cars\_2}
\]
OUTFLOW:
\[
\text{Discarding\_cars\_2} = \text{Australian\_Fleet\_2}/\text{Average\_ELV\_age\_2}
\]
\[
\text{Exported\_ELVs}(t) = \text{Exported\_ELVs}(t-\text{dt}) + (\text{Exporting\_or\_take\_backing}) \times \text{dt}
\]
INIT Exported\_ELVs = 0
INFLOWS:
\[
\text{Exporting\_or\_take\_backing} = \text{Discarding\_cars}\times\text{Exporting\_rate}
\]
\[
\text{Exported\_ELVs\_2}(t) = \text{Exported\_ELVs\_2}(t-\text{dt}) + (\text{Exporting\_or\_take\_backing\_2}) \times \text{dt}
\]
INIT Exported\_ELVs\_2 = 0
INFLOWS:
\[
\text{Exporting\_or\_take\_backing\_2} = \text{Discarding\_cars\_2}\times\text{Exporting\_rate\_2}
\]
\[
\text{Recovered\_Energy}(t) = \text{Recovered\_Energy}(t-\text{dt}) + 
\text{(Electricity\_production\_in\_MJ\_when\_abandonate\_rate\_is\_decreasing}) \times \text{dt}
\]
INIT Recovered\_Energy = 0
INFLOWS:
\[
\text{Electricity\_production\_in\_MJ\_when\_abandonate\_rate\_is\_decreasing} = 
\text{Recycling\_ELV\_Net\_energy\_recovery\_per\_kg\_of\_ASR\times\text{Remaining\_percentage\_of\_nonmetallic\_materials\times\text{Average\_ELV\_weight}}
\]
\[
\text{Recovered\_Energy\_2}(t) = \text{Recovered\_Energy\_2}(t-\text{dt}) + 
\text{(Electricity\_production\_in\_MJ\_when\_abandonate\_rate\_is\_unchanging}) \times \text{dt}
\]
INIT Recovered\_Energy\_2 = 0
INFLOWS:
\[
\text{Electricity\_production\_in\_MJ\_when\_abandonate\_rate\_is\_unchanging} = 
\text{Recycling\_ELV\_2\_Net\_energy\_recovery\_per\_kg\_of\_ASR\_2\times\text{Remaining\_percentage\_of\_nonmetallic\_materials\_2\times\text{Average\_ELV\_weight\_2}}
\]
UNATTACHED:

- Recycling_ELV = Discarding_cars*ELV_treating_rate

UNATTACHED:

- Recycling_ELV_2 = Discarding_cars_2*ELV_treating_rate_2

- Base_year_production = INIT(Electricity_production__in_MJ_when_abandonate_rate_is_decreasing)

- Base_year_production_2 = INIT(Electricity_production__in_MJ_when_abandonate_rate_is_unchanging)

- ELV_treating_rate = 1-(Abandonment_rate+Exporting_rate)

- ELV_treating_rate_2 = 1-(Abandonment_rate_2+Exporting_rate_2)

- Exporting_rate = 0.04

- Exporting_rate_2 = 0.04

- Net_energy_recovery_per_kg_of_ASR = 4.32

- Net_energy_recovery_per_kg_of_ASR_2 = 4.32

- Profits = Recovered_Energy

- Profits_2 = Recovered_Energy_2

- Relative_Electricity_Production_in_% =

  (Electricity_production__in_MJ_when_abandonate_rate_is_decreasing-Base_year_production)*

  100/Base_year_production

- Relative_Electricity_Production_in_%_2 =

  (Electricity_production__in_MJ_when_abandonate_rate_is_unchanging-Base_year_production_2)*

  100/Base_year_production_2

- Remaining_percentage_of_nonmetallic_materials =

  Weight_percentage_of_nonmetallic_materials_in_ELV-Weight_percentage_of_nonmetallic_removed_by_dismantlers

- Remaining_percentage_of_nonmetallic_materials_2 =

  Weight_percentage_of_nonmetallic_materials_in_ELV_2-Weight_percentage_of_nonmetallic_removed_by_dismantlers_2

- Weight_percentage_of_nonmetallic_removed_by_dismantlers = 0.04

- Weight_percentage_of_nonmetallic_removed_by_dismantlers_2 = 0.04

- Abandonment_rate = GRAPH(TIME)
Programming of Scenario 1

\[\text{Aband}_\text{Cars}(t) = \text{Aband}_\text{Cars}(t - dt) + (\text{Abandoning}) \times dt\]

\[\text{INIT Aband}_\text{Cars} = 0\]

\[\text{INFLOWS:}\]
\[\text{Abandoning} = \text{Discarding} \times \text{Abandonment}_\text{rate}\]

\[\text{INFLOWS:}\]
\[\text{Australian} \times \text{Fleet}(t) = \text{Australian} \times \text{Fleet}(t - dt) + (\text{Adding} \times \text{Discarding} \times \text{cars}) \times dt\]

\[\text{INIT Australian} \times \text{Fleet} = 134000000\]

\[\text{INFLOWS:}\]
\[\text{Adding} \times \text{cars} = \text{Purchasing} \times \text{new} \times \text{cars}\]

\[\text{OUTFLOWS:}\]
\[\text{Discarding} \times \text{cars} = \text{Australian} \times \text{Fleet} \times \text{Average} \times \text{ELV} \times \text{age}\]

\[\text{INFLOWS:}\]
\[\text{Exported} \times \text{ELVs}(t) = \text{Exported} \times \text{ELVs}(t - dt) + (\text{Exporting or} \times \text{take} \times \text{backing}) \times dt\]

\[\text{INIT Exported} \times \text{ELVs} = 0\]

\[\text{INFLOWS:}\]
\[\text{Exporting or} \times \text{take} \times \text{backing} = \text{Discarding} \times \text{cars} \times \text{Exporting} \times \text{rate}\]

\[\text{INFLOWS:}\]
\[\text{Recovered} \times \text{Energy}(t) = \text{Recovered} \times \text{Energy}(t - dt) + (\text{Electricity} \times \text{production} \times \text{in MJ}) \times dt\]

\[\text{INIT Recovered} \times \text{Energy} = 0\]

\[\text{INFLOWS:}\]
\[\text{Electricity} \times \text{production} \times \text{in} \times \text{MJ} = \text{Recycling} \times \text{ELV} \times \text{Net energy} \times \text{recovery per kg of ASR} \times \text{Remaining} \times \text{percentage of nonmetallic materials} \times \text{Average} \times \text{ELV} \times \text{weight}\]

\[\text{UNATTACHED:}\]
\[\text{Recycling} \times \text{ELV} = \text{Discarding} \times \text{cars} \times \text{ELV} \times \text{treating rate}\]

\[\text{Base} \times \text{year} \times \text{production} = \text{INIT} \times \text{Electricity} \times \text{production} \times \text{in MJ}\]

\[\text{ELV} \times \text{treating rate} = 1 - (\text{Abandonment} \times \text{rate} + \text{Exporting} \times \text{rate})\]

\[\text{Exporting} \times \text{rate} = 0.04 + \text{STEP}(0.14, 2025)\]

\[\text{Net energy} \times \text{recovery per kg of ASR} = 4.32\]

\[\text{Profits} = \text{Recovered} \times \text{Energy}\]

\[\text{Relative} \times \text{Electricity} \times \text{Production in} \times \text{%} = \frac{\text{Electricity} \times \text{production} \times \text{in} \times \text{MJ} - \text{Base} \times \text{year} \times \text{production}}{\text{Base} \times \text{year} \times \text{production}} \times 100\]

\[\text{Remaining} \times \text{percentage of nonmetallic materials} = \text{Weight} \times \text{percentage} \times \text{of nonmetallic} \times \text{materials} \times \text{ELV} \times \text{Weight} \times \text{percentage} \times \text{of nonmetallic removed by dismaniters}\]

\[\text{Weight} \times \text{percentage} \times \text{of nonmetallic removed by dismaniters} = 0.04\]

\[\text{Abandonment} \times \text{rate} = \text{GRAPH}(\text{TIME})\]

\[\begin{align*}
(2015, 0.08), & (2018, 0.08), (2020, 0.08), (2023, 0.08), (2025, 0.06), (2028, 0.0745), (2030, 0.0655), (2033, 0.0555), (2035, 0.049), (2038, 0.0435), (2040, 0.04) \\
\end{align*}\]

\[\text{Average} \times \text{ELV} \times \text{age} = \text{GRAPH}(\text{TIME})\]

\[\begin{align*}
(2015, 15.4), & (2018, 15.5), (2020, 15.6), (2023, 15.8), (2025, 16.0), (2028, 16.3), (2030, 16.6), (2033, 16.9), (2035, 17.3), (2038, 17.6), (2040, 18.1) \\
\end{align*}\]

\[\text{Average} \times \text{ELV} \times \text{weight} = \text{GRAPH}(\text{TIME})\]

\[\begin{align*}
(2015, 1250), & (2018, 1228), (2020, 1215), (2023, 1201), (2025, 1188), (2028, 1177), (2030, 1165), (2033, 1156), (2035, 1149), (2038, 1140), (2040, 1134) \\
\end{align*}\]

\[\text{Purchasing} \times \text{new} \times \text{cars} = \text{GRAPH}(\text{TIME})\]

\[\begin{align*}
(2015, 1e+06), & (2018, 1.1e+06), (2020, 1.1e+06), (2023, 1.2e+06), (2025, 1.2e+06), (2028, 1.2e+06), (2030, 1.3e+06), (2033, 1.4e+06), (2035, 1.5e+06), (2038, 1.6e+06), (2040, 1.9e+06) \\
\end{align*}\]

\[\text{Weight} \times \text{percentage} \times \text{of nonmetallic} \times \text{materials} \times \text{ELV} = \text{GRAPH}(\text{TIME})\]

\[\begin{align*}
(2015, 0.25), & (2018, 0.253), (2020, 0.257), (2023, 0.26), (2025, 0.266), (2028, 0.273), (2030, 0.282), (2033, 0.295), (2035, 0.307), (2038, 0.326), (2040, 0.35) \\
\end{align*}\]
Programming of Scenario 2

\[ \text{AbandCars}(t) = \text{AbandCars}(t - dt) + (\text{Abandoning}) \times dt \]
\[ \text{INIT AbandCars} = 0 \]
\[ \text{INFLOWS:} \]
\[ \text{\textcircled{3} Abandoning} = \text{Discarding Cars} \times \text{Abandonment rate} \]
\[ \text{INFLOWS:} \]
\[ \text{\textcircled{3} Adding Cars} = \text{Purchasing new cars} \]
\[ \text{OUTFLOWS:} \]
\[ \text{\textcircled{3} Discarding Cars} = \text{Australian Fleet Average ELV age} \]
\[ \text{INFLOWS:} \]
\[ \text{\textcircled{3} Exporting or take backing} = \text{Discarding Cars} \times \text{Exporting rate} \]
\[ \text{INFLOWS:} \]
\[ \text{\textcircled{3} Recovered Energy}(t) = \text{Recovered Energy}(t - dt) + (\text{Electricity production in MJ}) \times dt \]
\[ \text{INIT Recovered Energy = 0} \]
\[ \text{INFLOWS:} \]
\[ \text{\textcircled{3} Electricity production in MJ =} \]
\[ \text{Reycling ELV} \times \text{Net energy recovery per kg of ASR} \times \text{Remaining percentage of nonmetallic materials} \times \text{Average ELV weight} \]

UNATTACHED:
\[ \text{\textcircled{3} Recycling ELV} = \text{Discarding Cars} \times \text{ELV treating rate} \]
\[ \text{\textcircled{3} Base year production = INIT(Electricity production in MJ)} \]
\[ \text{\textcircled{3} ELV treating rate = 1 - (Abandonment rate + Exporting rate)} \]
\[ \text{\textcircled{3} Exporting rate = 0.04} \]
\[ \text{\textcircled{3} Net energy recovery per kg of ASR = 4.32} \]
\[ \text{\textcircled{3} Profits = Recovered Energy} \]
\[ \text{\textcircled{3} Relative Electricity Production in % =} \]
\[ \text{Electricity production in MJ - Base year production) \times 100 / Base year production} \]
\[ \text{\textcircled{3} Remaining percentage of nonmetallic materials =} \]
\[ \text{Weight percentage of nonmetallic materials in ELV} \times \text{Weight percentage of nonmetallic removed by dismantlers} \]
\[ \text{\textcircled{3} Weight percentage of nonmetallic removed by dismantlers = 0.04 + STEP(0.08, 2025)} \]
\[ \text{\textcircled{3} Abandonment rate = GRAPH(TIME)} \]
\[ \text{\textcircled{3} Average ELV age = GRAPH(TIME)} \]
\[ \text{\textcircled{3} Average ELV weight = GRAPH(TIME)} \]
\[ \text{\textcircled{3} Purchasing new cars = GRAPH(TIME)} \]
\[ \text{\textcircled{3} Weight percentage of nonmetallic materials in ELV = GRAPH(TIME)} \]
Programming of Scenario 3

\[ \text{Abandoned Cars}(t) = \text{Abandoned Cars}(t - dt) + (\text{Abandoning}) \times dt \]
\[ \text{INIT}\ Abandoned\ Cars = 0 \]
\[ \text{INFLOWS:} \]
\[ - \text{Abandoning} = \text{Discarding cars} \times \text{Abandonment rate} \]

\[ \text{Australian Fleet}(t) = \text{Australian Fleet}(t - dt) + (\text{Adding cars} - \text{Discarding cars}) \times dt \]
\[ \text{INIT}\ Australian\ Fleet = 13400000 \]
\[ \text{INFLOWS:} \]
\[ - \text{Adding cars} = \text{Purchasing new cars} \]
\[ \text{OUTFLOWS:} \]
\[ - \text{Discarding cars} = \text{Australian Fleet} \times \text{Average ELV age} \]

\[ \text{Exported ELVs}(t) = \text{Exported ELVs}(t - dt) + (\text{Exporting or take back}) \times dt \]
\[ \text{INIT}\ Exported\ ELVs = 0 \]
\[ \text{INFLOWS:} \]
\[ - \text{Exporting or take back} = \text{Discarding cars} \times \text{Exporting rate} \]

\[ \text{Recovered Energy}(t) = \text{Recovered Energy}(t - dt) + (\text{Electricity production in MJ}) \times dt \]
\[ \text{INIT}\ Recovered\ Energy = 0 \]
\[ \text{INFLOWS:} \]
\[ - \text{Electricity production in MJ} = \]
\[ \text{Recycling ELV} \times \text{Net energy recovery per kg of ASR} \times \text{Remaining percentage of nonmetallic materials} \times \text{Average ELV weight} \]

\[ \text{UNATTACHED:} \]
\[ - \text{Recycling ELV} = \text{Discarding cars} \times \text{ELV treating rate} \]
\[ - \text{Base year production} = \text{INIT}\ (\text{Electricity production in MJ}) \]
\[ - \text{ELV treating rate} = 1 - (\text{Abandonment rate} + \text{Exporting rate}) \]
\[ - \text{Exporting rate} = 0.04 + \text{STEP}(0.14, 2025) \]
\[ - \text{Net energy recovery per kg of ASR} = 4.32 \]
\[ - \text{Profits} = \text{Recovered Energy} \]
\[ - \text{Relative Electricity Production in %} = \]
\[ (\text{Electricity production in MJ} - \text{Base year production}) \times 100 / \text{Base year production} \]
\[ - \text{Remaining percentage of nonmetallic materials} = \]
\[ \text{Weight percentage of nonmetallic materials in ELV} \times \text{Percentage of nonmetallic removed by dismantlers} \]
\[ - \text{Weight percentage of nonmetallic removed by dismantlers} = 0.04 \]
\[ - \text{Abandonment rate} = \text{GRAPH}(\text{TIME}) \]
\[ \begin{array}{cccccccccccc}
2015, 0.08, & 2018, 0.08, & 2020, 0.08, & 2023, 0.08, & 2025, 0.08, & 2028, 0.0745, & 2030, 0.0655, & 2033, 0.0555, & 2035, 0.0499, & 2038, 0.0435, & 2040, 0.04 \\
\end{array} \]
\[ - \text{Average ELV age} = \text{GRAPH}(\text{TIME}) \]
\[ \begin{array}{cccccccccccc}
2015, 15.4, & 2018, 15.5, & 2020, 15.5, & 2023, 15.8, & 2025, 16.0, & 2028, 16.3, & 2030, 16.6, & 2033, 16.9, & 2035, 17.3, & 2038, 17.6, & 2040, 18.1 \\
\end{array} \]
\[ - \text{Average ELV weight} = \text{GRAPH}(\text{TIME}) \]
\[ \begin{array}{cccccccccccc}
\end{array} \]
\[ - \text{Purchasing new cars} = \text{GRAPH}(\text{TIME}) \]
\[ \begin{array}{cccccccccccc}
2015, 1e+005, & 2018, 1.1e+006, & 2020, 1.1e+006, & 2023, 1.2e+005, & 2025, 1.2e+006, & 2028, 1.2e+006, & 2030, 1.3e+006, & 2033, 1.4e+005, & 2035, 1.5e+006, & 2038, 1.6e+006, & 2040, 1.9e+006 \\
\end{array} \]
\[ - \text{Weight percentage of nonmetallic materials in ELV} = \text{GRAPH}(\text{TIME}) \]
\[ \begin{array}{cccccccccccc}
2015, 0.25, & 2016, 0.253, & 2017, 0.257, & 2018, 0.25, & 2019, 0.261, & 2020, 0.262, & 2021, 0.283, & 2022, 0.254, & 2023, 0.265, & 2024, 0.266, & 2025, 0.208, & 2026, 0.208, & 2028, 0.208, & 2029, 0.208, & 2030, 0.208, & 2031, 0.208, & 2032, 0.208, & 2033, 0.208, & 2034, 0.208, & 2035, 0.208, & 2036, 0.208, & 2037, 0.208, & 2038, 0.208, & 2039, 0.208, & 2040, 0.208 \\
\end{array} \]
APPENDIX C

The mathematics of AHP

(1) Normalization: “Behind the scene”

For a matrix of pair-wise elements:

\[
\begin{bmatrix}
C_{11} & C_{12} & C_{13} \\
C_{21} & C_{22} & C_{23} \\
C_{31} & C_{32} & C_{33}
\end{bmatrix}
\]

1) sum the values in each column of the pair-wise matrix

\[C_{\psi} = \sum_{i=1}^{n} C_{\psi}
\]

2) divide each element in the matrix by its column total to generate a normalized pair-wise matrix

\[
\begin{bmatrix}
\frac{X_{11}}{\sum_{i=1}^{n} C_{i,j}} & \frac{X_{12}}{\sum_{i=1}^{n} C_{i,j}} & \frac{X_{13}}{\sum_{i=1}^{n} C_{i,j}} \\
\frac{X_{21}}{\sum_{i=1}^{n} C_{i,j}} & \frac{X_{22}}{\sum_{i=1}^{n} C_{i,j}} & \frac{X_{23}}{\sum_{i=1}^{n} C_{i,j}} \\
\frac{X_{31}}{\sum_{i=1}^{n} C_{i,j}} & \frac{X_{32}}{\sum_{i=1}^{n} C_{i,j}} & \frac{X_{33}}{\sum_{i=1}^{n} C_{i,j}}
\end{bmatrix}
\]

3) divide the sum of the normalized column of matrix by the number of criteria used (n) to generate weighted matrix

\[
W_{ij} = \frac{\sum_{j=1}^{n} X_{ij}}{n}
\]

Source: (Bunruamkaew, 2012)
APPENDIX D

An overview of the computer software used in the research

**Expert Choice software**

Expert Choice is a multi-objective decision support software that reduces complex decisions to a series of pair wise comparisons and then synthesising the results. It syntheseses or combines the priorities that are derived for each facet of the problem to obtain the overall priorities of the alternatives. By performing "what-if" and sensitivity analyses, a change in the importance of an objective that would affect the alternatives of choice can be determined. Because the objectives are presented in a hierarchical structure in the software, decision-makers are able to “drill down” to their level of expertise, and apply judgments to the objectives deemed important to achieving their goals.

Expert Choice is based on the Analytic Hierarchy Process (AHP), a mathematical theory that was first introduced at the Wharton School of the University of Pennsylvania by one of Expert Choice's founders, Thomas Saaty (1977). The AHP and the Expert Choice software engage decision-makers in structuring a decision into smaller parts, proceeding from the goal to objectives to sub-objectives down to the alternative courses of action. Decision-makers then make simple pair wise comparison judgments throughout the hierarchy to arrive at overall priorities for the alternatives. The decision problem may involve social, political, technical, and economic factors.

Expert Choice is an intuitive, graphically based software that is structured in a user-friendly fashion. These make it valuable for conceptual and analytical thinkers, novices and experts. At the end of the process, decision-makers are fully confident with how and why the decision was made, with results that are meaningful, easy to communicate, and actionable.

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**STELLA software**

STELLA, stands for Structural Thinking Experimental Learning Laboratory with Animation, is a software package that allows the user to simulate systems without the use of any advanced programming language. The software allows its user to create a diagram of the interrelationships between the components of a model. It provides a visual representation of the differential equation (or coupled differential equations) that describes the problem of interest, and then solves it numerically.

STELLA is designed to increase the effectiveness of the set of processes by which we render, simulate, analyse and communicate our mental models. Mental models are those things we all necessarily carry around in our heads that help us to: (1) make meaning out of what we experience, (2) share and evolve that meaning by communicating with others, and (3) evaluate and decide upon appropriate courses of action. Learning to construct mental models that better reflect the reality they seek to mimic, and learning to simulate them more reliably, are vital to making your world, and our world, work more effectively. The aim of the STELLA software is to accelerate and enrich these learning processes\(^9\).

STELLA uses differential equations represented as stocks and flows. Stocks represent a balance unit that changes with each time step; flows represent a positive or negative change of flux. Simple graphing and table features of the software allow the user an easy visual or quantitative method for checking output values. Three numerical integration methods are available in STELLA: Euler, Runge-Kutta 2 and Runge-Kutta 4. Equations are easily accessed by clicking on the icons or by manually altering mathematical relationships in the equations editor. Tables and equations can be quickly exported as text files to be used in other software programs\(^{10}\).

\(^9\) [http://biology.kenyon.edu/courses/ENVS%20112/ENVS%20Images/STELLA%206.0.pdf](http://biology.kenyon.edu/courses/ENVS%20112/ENVS%20Images/STELLA%206.0.pdf)

\(^{10}\) D.M. Rizzo et al. / Environmental Modelling & Software 21 (2006) 1491–1502