Establishing a circular economy approach for the leather industry

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SYNOPSIS

This thesis reports on research undertaken to investigate the implementation of a Circular approach within the leather industry, through the definition of a framework and development of an economic decision-making support tool. The core objective of the research is to identify the underpinning opportunities and challenges involved in creating recycling solutions for leather waste. The research contributions can be considered in four key areas. The first part of the thesis consists of a review of the use of leather across industry sectors and the existing waste management and recycling systems for leather waste. On consideration of this review it clearly shows a lack of systematic thinking around the creation and optimisation of recovery systems for leather waste. This review concludes that there is significant room for improvement of the current waste management and recycling solutions for leather waste. A variety of value-added products can be recovered from these wastes but only if the leather can be successfully separated from the other materials (such as rubbers and polymers) within end-of-life products and manufacturing wastes.

The second part of the research defines a framework for implementing a Circular approach within the leather industry. This framework supports mapping and characterisation of the leather waste stream and the design of recycling and processing strategies for leather waste. The third part of the research is concerned with the development of a decision-support tool for the economic viability of leather recycling systems. The support tool considers all cost factors and combines them to give a single factor upon which the economic effectiveness of different leather recycling scenarios can be evaluated. Finally, the validity of the framework for leather waste recycling is assessed through the completion of two case studies. These case studies demonstrate the flexibility of the framework in supporting both horizontal (across lifecycle) leather recycling and vertical (across industry sector) leather recycling. In summary, the research clearly highlights the need for systematic thinking and flexible strategies when creating leather recycling systems. Failure to incorporate flexibility into future recycling systems puts the recycling industries at risk of being unable to effectively manage future waste streams. Conversely, early consideration and incorporation of flexible processing strategies into recycling systems could enable the recovery of high-quality recycled materials that support a circular approach to manufacturing and resource use.
ABBREVIATIONS

BOD : Biological Oxygen Demand
CBA : Cost-Benefit Analysis
CEA : Cost-Effectiveness Analysis
CBR : Cost-Benefit Ratio
CAL : Circular Approach in the Leather Industry
COD : Chemical Oxygen Demand
EOL : End-of-Life
EU : European Union
HDPE : High-Density Polyethylene
HORP : Horizontal Recycling and Processing Strategy
MFA : Materials Flow Analysis
MRF : Materials Recovery Facility
PET : Polyethylene Terephthalate
PVC : Polyvinyl Chloride
RFID : Radio Frequency Identification
SMART : Sustainable Manufacturing and Recycling Technologies
UK : United Kingdom
UNIDO : United Nations Industrial Development Organisation
VERP : Vertical Recycling and Processing Strategy
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CHAPTER 1       INTRODUCTION

Leather is a traditional material with a long history of use and it continues to be of great importance in today’s modern society due to its unique properties; in 2013, 6.4 million tonnes of leather was produced globally. It is used extensively in footwear, furniture, automotive applications, and apparel and luxury goods. As it is a by-product from the meat industry, the global supply of leather tracks the global consumption of meat. In recent decades, there has been an increase in the amount of meat consumed and hence an increase in the amount of leather produced globally. The lifecycle of leather is complex, the four key stages involve: tanning animal skins to produce leather, using leather to manufacture products, distributing and retailing leather products and disposing of the leather products at the end-of-life (see Figure 1.1). The production of leather has many associated environmental impacts that have been widely reported including: large volumes of hazardous effluent, large volumes of waste leather materials that contain chromium which can be hazardous to health and the environment if disposed of incorrectly.

Figure 1.1: Lifecycle stages of leather
Waste is generated at every stage of the leather lifecycle and the impact of this waste requires careful consideration. Leather is a unique waste material for which a large-scale commercial recycling system does not currently exist. The waste generated at different points across the lifecycle can be pure leather or it can be made up of multiple materials, including: leather, rubber, plastics, foam and metals. Current disposal and recycling options for leather materials are not effective in optimising the recovery of leather from mixed waste streams; hence, leather waste is often down-cycled into less valuable secondary materials such as insulation or oil spillages kits.

There has been a large increase in the variety of leather products being introduced to the market, this is largely due to the changing consumer market for products across all industrial sectors to keep up with consumer demand. Manufacturing has traditionally been understood as the process by which raw materials are transformed linearly and in large scale into value-added products for consumers. However, the future of the manufacturing industry looks very different, it will require manufacturing firms to be highly agile enterprises, capable of exploiting rapid market changes by increasing flexibility in their physical infrastructures and production processes based on closed-loop utilisation of resources. Figure 1.2 illustrates the shift towards the circular manufacturing model. Challenges driving these future changes within the manufacturing industry include: an increase in the demand for product variability, rapidly changing market conditions, an increase in the complexity of the material mix and design of products and depleting sources of virgin materials. (Fernandes et al., 2012).

Figure 1.2: Traditional linear manufacturing versus the new circular manufacturing concept
However, the shift towards flexible processing lines has not been echoed by the recycling processing industries, most recycling systems are still created as dedicated lines for specific products, as and when demand for material soars or legislation dictates. This has created a substantial gap between the volume of products that are manufactured globally and the volume of high-quality material that is recovered from recycling processes. This has created an ever-greater need to harmonise the desires of global industrial development with the needs of environmental safety, to prevent future damage that traditional cradle to grave models have caused. Consequently, there is a growing global recognition and governments and inter-governmental organisations are legislating to promote circular resource use, such as the producer responsibility legislation for waste electronic and electrical equipment and for packaging materials. This along with increasing resource scarcity, increasing political pressure to safeguard resources, producer responsibility pressures and the need to recover value from end-of-life products is driving research into alternative end-of-life resource management models and techniques.

The typical life span of products that contain leather has decreased as fashion cycles get shorter and consumers desire an ever-increasing turnover in product style and functionality (ElMaraghy et al., 2013). This is illustrated by products such as leather mobile phone cases, as the consumer purchases a new mobile phone they will typically also have to purchase a new leather case for it, as the new phone is a different shape and size than the old one. As the mobile phone lifecycle decreases, so does the lifecycle of the leather case. The decrease in product lifecycle and an increased frequency in product turnover creates an ever-increasing amount of leather waste that requires management. In addition, increased pressure from consumers about recycling products, along with upcoming targets within the European Union (EU) Landfill Directive for 2020 which state that England will need to reduce the amount of biodegradable municipal waste it sends to landfill each year, to no more than 10.2 million tonnes, is forcing companies to think differently about leather disposal. This will make the disposal of post-consumer leather waste more difficult in the future. The introduction of flexible and adaptable systems into the recycling industries could potentially enhance material recovery from end-of-life leather products enabling the material to be used again in high-quality, high-value applications, promoting a circular use of resources.

Effective end-of-life management of a product can positively affect the lifecycle costs, where products contain valuable materials, the implementation of effective recycling
processes may result in the recovery of a proportion of the original material value. In some cases, additional costs may be introduced to a waste management system through poor organisation of end-of-life logistics, or through the selection of inappropriate end-of-life processing routes.

Within this research, a need has been identified to better understand how the current disposal practices for end-of-life leather goods are limiting value recovery and limiting the circular use of the material. It is important to understand how recycling processes can progress technologically to contend with the increasing complexity and variety of products, and how the introduction of flexibility into recycling systems could create a step-change in the quality of recycled materials. Finally, it is important to fully understand how the flexibility of a recycling system impacts the economic considerations for manufacturers and waste processors. Therefore, the fundamental research assertion presented within this thesis states that greater flexibility is required within leather recycling systems to improve the quality of recycled materials.

Previous work on footwear recycling undertaken by researchers at The Centre for Sustainable Manufacturing and Recycling Technologies (SMART) at Loughborough University identified leather to be one of the most voluminous and valuable materials that could be recovered for potential reuse from waste footwear. This research helped to provide a steer for the author to focus on the recovery of leather from end-of-life products.

The overall aim of this research is to investigate contemporary challenges in recycling of leather products and to develop a decision-support framework to aid with the selection of an economically viable solution for reclamation of leather materials across the lifecycle of leather products. This will be achieved through:

1. The mapping and classification of the leather waste in terms of the technical and operational characteristics
2. The development of a decision-making support tool to evaluate the economics of leather recycling based on reconfigurable recycling methodologies

Figure 1.3 illustrates the thesis structure which is split into three sections namely: research overview and background; theoretical research, technology and decision-support tool development and case studies; and the research conclusions.

There are six chapters within the research overview and background and following this introduction, Chapter 2 presents the research context and scope. This is supported by a
literature review, which is focussed on leather use and recycling options in Chapter 3, and general recycling technologies in Chapter 4. A short review of the most recent research papers that are most relevant to the research is presented in Chapter 5. In Chapter 6, a brief review of research methodologies is provided, and the methodological approach used within the thesis is outlined.

The second part of the thesis presents the theoretical research, tool and technology development and case studies that validate the research tools and concepts. In Chapter 7, a framework that supports the economic evaluation of flexible recovery and recycling strategies for leather waste is presented. The framework consists of three key stages. The first stage requires mapping and characterisation of leather waste streams in terms of qualitative and quantitative characteristics; this is covered in Chapter 8. Chapter 9 presents collection and reprocessing strategies for leather waste and their associated cost implications. Chapter 10 presents the cost model which will support economic decisions about leather recovery and recycling and in Chapter 11 the application of the framework is demonstrated through case-studies.

The third and final section of the thesis presents the conclusions from the research. In Chapter 12 a discussion of the research findings is presented, and the outcomes of the research are assessed against the aims and objectives. Final conclusions are presented in Chapter 13 and opportunities for extending the research through further work are identified.

Appendix A contains one conference paper which has been published based on the research presented within the thesis.
Figure 1.3: Thesis structure
CHAPTER 2 RESEARCH CONTEXT AND SCOPE

2.1 Introduction

This chapter outlines the context of the research presented in the thesis and begins by outlining the research context and stating the research questions, after which a general research aim is derived. To support the research aim, several objectives are developed and for each objective the scope of the research is documented.

2.2 Research context and questions

Leather has become a popular material from which to make consumer products. This is in part due to the unique functional properties it has and in part due to the consumer impression of quality and luxury that leather provides (e.g. leather car seats). Due to the increase in global population and the increased demand for meat products, the production of leather has also increased. This increase has been concentrated in developing rather than developed countries (FAO, 2013).

Leather is made by putting animal skins through a process called ‘tanning’, this prevents the skins from rotting and turns them into a functional material. In the past, tanning and finishing processes were homogeneous and leather processing was much simpler than it is today. Current tanning and finishing methods vary widely and comprise a complex set of processes. This results in a huge variety in leather types and colours within leather products and leather waste streams. Combine this with the increasing variety of other materials within leather products and this makes the separation of leather from other materials very challenging during recycling and recovery processes. The floccinaucinihilipilification of leather waste on a global scale directly contributes to an ignominious fate for the waste material. Due to chemical contamination, disposal of leather waste from tanneries causes complex environmental problems in countries where waste disposal is not properly regulated. It also causes health problems for the people that work within tanneries, the people that live in the immediate vicinity and the people that live in areas downstream from the tanneries. For example, Kanpur is the leather export capital of India. A high percentage of the tanneries in this area are on the banks of the Gunga River, this is a holy river revered by 800 million Hindus, and it is a lifeline for northern India and is heavily polluted by the leather industry and the numerous unregulated tanneries that are situated along its banks. The leather waste in this region cannot be described as incognito and therefore the lack of preventative action against this problem is surprising. Little to no
regulation and the improper disposal of leather wastes causes toxic chemicals such as chrome to build up in the river, leading to many health problems including cancer, pigment bleaching, developmental problems in children and jaundice. Consequently, correct disposal of the waste from the leather industry is vital and strategies for creating a Circular approach within the leather industry are required.

A circular economy is an alternative to a traditional linear economy (make, use, dispose) in which resources are kept in use for as long as possible, products and materials are then recovered and regenerated at the end of each service life. The circular economy concept is broad and covers the whole lifecycle of materials and products in all industries, the work in this thesis focuses on a subset of the circular economy model called circular manufacturing.

The circular manufacturing concept is aims to create systems in which technical materials are designed to circulate at high quality in production cycles without being disposed of as waste. This is in alignment with the circular economy concept with a specific focus on manufacturing waste. The contrast between traditional manufacturing and a circular approach to manufacturing are illustrated in Figure 2.1.

A particularly challenging aspect of recycling leather wastes is the disproportionate value attribution given to leather products. A large percentage of leather goods are sold as high value consumer products; however, the material value of the leather contained within these products bears no relation to the physical volume of leather within the product, this creates challenges when creating an economically viable recycling system for leather wastes. Therefore, there are two primary questions that are posed by this research and these are:

1. How can flexible waste recovery strategies assist the implementation of a circular approach within the leather industry?

2. How can a circular approach improve the economic viability of leather recycling systems?
2.3 Research aims and objectives

With reference to the research context and questions in Section 2.2, the aim of this research is to establish a circular approach for the leather industry.

The following objectives have been identified to help achieve the aim of this research:

1. Review of the status of the leather industry and current disposal options for leather products along with waste management and recycling technologies from published literature
2. To develop a framework that supports the implementation of a circular approach within the leather industry
3. To develop a waste-flow map for leather and define the waste streams in terms of the quantitative and qualitative characteristics
4. To develop recycling and processing strategies for the recovery of leather waste
5. To develop a cost model to support economic decisions regarding the implementation of a circular approach in the leather industry
6. To demonstrate the validity of the research concepts, framework and tools through case studies

2.4 Research Scope

The objectives of the project form the scope of the research as follows:
2.4.1 Review of the status of the leather industry and current disposal options for leather products along with waste management and recycling technologies from published literature

A review of the use of leather within manufacturing and within consumer products is conducted, along with an investigation into current disposal routes for waste leather and waste leather products. Relevant literature is explored to enable best available systems and gaps in disposal practices to be identified.

To ensure that the research considers all relevant aspects of waste management and recycling, a comprehensive review of the literature will be conducted. This section of the review identifies the current advanced and automated technologies used within the recycling industries for processing of waste materials and products.

2.4.2 Develop a framework that supports the implementation of a circular approach within the leather industry

A framework for the implementation of a circular approach within the leather industry is developed. The framework allows flexible waste recovery strategies to be explored and developed and the economic viability of a circular approach to be evaluated.

2.4.3 Develop a waste-flow map for leather and define the waste streams in terms of the quantitative and qualitative characteristics

The opportunities and challenges arising during the management of leather waste are primarily defined by the technical and operational characteristics of the waste. A detailed analysis of these characteristics of the waste across the lifecycle of leather is conducted, which enables insight to be gained about the influence that these characteristics have on the economic viability of a circular approach for leather.

2.4.4 Develop recycling and processing strategies for the recovery of leather waste

To establish a circular approach within the leather industry it is vital to identify viable material recovery strategies for leather waste, which are based on detailed examinations of the typical material content of leather products and leather waste. Consequently, material characteristics are outlined and linked to the attributes of end-of-life processing technologies which will enable these materials to be recovered. Recovery methods are explored, and strategies developed that enable improvements in the quantity and quality of
leather that is recovered from waste. As flexible recovery strategies are defined, the implications on the cost of leather recycling systems will be noted. This work focussed on the recovery rather than reuse of leather material which was considered outside of the scope of the current research. The primary reason for excluding reuse of leather is that due its formation and use phase, it is typically unsuitable for reutilisation within its original application.

2.4.5 Develop a cost model to support economic decisions regarding the implementation of a circular approach in the leather industry

The economic viability of implementing a circular approach is evaluated using a cost model. The cost model incorporates all costs associated with creating a leather recycling system and considers the influences of the waste characteristics, the waste collection strategies and the processing technologies on the cost of implementation.

2.4.6 Demonstrate the validity of the research concepts, framework and tools through case studies

The validity and viability of the research concepts is assessed through application of the framework in two case studies: the first case study assesses the revenue improvement gained from increasing the purity of recovered leather; the second assesses the revenue improvement gained from increasing the quantity of leather recovered. The results are used to draw conclusions about the validity of the framework methodologies and economic model. Benefits and limitations of the framework and tool are assessed and reported along with opportunities for improvement and future extensions to the work.

2.5 Summary

This chapter presented the context of the research reported within the thesis and stated the research questions that underpin the work. The research aim was identified and objectives to support this were defined. Finally, the objectives were used to define the scope of the research. The following three chapters address the first research objective. Chapter 3 presents a review of how leather is produced and used and reviews the current disposal routes for leather waste. Chapter 4 reviews existing waste management and recycling processes and Chapter 5 presents a review of the current literature that is most relevant to the work within this thesis.
CHAPTER 3 REVIEW OF LEATHER USE AND RECYCLING

3.1 Introduction

This chapter presents a review of leather production and the use of leather in consumer goods. The chapter begins with a consideration of the place of leather in relation to the global meat and materials industries, before moving on to explore the technical aspects of leather relating to design and production of leather goods. Finally, previous studies evaluating the end-of-life management of leather waste are reviewed along with legislation related to leather waste disposal.

3.2 Leather as raw a material and as by-product of the meat industry

Leather is an organic material made from the skins of various animals and is composed as follows: Water 60-65%, Protein 25-30%, Fats 5-10%. Leather is defined by the British Standard BS: 2780 as meeting the following definition: 'Hide or skin with its original fibrous structure intact, tanned to be imputrescible. The hair or wool may, or may not, have been removed. It is also made from a hide or skin that has been split into layers or segmented either before or after tanning' (Leathermarks, 2015). Leather can be made from the skins of various animals, mainly cattle, goat, sheep and pigskins, along with more exotic sources such as fish, ostrich and kangaroo (Heidemann, 1993). It is a versatile material and the properties have long been exploited by humans for various uses, such as clothing, accessories and furnishings.

3.3 Global leather use and market analysis

The leather and leather products industry play a prominent role in the world’s economy, as leather is one of the most highly traded commodities in the world. It has an estimated global value of approximately 100 billion US dollars per year (UNIDO, 2000a). Leather from bovine sources is the most common leather in production globally; this is due to the demand for bovine meat and the availability of the animal skins as waste products from the meat production process. Global hide production from bovine animals has been increasing over the last few decades as shown in Figure 3.1 and the demand for such hides is closely linked to economic growth (UNIDO, 2010; FAO, 2013).
When broken down by continent, it is easy to see that demand for bovine hide production has slowed in the developed countries such as the United States and is growing in the developing countries such as India, Brazil and China. It is predicted that as the developing economies continue to grow, the demand for leather and luxury items that are usually made from these leather hides will also grow within them (UNIDO, 2010; Mwinyihija, 2014). The chart in Figure 3.2 shows that the largest producer of leather in the world is China and that its production is almost three times as great as the next largest producer which is Italy.
3.4 Overview of leather products

Leather is currently used in thousands of products globally. The uses for leather range from high-quality luxury items such as handbags, automobiles and clothing, to practical items such as saddles, sporting equipment and footwear. Categories of leather products are shown in Figure 3.3 below:

Historically the biggest user of leather was the footwear industry, with 65% of the market; however, this has been declining over past decades and was at 55% of global leather production in 2008, refer to Figure 3.4. The automotive industries have increased their use of leather and this is set to take the place of footwear as the largest global commercial user of produced leather, with upholstery and other leather products having the third and fourth places for largest percentage of leather used, as illustrated in Figure 3.4 (UNIDO, 2010).

![Figure 3.3: The use of leather within products](image)

![Figure 3.4: Approximate percentage volume of leather used by industry (UNIDO, 2010)](image)
3.5  Leather production and leather goods manufacture

This section provides background information on the various stages within the production of leather and leather products. The flow chart in Figure 3.5 provides an overview of the production processes used during the transformation of animal skins into finished leather and the subsequent wastes generated during production.

![Flow chart of leather production process and material flows](attachment:Karabay_2008.png)

Figure 3.5: The leather production process and material flows (Karabay, 2008)
The production of leather consists of three fundamental sub-processes and all true leathers will undergo these processes:

1. Pre-tanning Operations (Beam-house Operations)
2. Tanning Operations
3. Wet-Finishing Operations

An additional stage is the surface treatment of the finished leather, this stage is common but not compulsory for the material to be classified as leather (Heidemann, 1993). The surface treatment processes generate waste products; some of the waste products are classified as hazardous wastes due to the presence of chromium tanning agents. Once the leather has been produced, this material is then ready to be used in making leather products. During the manufacturing of leather products, many stages of production occur depending on the product being manufactured. However, each process usually has the following stages in common:

- Receive finished leather hides
- Selection and quality check of leather hides
- Cutting and sizing of the hides
- Joining of leather to other material/incorporation of leather into product
- Product samples and prototypes produced and tested

Within the various leather-using industries leather is combined with hundreds of different materials, the most common of which are listed in Table 3.1. This provides an indication of where separation efforts should be focussed when trying to recover leather material from products.

Table 3.1: The most common combinatory materials within leather-based products

<table>
<thead>
<tr>
<th>Industry</th>
<th>Material most commonly combined with leather</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footwear</td>
<td>Rubber, textiles and foam</td>
</tr>
<tr>
<td>Automotive</td>
<td>Foam, textiles, plastics</td>
</tr>
<tr>
<td>Furniture</td>
<td>Foam, wood, plastic, textiles</td>
</tr>
</tbody>
</table>
3.6 Legislation across the leather lifecycle

The production of leather hides is environmentally sensitive and subject to considerable legislation. Various pieces of hazardous waste legislation are applicable within the EU; however, legislation is not consistent across other continents. The biggest issue with regards to this review is the recycling legislation, this is particularly relevant in the EU where landfill regulations are becoming ever more stringent (UNIDO, 2010). Article 5 of the EU landfill directive deals with biodegradable waste and its suitability for landfill, this legislation is currently changing to divert biodegradable material away from landfill - where it produces greenhouse gases and contributes to global warming - towards other disposal routes. These changes are critical for the leather goods industry as leather is a biodegradable material, but it can take hundreds or even thousands of years to compose depending on landfill conditions. This means that the any changes to Article 5 will have a direct impact on the available disposal routes for leather waste material and waste products; this creates urgency for leather waste recycling systems. Article 5 also impacts a major user of global leather which is the footwear industry, currently most of the hazardous waste from the leather footwear sector is disposed of in landfill. This legislation means that in the future, materials contained within footwear such as natural rubber, leather and natural textiles will have to be recycled rather than sent to landfill.

3.7 Options for end-of-life management of leather wastes

The previous section explored the use of leather, its production and use in manufacturing along with the environmental challenges associated with leather. This section will go into further detail to explore relevant literature regarding the processing of wastes at different stages in the lifecycle of leather. On review of the previous work done in this area, it was found that most literature fell into three broad categories with regards to the type of leather waste being dealt with. These categories represent different stages in the lifecycle:

- Tannery waste
- Manufacturing/production waste, from the production of leather-based goods
- Post-consumer waste

These categories of waste are shown in Figure 3.6, which illustrates the point at which the waste is generated along the lifecycle of leather. A forth category of distribution and retailing waste does exist but no literature was found that examines this waste stream.
CHAPTER 3

Within the initial categories of literature, further patterns were observed with regards to the work that had been carried out. Many sources presented work based on the type of treatment used to process the waste; the four key types of processing technique are as follows:

- Mechanical processing
- Thermal treatment
- Chemical treatment
- Biological processing

These core treatment methods along with examples of processes associated with them are outlined in Figure 3.7.

The next section is structured to provide an overview of each stage of waste production within the lifecycle and the various processing techniques that are used to treat waste within these stages. Throughout the literature review it became clear that the intended secondary use for the recovered waste materials had a direct impact on what processing method was initially chosen, these intended secondary uses are also discussed in each section.

Figure 3.6: Waste generated at different points within the lifecycle of leather
Figure 3.7: Leather waste categories and processing techniques

3.7.1 Tannery waste

This section explores the different literature available for dealing with leather wastes associated with the production of leather in tanneries. It became evident throughout the literature review that tannery waste was a well-known problem and that a lot of work had been carried out in this area. The waste generated during the production of leather generates an immediate problem for the tanneries, it becomes economically and operationally imperative for them to consider alternative routes other than landfill for the waste, hence a large body of work exists in this area.

An outline of the tannery processes and the wastes associated with each step is provided in Figure 3.8. Various effluent wastes are created during the production of leather; however, this review has focussed on solid wastes produced during the tanning process and the technologies created to deal with them, as such, most of the reviewed literature focussed on technologies for processing the leather ‘shavings’ waste stream, as indicated in Figure 3.8.
The next sections explore the key processing methods for dealing with tannery waste.

3.7.1.1 Thermal treatment

Thermal methods for treating tannery wastes include incineration, pyrolysis and gasification. Through thermal treatment of waste it is possible to produce energy whilst also reducing the volume of waste substantially (up to 90%) (Godinho et al., 2007). Incineration of leather industry waste is garnering attention due to the restrictions on landfill and the increased global need for alternative energy sources. Investigations carried out using a bubbling fluidised bed combustion process by (Bahillo et al., 2004), show this method to be an effective technique for reducing the volume of footwear industry waste whilst generating energy, the bubbling fluidised bed schematic is shown in Figure 3.9. While evaluations of the value of leather waste incineration ashes by (Basegio et al., 2006) show that these ashes can be successfully combined with alumina to form ceramic products suitable for refractory purposes. However, emissions and hazardous ash by-products mean that incineration simply shifts the environmental problem from one of waste volume to one of waste toxicity.
Studies including the gasification of leather shavings have shown that as well as reducing waste volume (Godinho et al., 2011) the chromium-containing ashes can be used to produce compounds such as HC-FeCr alloy (Alves et al., 2012; Padilha et al., 2012). This compound is used as a raw material in the production of stainless steel and presents a high-value application for products generated from leather wastes. Other gasification work on vegetable tanned leather waste has successfully yielded hydrogen gas as a by-product of the gasification process (Yanik et al., 2008).

Pyrolysis is the process of heating carbonaceous material in an inert atmosphere, as such, the waste substances are not oxidised but turned into oil, gas and carbonaceous residue at high temperatures (Yılmaz et al., 2007). Pyrolysis, unlike traditional incineration, allows the stabilisation of residues for their subsequent deposition in landfills and reduces the risk of leaching (Gil et al., 2012). A study by (Sethuraman et al., 2014) focused on pyrolysis of micro-fine solid particulate matter from tanneries. This study successfully used pyrolysis to dispose of hazardous chromium containing leather wastes and produced residue that was within the safe limits for landfill disposal, this process is illustrated in Figure 3.10.

Figure 3.9: Bubbling fluidised bed boiler (Bahillo et al., 2004)
Figure 3.10: Pyrolysis coupled pulse oxygen incineration (Sethuraman et al., 2014)

A report by (Yılmaz et al., 2007) looks at a pyrolysis process used to recover gas, oil, ammonium carbonate and carbonaceous residue from different types of tannery wastes. Several uses for the residue were claimed, such as solid fuel and with further processing activated carbons could be produced that can be used as adsorbent materials for dye removal from aqueous solutions. Other studies by (Gil et al., 2012) and (Caballero et al., 1998) also used pyrolysis to produce solid fuels. While investigations by (Muralidhara et al., 1982) prove that energy and chrome tanning liquor can be recovered through pyrolysis of tannery wastes, with the added benefit of being able to re-use the chrome tanning liquor back in the tannery. The main disadvantage of using pyrolysis to process waste is the high temperatures required and hence high energy usage.

3.7.1.2 Chemical treatment

Chemical methods for the treatment of tannery waste involve alkali hydrolysis and result in the production of gelatine which has potential uses in cosmetics, printing and leather finishing (Cabeza et al., 1998; Mu et al., 2003). Reconstituted collagen has been produced which can be used in animal feed and as fertiliser and a re-tanning agent (Mu et al., 2003). Finally, adhesives, films and chrome cake can be obtained from chrome tanned leather, splits, buffing dusts and trimmings (Dixit et al., 2015). Other novel chemical approaches include the use of organic chelates to remove chromium from leather wastes (Malek et al., 2009), the production of pigments from chrome recovered from waste leathers (Berry et al., 2002) and the production of biodegradable hydrogels for packaging from collagen waste proteins (Langmaier et al., 2008).
3.7.1.3 Mechanical treatment

Mechanical methods for the processing of tannery wastes include physical processing techniques such as fragmentation and mechanical separation of wastes ready for incorporation into other products.

This includes the incorporation of powdered leather shavings into rubber compounds to improve the properties (Przepiorkowska et al., 2007; El-Sabbagh and Mohamed, 2011; Ravichandran and Natchimuthu, 2005) and the inclusion of shavings and buffing dust into cavity insulation materials (Lakrafli et al., 2013). Leather residue was incorporated into asphalt micro-surface layer in order to improve the properties and reduce road-surface wear (Krummenauer and de Oliveira Andrade, 2009), application of the leather residue is shown in Figure 3.11. Other examples include the fragmentation of leather shavings to be used in the adsolubisation of organic contaminants from wastewaters (Marsal et al., 2013; Gammoun et al., 2007) and dyes from aqueous solutions (Oliveira et al., 2007; Sekaran et al., 1998; Ali et al., 2012).

These applications are novel and are economically advantageous compared with commercial materials that perform the same job; however, these applications still represent down-cycling of the material and further problems are created with processing of the adsolubised waste material.

Figure 3.11: Application of micro-surface layer incorporating tanned leather residue (Krummenauer and de Oliveira Andrade, 2009)
3.7.1.4 **Biological treatment**

Various biological methods exist for processing organic waste material; several have been applied to the solid waste produced by tanneries with various results.

**Composting**

Composting of tanned residue has been studied by (Amir et al., 2008) and (Collivignarelli and Barducci, 1984) while (Nogueira et al., 2011) investigated the use of de-chromed leather waste as a nitrogen-rich fertiliser, illustrated in Figure 3.12.

Work by (Zuriaga-Agustí et al., 2015) investigated the potential biodegradability of leather shavings from tanneries. They processed vegetable, titanium and chromium-tanned leather samples under aerobic degradation conditions by means of a composting process. They found that while the process depended on the tanning agent used and any pre-treatments applied, the titanium-tanned sample was the only one to degrade when mixed with municipal food waste.

**Anaerobic digestion**

Anaerobic biodegradability of untanned, chrome tanned and vegetable tanned leather has been addressed in the work by (Dhayalan et al., 2007). The authors claim that degradation of all types of leather is possible and that the anaerobic digestion of vegetable tanned leather leads to more gas production than the others, the authors also found that de-tanning improved the biodegradability of both types of leather. This is important to consider when implementing alternative leather waste disposal solutions as it may be more

![Diagram of biological treatment](image)

**Figure 3.12: De-chroming and chromium recovery (Nogueira et al., 2011)**
environmentally and economically effective to de-tan the waste before the processing stage at the end-of-life.

**Microbial fermentation**

Another type of biological process found within the literature was microbial fermentation, a process by which bacteria use waste medium to grow and produce useful by-products.

Work by (Pillai and Archana, 2012) successfully achieved microbial growth on chromium-containing tannery shavings, with the result of producing a valuable protease by-product which has application in the pre-tanning process. While work by (Katsifas et al., 2004) used microbial fermentation to liquefy tannery waste and recover chrome. This presents a potential in-house solution to the management of chrome shavings and the circular use of resources within the tannery (Hu et al., 2011).

### 3.7.2 Manufacturing/production waste

This section reviews the literature associated with processing leather wastes from manufacturing. It became evident throughout the literature review that manufacturing waste was a well-known problem and that a lot of work had been carried out in this area. The waste generated during the production of leather goods generates an immediate problem for the manufacturers, it becomes economically and operationally imperative for them to consider alternative routes other than landfill for the waste, hence a large body of work exists in this area.

#### 3.7.2.1 Biological treatment

**Composting**

One example of biological treatment of leather manufacturing waste is the production of fertiliser from vegetable-tanned leather dust. This dust is produced during carding and cutting operations in the footwear manufacturing industry and gets mixed with water and calcium carbonate to form fertiliser for agricultural purposes (Tatàno et al., 2012), as shown in Figure 3.13. It is important to point out that this dust needs to be kept separate from chrome-tanned leather dust during manufacturing otherwise this application cannot be performed due to the hazardous nature of chromium-containing dust.
Other biological processing methods include anaerobic digestion which was studied by (Ferreira et al., 2010). This work investigated the production of an anaerobically-digestible substance from waste footwear manufacturing leather by prior-removal of the chromium content by wet-acid treatment. This work found that after chrome was removed the leather substance was three times more biodegradable than the original waste scraps; however, chrome was still present, and the waste was still classified as hazardous, see Figure 3.14.

### 3.7.2.2 Mechanical treatment

Mechanical methods produce recycled leather waste that is used as filler in poly vinyl chloride plastic fillers (Andreopoulos and Tarantili, 2000), this method isn’t without its drawbacks as the author states that chemical pre-treatment is required to ensure the continuity of the composite materials. A patent emerged from the literature that detailed the production of a fibrous mass from waste leather materials that can be formed into the desired state by twisting, weaving, felting, flocking, screening, rolling, pressing or moulding. This process uses scrap leather from production (Emmit and Schenck, 1941).
Figure 3.14: Characteristics of the residues obtained from leather de-chroming (Ferreira et al., 2010).

<table>
<thead>
<tr>
<th>Class of landfill</th>
<th>Leachate, mg/L</th>
<th>Cr total</th>
<th>Cr(VI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inert</td>
<td>&lt; 0.5</td>
<td>&lt; 0.1</td>
<td></td>
</tr>
<tr>
<td>Non-hazardous</td>
<td>&lt; 2</td>
<td>&lt; 0.1</td>
<td></td>
</tr>
<tr>
<td>Hazardous</td>
<td>&lt; 5</td>
<td>&lt; 0.5</td>
<td></td>
</tr>
</tbody>
</table>

Legend: W = weight, WR = Weight reduction, D = Dimension, M = Morphology, Cr = Chromium total and Cr (VI) from eluate by EN 12457-2:2002.
3.7.2.3 Thermal treatment

Forming

Ad-hoc attempts at re-using scraps from the manufacture of leather goods have been made in various production sites. The work done by (Kindlein Júnior et al., 2008) uses wet blue scraps and hot-melt polymers to form sandwiches of materials that can be transformed into thermal-protection mitts. This type of scrap re-use is time consuming, labour intensive and represents a down-grading of the material quality, when the gloves reach the end of their lives, the leather will be extremely difficult to recover from the product, the production steps are illustrated in Figure 3.15.

Incineration

Waste in the form of off-cuts from the manufacture of products such as leather footwear is often incinerated to provide ambient heat within the production facility, this provides the advantage of energy recovery from waste, but also creates ashes which are rich in chromium and hazardous to health. Novel ways of using the ashes created from incineration have been discovered, these include the incorporation of these ashes into ceramic tiles as a direct replacement for commercial pigments. This application of leather waste provides the benefit of energy generation and safe disposal of the chromium-rich ashes through landfill avoidance. The chromium-rich ashes are much lower in cost than the commercial pigments, this provides cost savings to the tile manufacturers and the ‘ash-as-pigment’ also gives the tiles superior properties (Fernandes and Ferreira, 2007). Other studies have used the chromium-rich ashes from incinerated leather waste to produce compounds that can be utilised back in the tanning process. Experiments by (Dettmer et al., 2010; Imai and Okamura, 1994) have successfully used these ashes to produce basic chromium sulphate, which is the most widely used mineral tanning agent in leather production (Sethuraman et al., 2014) and to produce sodium chromate which is a basic intermediate chemical product, from which all the other chromium compounds are produced. This represents a circular use of resources within the production lifecycle of leather and leather products.
3.7.3 Post-consumer waste

Post-consumer waste is a much more difficult category of waste to treat, the waste is geographically spread out across the globe, and there is no clear ownership of the leather product at the end of its useful life and the waste needs to be actively collected. The periodicity of disposal for leather goods is much longer than for other items such as plastic bottles, making regular collections economically less viable. There are very few examples of academic literature that tackle post-consumer waste, and so the following sections focus on disposal methods available from a variety of other sources.

3.7.3.1 Mechanical treatment of post-consumer waste

Mechanical treatment of post-consumer leather waste includes any process which fragments the leather product for direct use or combines fragmentation and separation processes to separate leather from other materials within consumer products. The only work present in the academic literature in this area was the previous work done at The Centre for SMART at Loughborough University on footwear recycling (Lee and Rahimifard, 2012a; Lee and Rahimifard, 2010; Rahimifard et al., 2007; Staikos et al., 2006). Other sources of information were reviewed including commercial operations and independent public initiatives with regards to the re-use of post-consumer leather.

Fragmentation and separation

Only one commercial scale fragmentation scheme for post-consumer leather is known, this is the Nike ‘Reuse-a-shoe’ program (Nike, 2015) as shown in Figure 3.16.

This program collects worn athletic footwear and grinds it up to be used in surfacing applications such as sports arenas and outdoor children’s play surfaces. However, this application does not represent a ‘waste leather initiative’ because the athletic shoes also contain several other materials such as rubber, polymers and textiles.
The work done by The Centre for SMART on footwear recycling encompasses fragmentation processes along with various separation processes for recycled materials. The full recycling line is shown in Figure 3.17 and a more detailed view of the processes is illustrated in Figure 3.18. The outputs from these processes are four materials: leather, rubber, textiles and foams, as shown in Figure 3.19.

Figure 3.16: Nike ‘Re-Use A Shoe’ processing stages (Nike, 2015)

Figure 3.17: Centre for SMART footwear recycling line
These systems can be used to produce recycled leather of purity up to 90% from footwear which can be used in multiple applications. Therefore, there is significant potential to extend this work to leather products from other industries to increase the percentage of post-consumer leather material that is recycled.

Proposals for use of post-industrial and post-consumer leather wastes have been made by (Kinyanjui et al., 2013). The authors believe that the production of non-woven items from waste leathers is an appropriate solution to the leather waste problem in Kenyan regions; however, this work is exploratory only and no experimental work has been carried out.
Direct re-use

A few examples of small-scale direct re-use of post-consumer leather were found, they were usually small-batch production of leather goods such as decorative leather interior panels (Ecodomo, 2015) and footballs made from used leather seat covers from the aviation industry (Braw, 2014). They are illustrated in Figure 3.20. These reuse efforts are extremely small-scale in comparison with the amount of leather that reaches the end of its life in consumer goods each year. This type of activity is only suitable if the end-of-life leather is not bacterially contaminated (this rules out the possibility of using athletic footwear in this way) and if the leather is of sufficient quality to be re-used in other products.

3.7.3.2 Thermal treatment of post-consumer waste

Thermal treatments processes for post-consumer leather waste are similar in nature to those used for manufacturing and production scraps. These materials can either be incinerated for energy-recovery or they can be fragmented and turned into leather boards or leather ‘composites’ through a thermal-rolling process, see Figure 3.21. A review of patented ideas revealed a patent for a ‘composite leather board material’ which can incorporate post-industrial or post-consumer leather waste (Coulson et al., 2007), it consists of leather fibres, non-leather fibres, a latex binder and a cushioning agent. One drawback to this process is that the purity of the post-consumer leather has to be very high in order for this process be technically feasible and for the leather board product to be of consistent quality (e-leather Group, 2015). In most cases the leather in post-consumer products is combined with numerous other materials, which generally makes it low quality and it will require extra pre-processing before leather board material can be produced.

Figure 3.20: (a) Decorative recycled leather panels (Ecodomo, 2015) and (b) Footballs constructed from recycled leather airline seat covers (Braw, 2014)
In summary, this section of the review has shown that the market for the use of leather in products is great, the geographical production of leather is undergoing a shift from developed nations to developing nations, and that the primary use of this leather in manufacturing is shifting from footwear to the automotive and furniture industries. Additionally, it was discovered that the lifecycle of leather is complex with many environmental hazards throughout, including waste production and that legislation is having an impact on how these wastes are managed. There are four main areas in which waste occurs during the lifecycle of leather products: within tannery operations, during manufacture of goods, during the distribution and retailing of goods and at the post-consumer stage when products reach the end of their useful lives. Various disposal and recovery methods are used at different stages in the waste-cycle, these include mechanical, chemical, biological and thermal recovery processes and the processing method chosen depends on the intended secondary use for the recovered materials. The focus of literature in waste leather processing is the tannery operations and the recovery of useful products from this waste. Very limited work has been done on the recovery of leather from post-consumer products. Most often, leather waste is re-used on very small scales on an ad-hoc basis by micro-companies or individuals because other viable large-scale alternatives are not yet available. Therefore, it is evident that there is a gap in the literature with regards to recovery of leather from products, and there is significant room for improvement of the current end-of-life situation for leather waste generated throughout the lifecycle of leather. A variety of value-added products can be recovered from these materials (as shown by the processing of tannery wastes), but only if they can be successfully separated from the other materials (such as rubbers and polymers) within end-of-life products. This presents scope for the development of a circular approach within the leather industry.
CHAPTER 4  REVIEW OF RECYCLING AND MATERIAL RECOVERY SYSTEMS

4.1  Introduction

This chapter presents a review of the literature related to waste management and recycling technologies. It begins by briefly explaining recycling systems and the benefits and drawbacks of implementing them for material recovery.

It then goes on to explore the relevant technologies that are currently available within recycling systems for processing waste and recovering materials. This chapter therefore provides an understanding of how the currently available technologies could be applied to recycling leather and how they could be combined to create a leather recycling system.

4.2  Recycling and material recovery systems

To select the most appropriate recycling technology for processing waste, it is first critical to understand more about the physical operation of recycling systems, this section provides an overview of recycling systems and the benefits and limitations of them.

Recycling systems are traditionally defined as any process or series of processes which recover materials from waste products to be used again in other products. The goal for recycling systems is to achieve high levels of material recovery with minimal input of energy and other resources (Fujii et al., 2014).

Traditional recycling programs are driven by legislation, in the EU this legislation is driven by a central body called The European Commission, and recycling targets are filtered down to all member states. The European strategy on the recycling of waste says that “the long-term goal is to become a recycling society that seeks to avoid waste and uses waste as a resource” (European Commission, 2013) and so the published waste directive 2006/12/EC states that waste should only be landfilled if other more appropriate options are not available (Darlington et al., 2009).

The most appropriate recycling method for any product depends on a range of considerations, such as the product construction and material content and how the waste has been produced. For instance, municipal recycling systems have been created in the United Kingdom (UK) for high-volume household waste such as cardboard, plastics, metals and glass. Waste materials are source-separated by individuals (households or small
businesses), collected by local authorities and sent to Material Recovery Facilities (MRF’s). Once the waste materials reach the MRF they are sorted and baled ready to be sold on the recycled materials market for use in other products.

However, recycling of materials within industrial and commercial premises is sometimes dealt with separately to the municipal recycling programs. The separation is due to the more complex nature of materials within industrial applications; specialist recycling contractors are needed to correctly process the materials for re-use.

Traditional municipal recycling systems (see Figure 4.1) are designed to deal with high-volumes of similar waste materials, and as such they are designed as dedicated systems which can only process a limited amount of core recylcates (Fujii et al., 2014).

Other smaller recycling systems for more specialised items such as mobile phones and waste electronics involve high levels of manual labour and are generally created on an as-needed basis, this occurs as legislation forces industry practices to change, processing the waste becomes more profitable or a waste becomes problematic to send to landfill.

![Figure 4.1: Typical design of a ‘dedicated’ municipal material recovery facility (Trims, 2016)](image-url)
4.2.1 Benefits of recycling

There are many benefits to recovering and recycling materials at the end-of-life including: the recovery of physical resources that would otherwise be lost to landfill, which reduces overall virgin material use, and the recouping of some of the embedded energy and resources within a product. Other benefits include the economic value of the recycled material and the re-capture of some of this value as the recycled material is sold on the secondary material market.

4.2.2 Drawbacks to recycling

While there are many benefits to recycling, there are also disadvantages, frequently the recycling processes used to recover waste materials are more energy-intensive than the initial processes used to prepare the virgin materials, this is environmentally unsustainable.

Recycling can be an extremely complex problem when source separation of materials is not practiced or is not feasible, this drives up the cost of the recycling processes and hence reduces the revenue from recycled materials. The large capital cost of recycling systems means that high-volume processing is required to make it economically feasible, this limits recycling system to materials which are widely used and makes it harder to recycle low-volume materials.

Traditional recycling systems are inflexible in design and are currently incapable of being reconfigured to deal with the changing market conditions and advances in product materials. Wolf et al., (2010) and Fujii et al., (2014) state that as products with more complicated material mixes reach the end-of-life and enter the waste stream, then the performance of recycling systems must increase to suit incoming waste streams.

Furthermore, Colledani et al., (2014) state that the current state of the art recycling systems are “extremely rigid with monolithic designs which make it difficult to modify the material flow routing for different mixtures that require treatment”. The authors go on to say that the “parameters of the recycling processes are usually set during the commissioning of the system and are normally kept constant during the lifecycle of the system”.

All of this makes current recycling systems unsuitable to meet the demands put on them by future waste materials and products. This leaves a significant opportunity to improve the
performance and flexibility of recycling systems to improve the quality and value of the recovered materials.

4.3 Recycling and material recovery technologies

Review of the literature indicates that recycling technologies and processes can be split into three areas: pre-fragmentation, fragmentation and post-fragmentation. These areas are outlined in the technology roadmap included in Figure 4.2 and further explored in Sections 4.3.1 to 4.3.3. Further technologies are required to convert the recycled materials into useful products.

4.3.1 Pre-fragmentation processes

Pre-fragmentation processes within recycling systems include any processes or technologies that sort the waste prior to fragmentation operations. These include various technologies for sorting, including manual, optical and automated sorting systems as shown in Figure 4.3, and literature relevant to these types of processes are discussed in more detail in the next sections.

![Technology roadmap of recycling processes](image-url)
4.3.1.1 Manual (All material fractions)

Manual pre-fragmentation sorting techniques include those used at conventional municipal solid waste facilities, conveyor belts are used to transport the waste as it moves through the facility and human-operators are used to manually sort out any contaminant materials from the desired recycled material streams. This is illustrated in Figure 4.4.

4.3.1.2 Optical sorting

Optical sorting methods include any process which uses optical instruments (such as cameras or colour sensors, along with lighting) to detect a certain type of waste, and then uses mechanical means to remove that item from the waste stream. An example of this is a system described by (Rahman et al., 2011), this system uses image processing techniques to sort different grades of waste paper. This system is illustrated in Figures 4.5 and 4.6.
4.3.1.3 **Automated sorting**

Automated sorting systems consist of detection and removal processes to separate different fractions of a waste stream automatically (without operator intervention). They can include simple systems such as magnets to detect and remove metal from waste or more complicated systems such as the ones described below.
An example of automated pre-fragmentation sorting is the custom system made by the company National Recovery Technologies called the ‘Vinylcycle Separator’. This system was used on plastic bottle recycling lines to separate Polyvinyl chloride (PVC) bottles from those made of other materials. In the system, X-rays were used to identify PVC materials and once identified an air-jet was used to separate the PVC bottles into a different material fraction (Pascoe, 2014). These systems are used at very high throughput facilities, but they are specific to one material type. A schematic of the system is presented in Figure 4.7.

Other automated pre-fragmentation separation systems include the separation of waste by automated reading of embedded radio frequency identification (RFID). These systems could be used for the tracking of household waste by weight or by type (e.g. glass or plastic), the idea being that once the waste reaches the processing facility the RFID tags will work in conjunction with a separation system to automatically move the different types of waste to different locations within the facility to undergo different processing operations (Gnoni et al., 2013). An example of how this could work in practice is shown in Figure 4.8.

![Figure 4.7: The Vinylcycle Separator automated separation system (Pascoe, 2014)](image-url)
4.3.1.4 Metal detection and removal

Metal detection and removal is widely used throughout waste recycling facilities for removing waste metals from mixed recycling loads, this usually takes the form of an over-band magnet that is positioned above conveyor belts and removes ferrous-metal items before transferring them to a separate waste bin. These systems are commonly found within wood recycling and composting systems, where magnets are used prior to fragmentation of the wood to remove any metal and protect the fragmentation machines, as illustrated in Figure 4.9.

Eddy-current separators are commonly used for non-ferrous metal items. These separators remove non-ferrous metals using a powerful magnetic force. Depending on the type of separator, a rotating drum with permanent magnets (see Figure 4.10) or an electromagnet can be used. The separator is applied to the end of a conveyor belt carrying the materials to be separated, non-metals fall off the end of the conveyor due to gravity, while non-ferrous metals are thrown forward from the belt into a separate bin.

Other types of metal detection and elimination include manual removal of metal before fragmentation of waste products, see Figures 4.11 and 4.12. Work done by Lee and Rahimifard (2012b) on footwear recycling found a need for the removal of metal before the footwear was fragmented for further processing.
Figure 4.9: Over-band magnet metal removal from composting waste line
(Mastermagnets, 2015)

Figure 4.10: Eddy current metal detection and removal

Figure 4.11: Hand-held metal detector for manual metal detection (Power Tool World, 2017)
This need to remove metal before fragmentation arose due to the ability of the embedded metal to damage the granulating machinery. A manual approach to removing the metal was applied because researchers found it highly challenging to find a way to automatically remove the metal which was heavily encapsulated within the toes and heels of the footwear (Lee et al., 2012b).

4.3.2 Fragmentation processes

Fragmentation is the process by which wastes are reduced in size before entering further separation operations downstream, these include shredding, granulation and powderising, as outlined in Figure 4.13 and discussed in more detail in the next sections.

4.3.2.1 Shredding

Within the vehicle and household appliance recycling sectors, technologies such as hammer-mills process very large items and tear them into smaller pieces by the repeated blows of hammers to the material; this makes them more manageable for the post-fragmentation processes to deal with. An example of a hammer-mill is shown in Figure 4.14.
Granulation processes are often used as secondary size reduction techniques for large waste or as primary size reduction for smaller waste types such as plastic bottles. Granulators fragment waste materials to a certain size to support further processing and separation of the materials.

The work done by Lee and Rahimifard (2012b) on footwear recycling used a granulator to reduce the size of the footwear to enable the materials to be more easily separated. Granulation of small pieces of waste makes material entanglement less likely and leads to a greater separation of materials.

Powderising

Recycling of scrap tyres and the recovery of the rubber material utilises shredding, granulation and finally powderisation (the term ‘secondary granulation’ is also used). The powder produced from the process is in demand for various industrial and chemical processes. The preliminary stages of tyre recycling are used to remove the majority of the metal beading from the waste tyres as this causes significant damage to equipment in later size reduction processes (Waste Management World, 2015). A typical system to produce rubber powder from waste tyres is shown in Figure 4.15.
Figure 4.15: Scrap tyre recycling (Waste Management World, 2015)

4.3.3 **Post-fragmentation separation processes**

Post-fragmentation processing consists of any processing done after a waste stream has been fragmented. The most common categories of post-fragmentation technologies used within recycling systems are outlined in Figure 4.16 and discussed in more detail in the next sections.

![Diagram of post-fragmentation processes](image)

**Figure 4.16: Post-Fragmentation processes used in recycling systems**
4.3.3.1 Gravity-based processes

Gravity-based processes for the separation of different waste streams include technologies such as screens, float-sink tanks and dense media separation processes, both wet and dry.

Gravitational float-sink tanks use fluids to separate materials. The principle behind them is that the less-dense materials will float on the fluid surface and the more-dense materials will sink to the bottom of the tank and hence the materials become separated. They have the advantage of being simple and can work very effectively when trying to separate materials with very different densities (Pascoe, 2014). An example of a gravity-based separation process is illustrated in Figure 4.17.

Screening or size separation

Another example of a gravity-based post-fragmentation separation technique is the use of screens to classify particles by size (Burt, 2000). Screens are widely used in a range of waste processing industries including the processing of construction waste to grade materials after they have been fragmented to enable the re-use of materials streams of uniform size, see Figure 4.18.

The advantage of using screens to separate materials is that they are widely-used, widely available in a range of sizes and relatively inexpensive. The drawback is that they only separate materials based on the size and cannot be used to separate materials by type unless the size of the material is related to its size (e.g. sand and rocks).

Figure 4.17: An example of a continuous float-sink separator (Pascoe, 2014)
Dense media separation processes

Dense media separation technology is commonly used within the mineral processing industries, and uses wet or dry media to separate particles of materials into fractions depending on density (Lim et al., 1995). Work by (Oshitani et al., 2010; Rasul et al., 2000) presents dry-dense media separation processes for minerals using gas-solid fluidised beds, these processes use media such as glass beads within a ‘bed’ and introduce materials into the bed to be separated. This type of dense media separation has been transferred to the recycling industries and (Sekito et al., 2006) present a gas-solid fluidised bed separator for the separation of fragmented municipal waste, see Figure 4.19.

Figure 4.19: Schematic diagram of the gas–solid fluidized bed separator: (a) cyclone; (b) top screw for recovery of the float fraction; (c) 3.7 kW blower; (d) Shredded Bulky Waste; (e) distributor; (f) bed material (340 m glass beads); (g) wind box; (h) valve; (i) separator for glass beads and shredded bulky waste; (j) bottom screw for recovery of the sink fraction; (k) motor (Sekito et al., 2006).
Their aim was to use the fluidised bed to separate two fractions of waste: combustibles and incombustibles. Within coal processing industries cyclonic dense media separation technologies are widely used (Albrecht, 2013). Gent et al., (2009) present a cyclone-type dense media separator for the separation of plastic fractions with waste plastic streams; a schematic of the system they propose is shown in Figure 4.20.

### 4.3.3.2 Air-based post-fragmentation separation processes

Various types of air classification processes were found within the literature, these are briefly discussed in the section below.

![Figure 4.20: A proposed dense media cyclone for plastic separation (Gent et al., 2009)](image-url)
Vibrating tables

Dodbiba et al., (2003) describe a process for separation of plastics using a dry mechanical air tabling technique. The technique works by fluidising a vibrating table with air and separating two fractions of materials from each other using differences in specific gravity of the particles. This system is illustrated in Figure 4.21. Other air-based vibrating table separation processes found in the literature include those described by Lee and Rahimifard (2012b), this system uses air to fluidise a bed of granulated particles in order to achieve separation into two fractions based on density differences, as shown in Figure 4.22 and Figure 4.23.

Figure 4.21: Schematic of the air-table separation process (Dodbiba et al., 2003)

Figure 4.22: Vibrating air-table for footwear material recovery (Lee and Rahimifard, 2012b)
Figure 4.23: Vibrating air-table for footwear material recovery (Lee and Rahimifard, 2012b)

Air cascade

Other air based separation processes include cascading air separation, the work performed by (Lee and Rahimifard, 2012a) presents a cascading zig-zag separator (Figure 4.24) which uses friction to separate particles of different densities as well as a cascading air-pulse separator (Figure 4.25) both are effective at separating granulated footwear materials.

4.3.3.3 Tribo-electric post-fragmentation separation processes

Electrostatic separation is a general name applied to a group of material processing technologies. These technologies are commonly used for sorting granular mixes by applying electrical forces that are acting on charged or polarised particles. These technologies are effective methods for sorting mixing of particles with similar densities (Dodbiba et al., 2005) and mainly used for separation of dry particles.

From the literature, a few examples of these technologies were identified and were mainly used within plastic recycling systems. Work by (Tilmatine et al., 2009) presented three different electrostatic separators: a ‘roll-type’ electrostatic separator as shown in Figure 4.26 which was employed for recycling of electrical cable waste, a plate-type electrostatic separator and a ‘free-fall’ electrostatic separator as shown in Figure 4.27.
Figure 4.24: Cascading zig-zag separator principles (Lee and Rahimifard, 2012a)

Figure 4.25: Zig-zag and air-pulse cascading separators (Lee and Rahimifard, 2012b)
Figure 4.26: A lab-scale ‘roll-type’ electrostatic separator (Tilmatine et al., 2009)

Figure 4.27: A lab-scale ‘free-fall’ type electrostatic separator (Tilmatine et al., 2009)

Other examples of electrostatic separator include a system proposed by Dodibba et al., (2005), the authors present a ‘tri-bo-cyclone’ which is shown in Figure 4.28. The system was used to separate granulated and flaked plastics and achieved a high separation result of different plastic fractions.

Figure 4.28: Diagrammatic view of a tri-bo-cyclone electrostatic separator (Dodbiba et al., 2005)
4.4 Summary

The literature review presented within this chapter provides an essential understanding of traditional recycling systems and technologies including elements such as their physical structure, operational function and the materials they are designed to process.

It was found that these technologies can be categorised into pre-fragmentation separation, fragmentation and post-fragmentation separation technologies. The pre-fragmentation technologies separate waste streams into fractions before the waste is fragmented into smaller particles. The fragmentation technologies include all technologies which fragment waste streams to smaller sizes ready for further processing. The post-fragmentation separation technologies include all processes which separate waste streams after they have been reduced in size, this includes: air classification, dense media separation and optical sorting.

The review presented examples from across different sectors including industrial applications and academic research trials. Within each of these categories there is a lack of a strategic approach to the creation of recycling systems; they are primarily created in reaction to legislation or changing market factors such as increase in value of recycled materials. The review of literature shows that traditional recycling systems are dedicated, high-volume systems which produce materials that are generally of down-graded quality when compared with virgin materials, and these systems are poorly suited to the future challenges of recycling.

This leaves extensive scope for explorations into more systematic approaches to recycling, with further work to be done on improving the flexibility of recycling systems to improve the quality of the materials recovered.
CHAPTER 5  REVIEW OF MOST RELEVANT RESEARCH

5.1 Introduction

This chapter presents a summary of the literature that is most relevant to the research within this thesis. Having reviewed the wider literature, this chapter contains recent publications most closely related to the work contained within this thesis. The chapter is split into three key areas: footwear recycling, leather waste and recycling, and recycling cost modelling and product recovery, as illustrated in Figure 5.1.

5.2 Relevant literature on footwear recycling

This section presents a review of the literature related to footwear recycling that is most relevant to the work contained within this thesis. As mentioned in the introduction in Chapter 1, a decade of work has been completed on footwear recycling by researchers at the Centre for SMART at Loughborough University. The footwear industry is the largest commercial user of leather, and therefore this work is highly relevant to the research presented within this thesis; hence, it is reviewed in the following section.

Figure 5.1: Focussed literature review
Work by Lee and Rahimifard (2012a) presents an air-based automated material recycling system for post-consumer footwear products. Within this research they develop an economically feasible automated material recycling process for mixed postconsumer footwear waste. This includes the development of bespoke air-based separation technologies that separate granulated shoe particles based upon the difference in size and weight. The experimental study focuses on three different types of postconsumer footwear products and the results show that it is possible to reclaim four usable material streams: leathers, textiles, foams and rubbers from end-of-life footwear. This work has similarities to the work in this thesis because both evaluate post-fragmentation material separation techniques that can be applied to the material found within footwear.

In another paper, Lee and Rahimifard (2010) present the development of an economically sustainable recycling process for the footwear sector. Within this paper a four-step methodology is developed to create a ‘market driven’ material recycling approach for footwear. This work found that it is not currently economically feasible to obtain recycled materials from low value products such as footwear that can compete with virgin materials in the market place. They instead suggest using commercially available automated recycling technologies to achieve a more realistic level of material recycling for footwear. The work has similarities to the work within this thesis because both pieces of research focus on developing a cost model for recycling; however, the work by Lee and Rahimifard (2010) is focussed on optimising the amount of processing to maximise the return for the footwear industry only and does not extend to other industries which use leather.

## 5.3 Relevant literature on leather waste and recycling

This section presents a review of the literature related to leather recycling that is most relevant to the work contained within this thesis. Within the general review of the leather industry and leather recycling in Chapter three, the focus of the literature was on managing the waste from the early stages of leather production. This section will explore key pieces of research that focus on other elements of leather waste and recycling.

Work by Joseph and Nithya (2009) looks at material flows in the lifecycle of leather. This piece of work evaluates the environmental profile of leather and considers the solids wastes and emissions produced, and the resources used within the production of the material. The results indicate that the greatest contributors to the environmental impact of leather production are the tanning and finishing stages of leather production, the transportation of leather goods and the energy used in the production processes. This
research incorporates a material flow analysis which encompasses all materials used in the production of leather. This overlaps the work within this thesis; however, the two pieces of work differ because the material flow analysis within this thesis considers the solid leather wastes over more of the lifecycle.

Work by United Nations Industrial Development Organisation (UNIDO) looks at the mass balance in the leather industry, it presents a quantification of tannery wastes at all stages of tannery processing (UNIDO, 2000b). This work overlaps the work within this thesis because both present the results of a mass flow exercise for materials that exist throughout the tannery lifecycle; however, this thesis goes further and extends the mass balance exercise for leather waste across the entire lifecycle of leather.

UNIDO also did another piece of work on leather wastes and produced a report called ‘14th panel on leather wastes’ (UNIDO, 2000a). This report quantifies the wastes that are generated globally in different countries for different types of leather products. This has similarities to the waste mapping exercise that is presented within this thesis; however, the authors do not perform any kind of economic assessment of the proposed processing routes for leather waste and this differentiates it from the work within this thesis.

A report by (Ernst and Young, 2013) called: ‘Sustainability in the leather supply chain’ assesses the sustainability issues in the leather supply chain with a focus on the effects and relevant trade flows for companies in the Netherlands. The research is split into three stages, the first stage addresses the main trends and trade flows within the leather supply chain. The second stage outlines the global sustainability issues that can occur and describes the main processes used in the different phases of the supply chain. The third stage identifies which of the global sustainability issues occur in each of the ten selected countries.

Although this work is examining the wider sustainability issues surrounding the leather supply chain which has similarities with the work within this thesis, they focus on the upstream problems associated with leather, which differentiates the work from this research.
5.4 Relevant literature on cost modelling and product recovery

This section presents a review of the literature related to cost modelling for recycling and product recovery strategies that is most relevant to the work contained within this thesis.

Gregory et al., (2006) introduces a modelling framework for recycling processes. The framework determines operational and resource requirements for the recycling process by developing a process-based cost model that incorporates technical aspects of the recycling process and the incoming material stream composition. This paper describes a model of end-of-life electronics recycling that uses process-based cost modelling and value-based metrics to determine the economic and value-recovery effectiveness of a processing operation. This bears similarities to the work in this thesis as it models the impact of recycling processes on the economic effectiveness; however, it is different because the work in this literature only represents partial costing for a recycling system and the work within this thesis considers processing costs and all other costs associated with developing and operations a recycling system.

Upon review of the literature surrounding cost modelling, work by Dahmus et al., (2008) was found that presents a model which provides a tool for analysing the performance, both economic and environmental, of a range of architectural and contextual options for electronics recycling systems. This work overlaps with the work within this thesis because they present a modelling framework to project the economic performance of both existing and prospective recycling systems; they also consider collection, processing and system management costs. This work differs from the work within this thesis because they are focused on electronic waste not leather waste.

On further review of the literature, a paper by Meng et al., (2017) called ‘Multi-objective optimization decision-making of quality dependent product recovery for sustainability’ was identified. In this paper, the authors identified the optimal product recovery solution that balances the economic, societal and environmental performances for sustainability, through the development and validation of a quality-dependent multi-objective optimisation model. They assess the cost-benefit of dismantling automotive engines versus remanufacturing of the engines. Although this research has similarities to the research within this thesis because both pieces of work look at the development of a model to evaluate the cost of recovering products, the scope is different because the work of Meng et al., (2017) is focussed on the reuse of parts after recovery.
Work by Johnson and McCarthy (2014) in a paper entitled: Product recovery decisions within the context of Extended Producer Responsibility, focusses on assessing the best strategy for products recovered through extended producer responsibility schemes. They consider how organisations can evaluate the economic trade-offs between remanufacturing versus de-manufacturing alternatives for products that manufacturers are forced by legislation to recover. Similar to the work in this thesis, Johnson and McCarthy (2014) create an economic model that helps to support decisions about material recycling and product recovery. However, the two pieces of work differ because the economic evaluations within this thesis are solely focussed on material recycling, whereas the work in the literature supports comparisons between remanufacturing and recycling activities.

5.5 Summary

This chapter presented a summary of the previous literature in five key areas that is most relevant to the work within this thesis. The chapter began by giving and overview of the key areas before moving on to examine literature in each area separately. Each section detailed the work done in the literature reviewed and how it is relevant to this thesis and what differentiates it from the work contained within this thesis. This chapter represents the final review chapter, and Chapter Six will outline the methodology that will be used for the research contained within this thesis.
CHAPTER 6 METHODOLOGY

6.1 Introduction

This chapter provides a description of the methodology used whilst undertaking the research presented in this thesis. Common research methodologies are presented at the start of the chapter and the principal attributes of each are discussed. This is then used as a guide to help formulate and justify the methodology for the current research reported in this thesis, which is presented at the end of this chapter.

6.2 Overview of research types

Many different types of research exist and research types can be categorised by the kind of research methodology used which in turn is dependent on the type of data to be collected and processed (Walliman, 2005). Historically the dichotomy of qualitative and quantitative research has been the most commonly used system for categorising research methodologies. These categorisations work well for research projects which involve either quantitative or qualitative data types. However, there are vast amounts of research carried out that uses both qualitative and quantitative data types and hence a more suitable ‘mixed-methods’ research design system is required for these projects.

Mixed-methods research involves investigations where a researcher or team of researchers uses a combination of qualitative and quantitative research approaches. This mixed approach helps to provide a better understanding of the research problem than using a singular method would.

The research problems that mixed-methods are most suitable for are those in which exploratory investigations need to be generalised, a primary method is best enhanced by using a secondary method and the overall research objective could be best met with multiple research phases (Creswell and Plano-Clark, 2011).

There are four key questions to ask when choosing a mixed-methods design, these are illustrated in Figure 6.1.
When answers to the four key questions in Figure 6.1 are known, then an appropriate mixed-methods research design can be selected.

There are four major categories of mixed method research design (Creswell and Plano-Clark, 2011), and these are:

- Triangulation Design
- Explanatory Sequential Design
- Exploratory Sequential Design
- Embedded Design

Each type of design has different characteristics and is used in different circumstances, with different types of data to be gathered. A description of each research methodology is given in the next section along with benefits and limitations of each.
6.2.1 Triangulation Design

Triangulation design is the most common and well-known approach for mixing methods, its purpose is to “obtain different but complementary data on the same topic” (Morse, 1991).

The intent with this type of mixed method design is to bring together non-overlapping strengths and weaknesses from a range of quantitative methods with those of qualitative methods. When researchers want to compare and contrast qualitative data with quantitative statistical results then this type of design is used.

The benefits of this type of research design is that each type of data can be separately collected and analysed using the techniques that suit the respective data types. This allows for a research team to be assembled with competencies in analysed both types of data. Another benefit is that this is an efficient design for research because both types of data can be collected at the same time.

The challenges associated with this type of research include situations where the two types of data disagree or contradict each other, these differences can be challenging to resolve and may necessitate extra data collection and analysis. It can also be challenging to integrate two very different types of data and their results in a meaningful way.

6.2.2 Explanatory Sequential Design

Explanatory design is a two-stage mixed-methods design in which initial quantitative results are built upon by qualitative data.

This type of research design is helpful when a researcher needs to explain significant, surprising or outlying quantitative results by providing extra qualitative data.

Explanatory design is the most straightforward of the mixed-methods and this is the greatest benefit. It also lends itself to greater delineation within the research report because the work can be clearly split into two phases.

The drawbacks of this method are that a long period of time is required to implement the two phases of work and the researcher may be required to draw subjects from two different populations for the different phases of the work, leading to a requirement for a large research population.
6.2.3 Exploratory Sequential Design

Exploratory Design is like the Explanatory Design method, they both use the results of the first phase to help develop the second phase, except in this case, the results from the qualitative phase help to develop the second quantitative phase.

This design is best used to explore a phenomenon, where exploration is needed because measures of instruments are not available, and variables are unknown. Exploratory Design shares many advantages with the Exploratory Design method; only one type of data is collected at a time and makes the design easy to implement, describe and report.

The added advantage is that this design is easy to apply to both multiphase and single research studies. It is difficult to specify the methodology for the quantitative phase before undertaking the qualitative phase; this makes project planning more difficult. Time needed to implement the two separate phases of this design can be one of the most challenging aspects.

6.2.4 Embedded Design

Within Embedded Design, a study based primarily on one data type is supported by the other data type that plays a secondary role. The premise is that one data type is not sufficient to answer all the research questions and that another data type is required. In studies that are largely quantitative qualitative data will provide support and the reverse is also true.

This design can be used when there is not enough time to dedicate to extensive quantitative and qualitative data collection and where one data type is given priority over the other, this is the greatest advantage of this method.

The drawback with Embedded Design is that integration of the results when two methods are used to answer two different questions is challenging, additionally it can be challenging to specify the purpose of collecting the lower priority data.

The attributes of each method are summarised in Figure 6.2.
1. Triangulation Design
   - Researcher uses concurrent timing to implement quantitative and qualitative strands
   - Researcher prioritises strands equally and keeps them independent during analysis
   - The researcher mixes the results of the two strands during final interpretation

   Qualitative data collection and analysis
   Compare or relate
   Interpretation
   Quantitative data collection and analysis

2. Explanatory Sequential Design
   - Researcher implements two distinct interactive phases of qualitative and quantitative work
   - The first phase of the research consists of quantitative data collection and analysis
   - Researcher interprets the secondary qualitative results to help explain the initial quantitative results
   - The priority can be placed on either the qualitative or quantitative phase

   Quantitative data collection and analysis
   Builds to
   Qualitative data collection and analysis
   Interpretation

3. Exploratory Sequential Design
   - The researcher implements two distinct interactive phases of qualitative and quantitative work
   - The first phase of the research consists of qualitative data collection and analysis
   - The researcher conducts a second quantitative phase to test or generalise the initial qualitative findings
   - The priority can be placed on either the qualitative or quantitative phase

   Qualitative data collection and analysis
   Builds to
   Quantitative data collection and analysis
   Interpretation

4. Embedded Design
   - The researcher collects and analyses both quantitative and qualitative data within a traditional design, adding a supplemental qualitative strand to a quantitative design or a quantitative strand to a qualitative design
   - The supplemental strand is added to enhance the overall design of the research

   Principal study either qualitative or quantitative
   Embedded qualitative or quantitative study

Figure 6.2: Four primary categories of mixed-methods research design
6.3 Research methodology

In review of the research objectives in Chapter 2, it has been identified that both qualitative and quantitative data will be collected and analysed during this research. Therefore, to best meet the objectives of the research, it is necessary to use a mixed-methods research design with multiple phases to effectively capture, analyse and combine both qualitative and quantitative data which is required for this research.

6.3.1 Research methodology selection

To select the most suitable mixed-methods design for the research, it is necessary to apply the questions from Section 6.2 to the research aims and objectives from Chapter 2. On application of these questions, it has been identified that this work incorporates primarily qualitative data in the first instance, which is then used to build a quantitative understanding of the research problem. For this reason, an ‘Exploratory Sequential’ mixed-methods research design is used within this research.

Two variants of Exploratory Sequential design exist and they are called: Theory development variant and Instrument-development variant (Creswell and Plano-Clark, 2011). Within the Theory-development variant the emphasis of the research is placed in the initial qualitative phase, and with the Instrument-development variant the emphasis lies in the latter quantitative phase, as outlined in Figure 6.3. This thesis will follow the Instrument-development variant of the mixed-methods research design and a more detailed explanation of why this method is suitable is presented in the next section.

Figure 6.3: Theory-development and Instrument-development research emphasis
6.3.2 Research methodology application

The Instrument-Development variant of the Exploratory Sequential Design is the most suitable for application to this research because, by definition, the initial phase of the Instrument-Development variant plays a secondary role within the research project and is often used for gathering information to build a quantitative instrument for the second phase of the research, which aligns with the intentions for this research.

The four-stage research methodology used in the thesis is outlined in Figure 6.4. It begins with the definition of the research questions and the formation of preliminary objectives assisted by primary exploratory research. The next stage is the theoretical development of a framework and research model and following this the testing and validation of the theoretical work through case study applications. The final stage of the research methodology includes the analysis of the research results and the formation of conclusions.

The author of this research has prior knowledge and experience of recycling systems and waste management requirements for leather waste which helped to define the initial research questions. The prior knowledge is built upon and developed by conducting an extensive review of both academic and industrial literature regarding the management of leather waste and the technology for waste management.

The author of this research also undertook a number of visits to a range of industrial partners, including: tanneries, manufacturers, distributors and retailers of leather products. The visits provided an opportunity to collect qualitative data about the types of waste that is generated. The visits allowed for exploratory conversations to understand the industrial challenges surrounding leather waste and potential technological solutions for processing leather materials and leather wastes.

Once the initial discussions and visits were over, initial aims and objectives for the research were set. The results from the qualitative data gathered during the exploratory research and information gained from the literature review helped to develop the second, quantitative, phase of the research. Before the quantitative phase was developed, the information from the initial exploratory phase was used to further refine the aims and objectives of the research, as shown in Figure 6.4.
Figure 6.4: Research methodology applied within the thesis
The next phase of the research builds on the initial qualitative data collection and focusses on the development of a framework with three core elements: waste-flow mapping and characterisation; collection and processing strategies; and the development of an economic decision-support tool. The waste-flow mapping involved the collection of quantitative and qualitative data, the recycling and processing investigations involved the collection of qualitative data and the two were combined to form a quantitative tool to support economic decisions associated with the implementation of a circular approach within the leather industry.

Phase three of the research involves the quantitative validation of the research through the application of the framework to case studies. The case studies will assess the viability of different economic scenarios. A systematic approach will be developed to conduct both case studies, with data to use within the studies to be collected from a variety of primary and secondary sources.

The fourth and final phase of the research methodology is the analysis and interpretation of the research findings and the drawing of overall conclusions from all available research data. On the completion of the research, areas of expansion for the current research are identified to provide scope for future projects to build on this work.

6.4 Summary

This chapter identified different types of mixed-methods research methodologies and detailed the key distinctions between them. A detailed description of the four phases of the research methodology was then presented and the most suitable methodology for the work in this thesis was selected. The application of this research methodology to the author’s research was presented along with a flow chart which illustrates the sequential development of the thesis and how the methodology applies to each section.

The review in Chapters 1-5 of the thesis evolved from the first exploratory phase of the research methodology, and the remainder of thesis addresses the framework development, testing and validation and evaluation phases.
CHAPTER 7 FRAMEWORK FOR THE IMPLEMENTATION OF A CIRCULAR APPROACH WITHIN THE LEATHER INDUSTRY

7.1 Introduction

In this chapter, a framework for establishing a circular approach in the leather industry is developed. To begin with, the philosophy upon which the framework is built is presented, after which the four-stage framework is presented in its entirety. This is followed by more in-depth discussions about the individual stages of the framework. The chapter concludes with a discussion about the application of the framework and any perceived limitations it has.

7.2 Circular approach to managing leather waste

To meet the objectives of this research set out in Chapter 2 of this thesis, a framework was developed, and it has been given the name: The Circular Approach within the Leather Industry (CAL) framework. It is built upon the fundamental principles of the circular manufacturing concept: promoting resource productivity and reduction of waste. The circular manufacturing concept aims to create systems in which technical materials are designed to circulate at high quality in production cycles without being disposed of as waste. This is in contrast to a linear manufacturing system which is a 'take, make, dispose' model of production. The contrast between the traditional manufacturing approach and the circular manufacturing approach is illustrated in Figure 2.1.

The circular manufacturing approach advocates a proactive approach to designing out waste; however, this is not yet a possibility within the leather industry. Therefore, it is important to note that the framework within this thesis represents a ‘reactive approach’ to managing leather waste. It is intended that the reactive approach will inform any future measures that are designed to proactively eliminate leather waste.

7.3 The CAL framework

The CAL framework has been developed to support the implementation of a circular approach in the leather industry. This framework has three aims: To identify the key challenges associated with developing a leather recycling system; to define several practical scenarios for implementing a leather recycling solution; and lastly, to develop a model for
assessing the economic viability of leather recycling solutions. The framework is comprised of four distinct stages: waste-flow mapping and characterisation, defining collection methods and strategies for recovering leather waste, evaluating technologies for processing leather waste and developing a cost model for evaluating the economic viability. An overview of the framework is provided in Figure 7.1.

The first stage within the framework investigates the leather waste problem across the lifecycle of the material and provides a detailed definition of it, with the aim of fully understanding the key problems and opportunities associated with managing this waste. This stage involves mapping and characterisation (both quantitative and qualitative) of the leather waste streams at all stages in the material and product lifecycle.

During the second stage of the framework, two waste grouping strategies are defined and the benefits and limitations of both are discussed. The strategies are based on the need to improve the quality and quantity of the recovered leather waste streams across the lifecycle. This stage also investigates methods for the collection of leather waste across the lifecycle.

<table>
<thead>
<tr>
<th>CAL FRAMEWORK</th>
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<tbody>
<tr>
<td><strong>Stage 1: Waste-flow mapping and characterisation</strong></td>
<td><strong>Mapping &amp; characterisation</strong></td>
</tr>
<tr>
<td>Characterisation of leather waste across lifecycle in terms of the qualitative and quantitative characteristics.</td>
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<tr>
<td><strong>Stage 2: Collection methods and waste grouping strategies</strong></td>
<td><strong>Collection and grouping</strong></td>
</tr>
<tr>
<td>Definition of collection methods and waste grouping strategies for recovery of leather waste.</td>
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<tr>
<td><strong>Stage 3: Material recovery technologies and processing</strong></td>
<td><strong>Technology and processing</strong></td>
</tr>
<tr>
<td>Evaluation of end-of-life processes, including sorting, recycling technologies and redistribution of recycled materials.</td>
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<tr>
<td><strong>Stage 4: Cost modelling and implementation strategies</strong></td>
<td><strong>Economic Evaluation</strong></td>
</tr>
<tr>
<td>Development of a model to support economic decisions for implementing a circular approach in the leather industry.</td>
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Figure 7.1: The four stages in the CAL framework
During the third stage of the framework, technologies for recycling of leather waste materials and products are evaluated for suitability. Waste characteristics are matched with attributes of processing technologies to identify which technologies would be required to recover leather from mixed waste streams.

During the fourth stage of the CAL framework, a cost model is developed, and flexible business strategies are discussed. A series of business strategies that could be applicable in a circular manufacturing approach are explored and defined and the benefits and limitations are evaluated. The cost model evaluates the economic viability of implementing a circular approach in the leather industry. The cost model is then applied to two case studies to validate and evaluate the effectiveness of the research concepts and methodologies. The economic decision-support tool used in in fourth stage of the research evaluates short-term, reactive approaches to leather waste management (as justified in Section 7.2). However, the knowledge generated during the third stage of the research can be used as a foundation upon which a long-term, proactive solution can be built to encourage more sustainable product design and material choices during the manufacture of leather goods. The following sections describe each stage of the framework in greater detail.

### 7.3.1 Stage 1 – Waste-flow mapping and characterisation

The first stage of the framework involves the mapping and characterisation of the waste streams that are generated across the lifecycle of leather, as illustrated in Figure 7.2.

In order to quantitively map the leather waste several methods were reviewed including: waste stream modeling, Materials Flow Analysis (MFA) and life-cycle assessment. Upon review of these methods, MFA was deemed to be the most suitable for mapping the quantities of leather waste across the lifecycle.

MFA has two fundamental principles: a systems approach and mass balance. It often covers the entire lifecycle including: mining, production, manufacturing, use and is a systematic, descriptive approach to assessing the metabolism of a defined system (Brunner and Rechberger, 2004). MFA has been applied widely to support solid waste management decision making and devise strategies for material flow management (Turner et al., 2016).

MFA differs from other industrial ecology methods such as life-cycle assessment and Input-Output (I/O) models through the data requirements, purpose and scope.
When comparing MFA to I/O analysis the differences are evident. The number of processes considered in I/O analysis are much higher than in MFA and flow of by-products or waste are often not included in I/O studies due to their lack of economic value. MFA are usually centered on one material used across different products, while Life-cycle Assessment captures the demand for multiple materials across several products.

The other industrial ecology approaches do have some similarities to MFA, the overlaps include the mass balance principle and the systems approach. Full Materials Flow Analysis for vertical and horizontal leather waste were performed within the research and the boundaries and mass balance are fully detailed in Chapter 8.

In order to map the qualitative characteristics of the leather waste streams across lifecycle it was necessary to define the waste in terms of the technical and operational characteristics. Technical characteristics are those defined principally by the product design and product assembly choices, while operational characteristics are those defined by external influences, such as geographical distribution of waste. The characteristics of the leather waste streams which are considered relevant to the development and evaluation of
a leather waste recycling solution are described in Table 7.1 and are considered within Stage 1 of the CAL framework.

The characteristics of the leather waste can be identified by characterisation of existing leather waste streams from various points throughout the material and product lifecycles. This enables the principal attributes of the waste to be established and will identify the most-common material mixes found within products containing leather.

Table 7.1: Technical and operational characteristics of leather waste streams

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Relevance to recycling solution for leather waste</th>
<th>Class</th>
</tr>
</thead>
</table>
| Weight         | • Influences the suitability of recycling process selection; some recycling technologies use air or vibration for separation which makes it important to carefully match the weight of the materials to the appropriate technology  
• Weight has influence on transportation requirements; heavier materials will require different types of vehicle to transport them. | Technical |
| Density        | • Density influences the suitability of recycling process selection; processes that separate materials based on density will require the input materials to have specific range of density in order to perform the separation correctly  
• Density has influence on transportation requirements; 1 tonne of foam will require a much greater volume of space to be transported than 1 tonne of rubber due to the different in density of the materials | Technical |
| Geometry       | • Influences the suitability of recycling process selection. For example, shredding is more suitable for large pieces of waste leather, for geometrically smaller more compact waste streams, granulation is more appropriate. | Technical |
| Leather purity | • Influences economics of waste processing. This is because purer materials will command a higher price on the secondary materials market due to the lower level of contamination from other materials.  
• Influences the configuration of the recycling process line because purer streams of leather will require less processing in order to separate out the contaminant materials. | Technical |
| Quality/condition of leather waste | • Influences the amount of sorting required before the material can be recovered via the recycling line. Waste materials that have a higher level of soiling or damage will require a greater level of sorting to determine whether or not the materials are suitable to be processed by a recycling line. | Operational |
| Geographic distribution of waste generated | • Influences the costs of collection and the waste collection strategy. If the materials are further apart geographically then the costs of collection will be higher due to the high level of fuel required to collect them.  
• Determines transport requirements. If the materials are collected within a supermarket recycling bank environment the most appropriate transport for collection may be a single haulage lorry capable of lifting the banks. If the materials are spread further afield and collected from households, then having more but smaller collection vans may be a more appropriate form of transport. | Operational |
7.3.2 Stage 2 – Collection methods and waste grouping strategies

The second stage in the CAL framework defines collection methods and develops waste grouping strategies that could assist the implementation of a circular approach within the leather industry, as shown in Figure 7.3. This stage of the framework begins with the identification of collection methods for leather waste across the lifecycle and then goes on to develop two waste grouping strategies. These strategies are developed based on the need to increase the quality and quantity of recycled materials, which will in turn increase the economic viability of a leather recycling system.

![CAL FRAMEWORK Diagram](image_url)

- **Stage 1: Waste-flow mapping and characterisation**
  - Characterisation of leather waste across lifecycle in terms of the qualitative and quantitative characteristics.

- **Stage 2: Collection methods and waste grouping strategies**
  - **i) Identification of collection methods for leather waste**
  - **ii) Definition of waste grouping strategies for leather waste**
    - Waste grouping strategy 1
    - Waste grouping strategy 2
    - To increase quality of recovered materials
    - To increase quantity of recycled materials

- **Stage 3: Material recovery technologies and processing**
  - Evaluation of end-of-life processes, including sorting, recycling technologies and redistribution of recycled materials.

- **Stage 4: Cost modelling and implementation strategies**
  - Development of a model to support economic decisions for implementing a circular approach in the leather industry.

Figure 7.3: Stage 2 of the CAL framework
7.3.3 Stage 3 – Material recovery technologies and processing strategies

To develop a circular approach within the leather industry, it is vital to evaluate the recycling technologies which could be implemented to recover leather material from waste. During Stage 3 of the framework a detailed examination of typical material content of leather waste and products will be presented. Within this examination, material characteristics will be outlined and linked to the attributes of end-of-life technologies, this stage is illustrated in Figure 7.4.

Figure 7.4: Stage 3 of the CAL framework
7.3.4 Stage 4 – Cost modelling and implementation strategies

The final stage of the framework evaluates the economic viability of implementing a circular approach by developing a cost model; this stage is illustrated in Figure 7.5. The first task within this stage of the framework is to define how the cost model can help to support decisions associated with leather recycling systems. Decision-making fundamentals are discussed in the next section.

![CAL FRAMEWORK](image)

**Figure 7.5: Stage 4 of the CAL framework**
7.3.4.1 Decision-making fundamentals

Decision-making occurs across all stages of the development cycle of a recycling system (see Figure 7.6).

![Influential factors in decision-making](image)

Figure 7.6: Factors which influence decisions about the development of recycling systems

Decisions about recycling systems generally revolve around the assessment of the effectiveness of a system within three key categories: economic, technical and environmental (Colledani et al., 2014). There are many definitions of what an ‘effective’ recycling system looks like, for example:

- The system is economically viable e.g. process pays for itself
- The system is technologically feasible e.g. system can achieve desired material recovery targets
- The system is environmentally sustainable e.g. system has an acceptable level of environmental impact

These are just a few examples of what ‘effective’ means within the three key categories. The designers of recycling systems may take all three of the key factors into account before they develop a system, or they may only choose to focus on a few of the factors, this means that each stakeholder has a unique perspective on the decisions that need to be made about recycling systems. The number of decision factors that are considered is dependent upon which stakeholder is creating the recycling system (manufacturer, recycling company or tannery) and at which point in the lifecycle this stakeholder holds the most interest (e.g. pre-production, post-consumer or production stages).

It is important to consider whether decisions are made proactively or reactively, this heavily influences decisions in the three key areas. Proactive decisions are made at the beginning of a product’s lifecycle; they are decisions that help to plan recycling and recovery systems for products that have yet to be created. Reactive decisions are made after waste has...
already been produced, recycling systems are then created to deal with this waste and recover material. Both approaches to decision-making have an influence on the way that decisions are made. As discussed in Section 7.2, the work within this thesis focusses mainly on reactive recycling solutions which deal with waste that is already being produced, therefore only reactive decisions will be considered within this chapter. The interconnectedness of stakeholder motivations with the decisions that they are making about the economics of the recycling system is further explored in Chapter 10. Understanding these decisions provides a basis for developing a cost-model to support them.

The second task in developing a cost-model is to economically evaluate the chosen recycling systems. For this purpose, it is necessary to have a tested, verifiable and repeatable method for economic evaluation of alternative scenarios. Throughout the development of the framework several methods we reviewed, these include:

- Cost effectiveness analysis
- Cost benefit analysis

Cost-effectiveness analysis (CEA) is a method of economic analysis which compares the outcomes and costs of two or more alternative course of action (Levin, 1983). It is often used where it is not always appropriate to monetise the outcomes of a project, for instance, in health services. It has been applied in other fields such as environmental policies (Dissou, 2005; Goulder et al., 1999) and recycling initiatives (Gradus et al., 2016; Lund, 1990; Deyle and Schade, 1991; Tonjes and Mallikarjun, 2013).

Cost-Benefit Analysis is an approach which evaluates the economic strengths and weaknesses of alternative scenarios, decisions or policies.

The two main purposes of CBA are:

1. To provide a method of comparing projects by evaluating the total expected benefits against total expected costs.
2. To evaluate whether an investment is sound and whether the benefits of the investment outweigh the costs

Cost benefit analysis proceeds in four essential steps:

1. Identification of relevant costs and benefits
2. Measurement of costs and benefits
3. Comparison of cost and benefit streams
4. Project selection

During the measurement of costs and benefits tangible elements of a project, such as land, labour and capital equipment must be priced, and values must also be generated for other categories of costs and benefits for which no price information exists (Tevfik, 1996).

CBA differs from cost-effectiveness analysis because in the CBA method, benefits and costs are expressed in monetary terms and this is not always the case with cost-effectiveness analysis.

Cost-Benefit Analysis was selected as the most suitable foundation for the economic evaluation within this thesis due to its ability to verify whether investment outweighs the cost of a system and its ability to compare two alternative projects on an economic basis.

The CBA incorporates all costs associated with creating and operating a leather recycling system, including: the variable costs of collecting the waste and processing it; and the fixed costs including: the purchase of capital equipment to establish the recycling system. The CBA also considers the influences of the waste characteristics, the waste collection strategies and the processing technologies on the cost of implementation. Further detail about the CBA is provided in Chapter 10.

7.4 Summary

This chapter introduced the four-stage CAL framework and discussed each of the stages. At the beginning of the chapter the circular manufacturing approach to managing waste is introduced as the basis for the CAL framework. Each stage of the CAL framework: Mapping & characterisation; collection and grouping; technology and processing and economic evaluation are then discussed in detail. Finally, the fundamentals of decision making are discussed as the basis for the cost model stage of the framework.

The first stage of the framework, in which the leather waste across lifecycle is characterised in terms of technical and operational characteristics, is explored in detail in the following chapter. Chapter 9 contains the research which supports Stages 2 and 3 of the CAL framework. It defines collection methods and waste grouping strategies for leather waste and defines two processing scenarios for end-of-life leather waste along with an evaluation of redistribution methods for the recovered materials. Chapter 10 presents Stage 4 of the
CAL framework in which a cost model is developed which supports economic decisions associated with implementing a circular approach in the leather industry. Finally, Chapter 11 documents the application of the research concepts and tools in two case study scenarios.
CHAPTER 8  WASTE-FLOW MAPPING AND CHARACTERISATION OF LEATHER WASTE

8.1 Introduction

This chapter describes Stage 1 of the CAL framework, which aims to investigate the leather waste problem across the lifecycle of the material. This is to provide an understanding of the key problems and opportunities associated with managing this waste. This stage involves mapping and characterisation, based on quantitative and qualitative methods (of the leather waste streams) during all stages in the material and product lifecycle.

8.1.1 Waste-flow mapping and waste characterisation

In Chapter 7 methods for mapping leather waste were described and the most suitable one was selected, this was: Materials Flow Analysis (MFA). This first part of this chapter describes the two MFA’s that were performed to map the leather waste both horizontally and vertically. The second part of the chapter presents the work that was done to characterise the leather waste across the lifecycle. The methods used to map and characterise the waste are illustrated in Figure 8.1.

![Figure 8.1: Structure of Chapter 8](image-url)
The key waste characteristics identified from the analysis in this chapter are used as input into Stage 2 of the CAL framework, where the influence of these characteristics on the selection of individual recycling technologies will be evaluated.

To map the waste associated with a material or product and perform the MFA, it is important to first understand the stages in the material or product lifecycle and what happens to this material or product from the beginning to the end of its life, this will help to define the system that is under study within the MFA. The lifecycle stages that leather material and leather products pass through are presented in the next section and the ‘chain’ of accompanying wastes at each stage in the lifecycle is also described. A more detailed analysis of the technical and operational characteristics of the waste within the horizontal and vertical concepts will be further developed in Section 8.3.

8.1.2 Lifecycle stages of leather

The key lifecycle stages during the manufacturing and distribution of leather material and leather products include: tannery processing; the use of leather material to manufacture leather products; the distribution and retailing of leather products; the consumer use phase and the post-consumer disposal stage, as illustrated in Figure 1.1.

During the tannery stage, three fundamental sub-processes are present (these stages are presented in further detail in Section 8.2.1.1):

1. Pre-tanning Operations (Beam-house Operations)
2. Tanning Operations
3. Wet-Finishing Operations

These operations take raw animal skins and convert them to leather hides. At this stage, it is important to emphasise that there is a distinct difference between an animal skin and a leather hide. An animal skin is still putrescible and will biologically decompose (skins are found at the pre-tanning stage) and a tanned hide is processed specifically to avoid the decomposition process.
The first point at which a skin is fully converted to a leather hide is at the ‘wet blue’ stage during the tanning operations phase; the blue colour of the material indicates the presence of chromium (when chrome is used as the tanning agent). Any wastes associated with the processing of animal skin before it is converted to a leather hide (i.e. before the wet-blue stage) are not considered in this thesis.

During the manufacturing stage leather hides are converted into products through a series of processes that typically consists of:

- Receive the finished leather hides
- Selection and quality check of leather hides
- Cutting and sizing of the hides
- Joining of leather to other materials/incorporation of leather into product
- Product samples and prototypes produced and tested

During the distribution and retail stages, leather goods are shipped to a network of retailers so that consumers can purchase them. When the consumer has a leather product which has reached the end of its life through wear and tear or because it is no longer wanted, the consumer needs to dispose of this item and this is called the post-consumer stage. The most common method of disposing of end-of-life leather goods is to put them into general waste streams. These waste streams are typically sent to incineration plants or landfill sites. Now that the lifecycle stages have been identified, it is possible to use this knowledge for the mapping and characterisation phase of the work. Section 8.2.2 and Section 8.2.3 present the horizontal and vertical waste-flow mapping respectively, and Section 8.3 presents the characterisation of the waste across the lifecycle.

### 8.1.3 Horizontal and vertical waste-flow mapping concepts

During the early stages of the research and during the many conversations with industrial partners, it became clear that the interest in leather waste can be envisaged in several different ways. Table 8.1 provides an overview the range of viewpoints that companies take when considering leather waste.
Table 8.1: Industrialist viewpoints about leather waste

<table>
<thead>
<tr>
<th></th>
<th>One stage of lifecycle</th>
<th>Whole lifecycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Own waste/ waste of one company</td>
<td>Interested in the leather waste produced at a single point in supply chain e.g.</td>
<td>Interested in the leather waste produced across the whole supply chain of</td>
</tr>
<tr>
<td></td>
<td>cutting operations during manufacturing</td>
<td>one company</td>
</tr>
<tr>
<td>Waste across all leather</td>
<td>Interested in the leather waste produced across all industries at one stage in the</td>
<td>Interested in the leather waste produced across the whole lifecycle by all</td>
</tr>
<tr>
<td>industries</td>
<td>lifecycle e.g. post-consumer leather waste</td>
<td>industries</td>
</tr>
</tbody>
</table>

Several companies are only interested in their own leather waste streams, either at one specific point in their supply chain or across the entire lifecycle of their products. Other companies show a more systemic interest in leather waste, they are interested not only in their own waste but also the waste of other companies. This systemic interest is either based across the entire leather industry and all stages of the lifecycle, or focussed at one point in the supply chain, for example, post-consumer leather waste across all leather product sectors. The complexity of the viewpoints about leather waste varies markedly; clearly to consider all leather waste across all industries is significantly more complex than considering waste from one lifecycle stage within one company.

The conversations with industrialists and subsequent discoveries about differing viewpoints led to dichotomous concepts for mapping of the waste, referred to as ‘horizontal waste’ and ‘vertical waste’ (see Figure 8.2).
The term ‘vertical waste’ encompasses the waste streams that are produced by processes that occur across the whole lifecycle of leather including tannery waste, manufacturing waste, distribution waste and post-consumer waste. The term ‘horizontal waste’ groups the leather waste in a different way, it considers the waste at a point in the lifecycle and groups waste across product sectors at that stage. For instance, if the post-consumer stage is selected as the primary lifecycle point at which to assess the waste, the vertical waste associated with this stage encompasses all leather goods at the end of their lives, including: footwear, furniture, apparel, vehicle interiors, leather car seats and luxury leather goods including: handbags, suitcases and mobile phone covers.
CHAPTER 8

8.2 Waste-flow mapping (MFA)

To get a full understanding of the waste that exists across the leather lifecycle it is necessary to map the quantity of leather waste at each stage in the lifecycle. Section 8.2.1 and 8.2.2 present the quantification of the vertical and horizontal wastes respectively.

8.2.1 Vertical waste-flow mapping (MFA)

Within this section, the quantity of waste generated across the vertical lifecycle of leather is identified and analysed and a mass balance exercise of leather waste is performed. From the literature review in Chapter 3, it was discovered that according to The World Bank (1999), up to 70% of the wet weight of the original leather hides can be wasted over the course of the lifecycle. This data requires further investigation to discover the exact quantitative breakdown of waste at specific lifecycle points.

The composition of the waste at individual points in the lifecycle depends on multiple factors and collectively these individual waste streams make up the ‘waste chain’ associated with the material. Figure 8.3 gives an overview of the ‘waste chain’ associated with the lifecycle of leather, it highlights the key sub-sections of the lifecycle at which waste is produced and highlights the need for more data collection and further investigation.

Within each of the four key sub-sections of the lifecycle there are various processes that occur and various waste streams that are produced. Each of the four sub-sections is explored in more detail within this part of the thesis and flowcharts that describe the processes and material streams within each of these sub-sections are outlined and analysed.

Figure 8.3: The leather waste chain and the key waste generating stages
To perform a more detailed analysis on the vertical waste streams, an investigation was carried out to find relevant data that could quantify the waste produced at each of the four key stages in the lifecycle. Figures were obtained from the report entitled ‘Mass balance in leather processing industries’ (UNIDO, 2000b). This report contains an overview of the waste practices of the entire leather industry on a global scale. The report provides data on types of waste that are typically generated throughout all tannery and manufacturing processes (such as cutting operations). Notably, this report did not contain any data relating to waste generated at the product distribution stage or at the post-consumer disposal stage. Other methods used to represent the waste quantity at these stages are discussed in Section 8.2.1.3.

8.2.1.1 Quantification of tannery waste (Mass balance)

Within the tannery stage there are three key stages after the ‘wet blue’ stage that produce leather-based waste, namely: tanning; post tanning (Contains two parallel streams of grain and split leather material) and Finishing (Contains two parallel streams of grain and split leather material).

Data about the mass of wastes produced at these stages were identified from flow charts and tables contained within the (UNIDO, 2000b) report. Figures 8.4 to 8.6 provide the process flowcharts and Tables 8.2 to 8.6 provide quantitative mass balance data on the inputs and outputs to a typical tanning, post-tanning and finishing process for both grain and split leather materials. The red outlined boxes in these tables indicate the specific data that are of interest for the vertical waste-flow mapping.

It is important to note that data related to the production of leather is often quoted in one of two ways: either in terms of the weight of leather produced (in tonnes or kg), or in terms of the area of leather produced (the amount of leather in square metres, m²). The mass balance data contained within the (UNIDO, 2000b) report only contains details about the weight of leather at each stage in the production.

Therefore, to provide consistency throughout this thesis, the data regarding leather production and leather waste will only be quantified in terms of the weight in metric tonnes or kilograms.
Table 8.2: Mass balance of the tanning process (UNIDO, 2000b)

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>INPUT (kg)</th>
<th>OUTPUT (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelts</td>
<td>1100</td>
<td>0</td>
</tr>
<tr>
<td>Process water</td>
<td>1300</td>
<td>0</td>
</tr>
<tr>
<td>Effluent</td>
<td>0</td>
<td>1650</td>
</tr>
<tr>
<td>NaCl</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>H2SO4/HCOOH</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Chrome extract (25% Cr2O3)</td>
<td>88</td>
<td>62</td>
</tr>
<tr>
<td>MgO/NaHCO3</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Reaction salts</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Grain leather (wet blue)</td>
<td>0</td>
<td>262</td>
</tr>
<tr>
<td>Split leather (wet blue)</td>
<td>0</td>
<td>88</td>
</tr>
<tr>
<td>Unusable split</td>
<td>0</td>
<td>107</td>
</tr>
<tr>
<td>Trimmings</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Shavings</td>
<td>0</td>
<td>99</td>
</tr>
<tr>
<td>Sammying water</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>2562</strong></td>
<td><strong>2562</strong></td>
</tr>
</tbody>
</table>
Table 8.3: Mass balance of post-tanning process for wet-blue grain leather (UNIDO, 2000b)

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>INPUT</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain leather wet blue (50% H2O)</td>
<td>262</td>
<td>0</td>
</tr>
<tr>
<td>Process water</td>
<td>4400</td>
<td>0</td>
</tr>
<tr>
<td>Effluent</td>
<td>0</td>
<td>4400</td>
</tr>
<tr>
<td>Vacuum drying water</td>
<td>0</td>
<td>104</td>
</tr>
<tr>
<td>NaHCO3/HCOONa</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Chrome extract (25% Cr2O3)</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Organic tannins</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>Fatliquors</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>Dyestuffs</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Acids</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Leather waste (fibres)</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Grain leather crust (14% H2O)</td>
<td>0</td>
<td>190</td>
</tr>
<tr>
<td>TOTAL</td>
<td>4726</td>
<td>4726</td>
</tr>
</tbody>
</table>
Figure 8.5: Post-tanning work of wet-blue grain leather and split (UNIDO, 2000b)
Table 8.4: Mass balance of post tanning operations for wet blue split leather (UNIDO, 2000b)

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>INPUT</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split leather wet blue (50% H2O)</td>
<td>88</td>
<td>0</td>
</tr>
<tr>
<td>Process water</td>
<td>1500</td>
<td>0</td>
</tr>
<tr>
<td>Effluent</td>
<td>0</td>
<td>1500</td>
</tr>
<tr>
<td>Vacuum drying water</td>
<td>0</td>
<td>35.8</td>
</tr>
<tr>
<td>NaHCO3/HCOONa</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Organic tannins</td>
<td>5.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Fatliquors</td>
<td>6.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Dyestuffs</td>
<td>1.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Acids</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Leather waste (fibres, trimmings)</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Split leather crust (14% H2O)</td>
<td>0</td>
<td>59</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1605</strong></td>
<td><strong>1605</strong></td>
</tr>
</tbody>
</table>

Figure 8.6: Finishing of crust leathers (grain and split) (UNIDO, 2000b)
Table 8.5: Mass balance for finishing of grain leather (UNIDO, 2000b)

<table>
<thead>
<tr>
<th>Chemicals: binders(s), pigments, solvents, water, auxiliaries</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUT</strong></td>
</tr>
<tr>
<td>Dry substances</td>
</tr>
<tr>
<td>Solvents</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Wet finish (total)</td>
</tr>
<tr>
<td><strong>OUTPUT</strong></td>
</tr>
<tr>
<td>Dry substances</td>
</tr>
<tr>
<td>Solvents</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Loss by overspray etc. (Total)</td>
</tr>
<tr>
<td>Actual dry substance added</td>
</tr>
<tr>
<td>Buffing dust:</td>
</tr>
<tr>
<td>Off-cuts</td>
</tr>
<tr>
<td>Net weight increase:</td>
</tr>
</tbody>
</table>

Table 8.6: Mass balance for finishing of split leather (UNIDO, 2000b)

<table>
<thead>
<tr>
<th>Chemicals: binders(s), pigments, solvents, water, auxiliaries</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUT</strong></td>
</tr>
<tr>
<td>Dry substances</td>
</tr>
<tr>
<td>Solvents</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Wet finish (total)</td>
</tr>
<tr>
<td><strong>OUTPUT</strong></td>
</tr>
<tr>
<td>Dry substances</td>
</tr>
<tr>
<td>Solvents</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Loss by overspray etc. (Total)</td>
</tr>
<tr>
<td>Actual dry substance added</td>
</tr>
<tr>
<td>Buffing dust:</td>
</tr>
<tr>
<td>Off-cuts</td>
</tr>
<tr>
<td>Net weight increase:</td>
</tr>
</tbody>
</table>
8.2.1.2 Quantification of manufacturing waste

During the manufacture of leather products, there are multiple processes, which produce waste, a few do not, and this is intrinsically linked to the type of product that is being manufactured. However, there are a series of core processes that all products undergo during the manufacturing stages and these are represented in Figure 8.7.

The data for manufacturing waste were obtained from a report entitled ‘14th Session of leather and leather products industry panel’ (UNIDO, 2000a). This report showed that, by far, the largest quantity of waste is generated at the cutting step which can range between 25-60%.

The efficiencies of cutting processes is illustrated in Figure 8.8 which shows the waste that is left behind in a leather hide once panels have been cut out for use in leather products.

![Diagram showing manufacturing processes and waste streams associated with the production of leather goods](image_url)
As depicted in the flow chart in Figure 8.8, cutting operations are one of the first operations to take place within the production of leather goods. For this reason, it is possible to use the data about the weight of the grain and split hides that leave the finishing stage of the tannery (see Tables 8.2 – 8.6) and calculate 25-60% wastage of this material to provide an estimate for the waste generated during the cutting operations of the manufacturing stage. For the purposes of creating the vertical waste-flow map, it was decided that the maximum figure of 60% wastage should be used to represent a worst-case scenario for the quantity of waste generated at this stage. Therefore, by taking the combined grain and split weights of 195kg and 60kg and calculating 60% wastage, this gives a figure of **152kg of cutting wastes at the manufacturing stage for every 1100kg of wet raw hide that is processed**. It was deemed that all other wastes at the manufacturing stage are negligible when compared to the cutting wastes. This is illustrated in the Sankey diagram in Figure 8.9.

### 8.2.1.3 Quantification of Distribution, Retailing and Post-consumer waste

The final stages in the leather lifecycle are the distribution and retailing, and post-consumer stage, and the author found no data that quantifies the waste generated during these stages. The waste generated at the distribution and retailing stages includes damaged and returned products, counterfeit goods and any unsold stock. These types of wastes are
mixed-material product wastes and are generally only recorded by companies to understand the financial losses that the company is making on these products. The data recorded by companies at this stage consists only of the quantities of the product that are discarded, and the financial losses associated with them, the material composition of the product is not recorded. Therefore, measuring the leather content of products during these stages is infeasible for the following reasons:

- There is a lack of business incentive for the retailers and distributors of leather products to record the component materials within the products that they dispose of.

- Products at the post-consumer stage are made from multiple materials and the interconnectedness of the materials makes quantification of individual materials difficult. A consumer or a waste disposal authority has no reason to record the weight of these materials. The destination of these products (either incineration or landfill) does not require the authorities to know the breakdown of individual materials within a product if they are not classified as hazardous (which post-tanned leather material is not).

- Another factor that makes the collection of this data complex is the large volume of data points to be recorded. The volume of individual waste data points increases as the lifecycle moves downstream. For example, there are far fewer tanneries and leather product manufacturers than there are distributors, retailers and consumers of these products. Therefore, trying to collate data about the amount of leather products that millions of consumers have discarded is significantly more complex than trying to gather data from a few thousand tanneries and leather goods manufacturers.

The only certainty about the post-consumer stage is this: every product will eventually need disposal. Therefore, for every kilogram of leather used in a product which is purchased at the retailing stage, there is an equal weight of leather (in kg) that will eventually be sent for incineration or landfilling at the post-consumer stage. With this assumption in mind, it was decided to combine the waste from the retailing and distribution stages with the waste from the post-consumer stage. The data for all stages were combined to construct a Sankey diagram for the waste generated across the whole lifecycle of leather and leather products, which is illustrated in Figure 8.9.
8.2.1.4 Mass balance results: Sankey diagram and analysis

Figure 8.9: MFA results for vertical waste (diagram authors own with reference data from (UNIDO, 2000b).
From this Sankey diagram, it can be seen that there are many different waste streams to consider throughout the vertical lifecycle of leather. When analysing the data on the weight of leather waste produced at each stage in the lifecycle, it is important to be careful of misrepresenting the waste figures. At the start of this section a statistic from The World Bank was quoted as saying that “up to 70% of the wet weight of the original hides can be wasted” (World Bank, 1999). While this is technically true, for every 1100kg of original skin processed, only 255kg of finished hide is produced this figure is because the original animal skin contains 75% water which is reduced to 14% as the final finished leather hide is produced. The analysis within this research shows that in total, 493kg of waste is produced for every 1100kg of wet animal skins that are processed into leather hide, this represents 45% of the original weight, as illustrated in Table 8.7, and this represents the real amount of leather waste that needs to be disposed of. Figure 8.10 provides a graphical representation of the results.

Table 8.7: The percentage of waste generated at each stage in the lifecycle of leather

<table>
<thead>
<tr>
<th>Waste generation point</th>
<th>Weight of leather waste produced for every 1100kg animal skin processed</th>
<th>% of total waste (based on 493kg total waste)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tannery</td>
<td>239 kg</td>
<td>48.4%</td>
</tr>
<tr>
<td>Leather goods manufacturing</td>
<td>152 kg</td>
<td>30.8%</td>
</tr>
<tr>
<td>Distribution and post-consumer</td>
<td>103 kg (Figure taken from Sankey diagram)</td>
<td>20.8%</td>
</tr>
<tr>
<td>Total</td>
<td>493 kg</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 8.10: Percentage of total waste generated at each stage in the lifecycle
This data can be scaled up to estimate the amount of leather-based waste generated globally every year across the lifecycle of leather, the global figures are shown below:

- Global production of bovine skins and hides = 6,428,000 tonnes (FAO, 2013)
- Global production of sheep skins and hides = 400,200 tonnes (FAO, 2013)
- **Total global production of skins and hides = 6,828,200 tonnes**

With 6,828,200 tonnes of skins and hides produced globally on an annual basis, this means there is 3,072,690 tonnes of solid leather waste produced, which is 45% of the total amount. This can be divided according to the ratios in Figure 8.11 and this provides a global total for leather waste generated across different stages of the lifecycle, as illustrated in Figure 8.11.

From these figures, it is clear to see that almost half (48%) of the total lifecycle waste is generated at the tannery stage and the post-consumer stage represents approximately a fifth (20.8%) of the total waste. **Therefore, for every piece of leather that is discarded at the post-consumer stage, four times that amount of leather is wasted upstream in the supply chain.** For every pair of leather shoes that a consumer throws away, there is the equivalent of four more pairs thrown away further up the supply chain. The analysis of the Sankey diagram and mass balance data provides a good understanding of the quantities of waste generated throughout the vertical lifecycle.

![The leather waste chain](image)

**Figure 8.11: Global waste generated at each stage in the lifecycle annually**
8.2.2 horizontal waste-flow mapping

The aim of mapping the quantity of leather waste horizontally is to understand how the leather waste is distributed across various industry sectors. Mapping the waste in this way will reveal which industry sectors produce the most leather waste and this information will support decisions that need to be made about the effective recycling of leather waste.

To map leather waste horizontally across industries, it is crucial to collect data on how much of the leather that is produced globally is used by each industry. UNIDO produced a report that provides this information and Figure 8.12 illustrates this data (UNIDO, 2000a). From this information, it is clear to see that that the footwear industry is the sector which uses most of the globally produced leather on an annual basis (60% of the total).

This data is used in conjunction with data from the vertical map to create a horizontal map of leather waste for all industry sectors at each point in the supply chain, as shown in Table 8.8.

Geographical location of the waste is important when making decisions about grouping waste from different industries; this is used along with the data from Table 8.8 to support the economic decision-making that will be presented in Chapter 10.

Figure 8.12 Global leather use, split by industry sector (data taken from UNIDO, 2000a)
Table 8.8: Combined data from horizontal and vertical maps regarding the weight of leather waste across industries at each stage in the supply chain

<table>
<thead>
<tr>
<th>Industry</th>
<th>Proportion of material used by industry</th>
<th>Weight of material going into tannery (tonnes)</th>
<th>Weight of waste from tannery @48.4%</th>
<th>Waste from manufacturing @30.8%</th>
<th>Waste from distribution and retailing @20.8%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footwear</td>
<td>60</td>
<td>4096920</td>
<td>892309</td>
<td>567833</td>
<td>383472</td>
</tr>
<tr>
<td>Leather goods</td>
<td>20</td>
<td>1365640</td>
<td>297436</td>
<td>189278</td>
<td>127824</td>
</tr>
<tr>
<td>Garments</td>
<td>14</td>
<td>955948</td>
<td>208205</td>
<td>132494</td>
<td>89477</td>
</tr>
<tr>
<td>Upholstery</td>
<td>5</td>
<td>341410</td>
<td>74359</td>
<td>47319</td>
<td>31956</td>
</tr>
<tr>
<td>Gloves</td>
<td>1</td>
<td>68282</td>
<td>14872</td>
<td>9464</td>
<td>6391</td>
</tr>
<tr>
<td><strong>Total (tonnes)</strong></td>
<td><strong>6828200</strong></td>
<td><strong>1487182</strong></td>
<td><strong>946389</strong></td>
<td><strong>639120</strong></td>
<td></td>
</tr>
</tbody>
</table>

8.3 Waste Characterisation

To get a full understanding of the waste produced across the leather lifecycle, it is important to know not only the quantity of waste but also the qualitative attributes of the waste. This section investigates and defines waste characteristics and records how they impact the selection of recycling processes for leather waste.

8.3.1 Definition of waste characteristics

Each of the ‘actors’ in the leather lifecycle including: tanneries, manufacturers, retailers, distributors and consumers all generate waste streams that have differing characteristics. These differences arise because during each phase of the lifecycle the leather is in a different form. In the early phases of the leather lifecycle, the leather is still in its pure material form, and there is little to no contamination of the leather by other materials such as rubber or foam. In the later stages, the leather is mixed with a high variety of other materials to form products, which impacts the characteristics of the waste at those stages.

This limits the value of exploring ‘general’ leather waste attributes that describe the whole lifecycle and highlights the need for more focussed exploration of the qualitative characteristics of each stage of lifecycle waste. This will in turn enable a more in-depth understanding of how these characteristics impact the management of leather waste and will enable the development of a tailored, sector-focussed recycling solution to compensate for a wide variety of waste characteristics.
Four specific qualitative attributes of the leather waste have been identified by this research to impact the choice and range of recycling options, these are:

1. Purity of leather within the waste stream: How much leather is present per kilogram of waste material? And what variety of other ‘contaminant’ materials is present?

2. Quality of the waste: What condition (e.g. high quality or degraded/dirty) is the waste in?

3. Geographical distribution of the waste streams: Is the waste confined to one manufacturing facility or is it dispersed over a global region?

4. Geometry (form and size) of the waste materials: Is the leather a flat offcut from a tannery or is the leather a three-dimensional panel (e.g. from an automotive seat?)

A summary of these characteristics and their categorisations is provided in Figure 8.13. Both the technical and the operational characteristics of the waste have influences over the design and development of a leather recycling system, these influences are discussed below and summarised in Table 8.9. Technical characteristics are influenced by the required material or product function and the aesthetic design of a product. Technical characteristics have a direct impact on the selection of technologies used for material recovery and recycling. In addition, several of these technical characteristics influence the yield and purity of the material recovered during the various waste processing stages. This clearly influences the economic viability of the recycling system. For instance, waste streams with a high purity of leather and uniform size and geometry may require less processing steps to separate and recover. Conversely, waste streams with higher variety of materials (other than leather) and complex product geometry may require a greater amount of processing and result in a lower yield and purity of leather recovered from the waste stream. The initial quality (or also condition) of the waste stream, before it undergoes recycling and material recovery, has a direct impact on the final quality (condition) of the recovered leather material. These operational attributes are important because they will ultimately determine the value in the secondary materials market. Therefore, it is crucial to characterise the quality of the waste to understand the economic viability of a leather recycling system.
Table 8.9: Waste attributes and categorisations

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Technical or operational?</th>
<th>Quantitative or qualitative?</th>
<th>Influences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>Technical</td>
<td>Quantitative</td>
<td>Economic viability and selection of recycling processes</td>
</tr>
<tr>
<td>Geometry</td>
<td>Technical</td>
<td>Qualitative</td>
<td>Selection of recycling processes</td>
</tr>
<tr>
<td>Leather purity within waste stream (percentage of leather present)</td>
<td>Technical</td>
<td>Qualitative</td>
<td>Economic viability and selection of recycling processes</td>
</tr>
<tr>
<td>Quality/condition of leather waste</td>
<td>Operational</td>
<td>Qualitative</td>
<td>Economic viability</td>
</tr>
<tr>
<td>Geographical distribution of waste</td>
<td>Operational</td>
<td>Qualitative</td>
<td>Economic viability</td>
</tr>
</tbody>
</table>
Furthermore, the ‘geographic distribution of waste’ has a direct effect on the business case for recovering the materials from waste streams. The geographic distribution of the waste impacts the transportation costs, rate of processing per shift/day/week, and the overall achievable throughput for a recycling system. A more in-depth analysis of the economic feasibility of a leather recycling system is provided in Chapter 10. For each stage in the leather lifecycle, these characteristics will be assigned a rating, the range of these ratings is summarised in Table 8.10. These ratings will help to compare the qualitative characteristics in a structured way across the different stages in the lifecycle. For the attribute of ‘leather purity’, a high purity (desirable) rating will be given to a waste stream that contains 70%-100% by weight of leather. A medium purity rating will be allocated to a waste that contains 50%-70% leather. And a low purity rating (undesirable) will be given to a waste stream that contains 20-50% leather (i.e. this waste stream contains a large proportion of materials that are not leather). For the attribute of ‘leather quality or condition’, the rating of ‘good condition’ will be given to a waste stream in which the leather is uncontaminated by dirt or bacteria and has not been used by a consumer. This could be unsold product samples or tannery off-cuts. The rating of ‘medium condition’ will be given to a waste stream in which some of the leather is contaminated and some is uncontaminated. The rating of ‘poor condition’ will be given to a waste stream in which the leather is worn, degraded, dirty and/or bacterially contaminated by consumers through use. For the attribute of ‘geographical distribution’, a rating of ‘confined’ will be given to a waste stream

Table 8.10: Qualitative waste characteristics and their rating scales

<table>
<thead>
<tr>
<th>Qualitative characteristic</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leather purity within waste stream (percentage of leather present)</td>
<td>Low purity</td>
</tr>
<tr>
<td>Quality/condition of leather waste</td>
<td>Good condition</td>
</tr>
<tr>
<td>Geographical distribution of waste</td>
<td>Confined</td>
</tr>
<tr>
<td>Geometry of waste</td>
<td>Simple geometry</td>
</tr>
</tbody>
</table>
that is confined within one location, for example, within one tannery or one manufacturing facility. A rating of ‘medium distribution’ will be given to a waste stream that is under the control of one company but spread over several of their facilities within the same country. A rating of ‘globally spread’ will be given to leather waste that is spread across more than one country, for example, post-consumer waste.

For the attribute of geometry, a rating of ‘simple geometry’ will be given to a waste stream that contains two-dimensional pieces of leather waste, for instance, off-cuts from tanneries. A rating of ‘complex geometry’ will be given to a leather waste stream in which the leather panels are formed into complex shapes, for example, automotive seating.

### 8.3.1.1 Qualitative characteristics of tannery waste

The post-tanning leather waste can be further split into two categories: ‘tanned’ and ‘tanned and finished’ wastes. All wastes within the ‘tanned’ category occur before the leather goes through any dyeing or finishing processes. This means that the chemical composition of the leather includes only the original protein leather structure and the tanning agent which was used during processing (chrome or vegetable tanning).

All wastes produced within the ‘tanned and finished’ category occur after the tanned leather has undergone dyeing and finishing processes. This means that the chemical composition of the leather includes the leather structure, the tanning agent, any dyes that have been used and any finishing agents that have been applied, such as materials for surface treatments for wear or colour protection. On review of the waste streams produced by the tannery, it was found that they all contain over 99% pure leather; hence they contain less than 1% of other contaminant materials. This estimate was taken from an analysis of waste samples provided by one of the tanneries who were an industrial collaborator in this project. This analysis applies only to tanneries that do not manufacture any of their own leather products. For tanneries that do produce their own leather products there is another waste stream consisting of mixed waste. This waste has the same composition as the waste generated from the manufacturing stages; this type of mixed-material waste stream is covered in the next section. However, it is important to recognise that although the tannery waste is uniform in material composition, the wastes produced may contain materials that vary greatly in size and geometry. This has an impact on the technical and economic issues connected to the recycling of this waste; this is discussed further in Chapters 9 and 10. An exploration of the operational characteristics of the tannery waste streams show that the volume of waste from tannery processes is high and is all located geographically in one area.
(usually the tannery site). These conditions are prerequisites for an economically viable leather recycling system. Low transportation costs and minimal processing means that recovery and recycling costs are low, and a profitable system is more viable. Table 8.11 provides a summary of the qualitative characteristics of tannery waste.

### 8.3.1.2 Qualitative characteristics of manufacturing waste

In this section, consideration is given to wastes that are generated between the point at which the manufacturer receives the leather hides from the tannery and the point at which the finished leather goods leave the site.

Initial operations within manufacturing involve the cutting to size of leather hides from the tannery supplier. This operation results in waste streams that vary in size and form but are 100% leather. The operations carried out during the assembly of leather products involves the joining of leather to other pieces of leather or to other materials, which can involve adhesive, stitching or stapling. Other operations carried out at this stage include the cutting and trimming of joined components. For example, after the leather upper of a shoe is stitched to the midsole, trimming of the joined assembly is carried out to achieve the final

<table>
<thead>
<tr>
<th>Qualitative characteristics</th>
<th>Stage of lifecycle</th>
<th>Leather purity/material mix</th>
<th>Quality of waste</th>
<th>Geographical distribution</th>
<th>Geometry of waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tannery</td>
<td>High purity/low mixing</td>
<td>Good condition</td>
<td>Confined</td>
<td>Simple geometry</td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td>Medium purity/some mixing</td>
<td>Medium condition</td>
<td>Medium distribution</td>
<td>Medium complexity</td>
<td></td>
</tr>
<tr>
<td>Distribution and retail</td>
<td>Low purity/ high level of mixing</td>
<td>Medium condition</td>
<td>Global distribution</td>
<td>Complex geometry</td>
<td></td>
</tr>
<tr>
<td>Post-consumer</td>
<td>Low purity/ high level of mixing</td>
<td>Poor condition</td>
<td>Global distribution</td>
<td>Complex geometry</td>
<td></td>
</tr>
</tbody>
</table>
shape and size of the shoe. These operations produce mixed-material waste streams. This is the point in the leather waste chain at which the waste starts to become more complex and the percentage of other materials alongside leather in the waste stream increases. At this stage, the waste streams are now comprised of not only the original leather structure, the tanning agent, dyes and finishing agents but also different materials such as rubber, plastic and foam.

During product design and manufacturing, samples and prototypes of the products are made to check quality, design and features. These samples can be either full product samples or component pieces of the product. Once the design and function of the product is finalised the samples and prototypes are no longer needed, and they become another waste stream in the production process. This product sample waste stream is even more complex than the cutting and trimming wastes. It is extremely rare that leather products will be made from 100% leather with no other materials. Other materials such as textiles help to add aesthetic appeal and components such as metal supports provide a functional role in the product. Hence, the product sample waste stream will always contain multiple materials joined to each other in complex shapes and forms. The product-sample waste stream can also include different types of leather on the same product, for instance, cow or sheep leather, and depending on the product, this waste stream will have a very complex chemical composition.

The final category of waste produced during manufacturing is the product testing category. This category is different from the product sample category because it includes wastes from products that have undergone a series of testing to ensure safety, reliability and function. These tests can include items that are tested to destruction, set on fire and even crash tested in the case of leather automobile seats. This category of waste is often produced off-site at test facilities and is negligible in size compared to the other waste streams; therefore, it will not be considered further in this work. Analysing the operational characteristics of all the manufacturing waste streams reveals general trends. The waste from the manufacturing of leather goods can be localised on site for some leather goods, this results in a high volume of similar types of waste in one area. However, if the production of individual leather components is contracted out to other companies, the waste will be geographically spread over the supplier’s sites possibly on a global scale.

The value of the material is dependent of the purity/ percentage of leather present within the waste stream. Hence, the material at the start of the manufacturing process from the
initial cutting operations is the most valuable, and the highly-mixed material waste at the end of the process is of a lower value. Table 8.1 provides a summary of the qualitative characteristics of manufacturing waste.

8.3.1.3 Qualitative characteristics of distribution and retailing waste

The schematic in Figure 8.14 shows the variety of waste produced during the distribution and retailing of leather products. The wastes within this category consist almost exclusively of complete products that have either been returned to a retailer by a customer, are unsold by retailers and are returned to the manufacturer’s distribution centre, are damaged during transportation or are counterfeit goods seized by trading authorities.

8.3.1.4 Qualitative characteristics of post-consumer waste

The most challenging area of leather waste occurs at the end of the leather lifecycle, this is the post-consumer stage. Figure 8.15 illustrates a selection of items that fall into the category of post-consumer waste. This waste stream consists of any leather products that are no longer required by the consumer and require disposal.

The qualitative characteristics of this waste stream are extremely varied. The waste contains a multitude of different materials including but not limited to leather, rubber, foam, metal, wood, textiles and plastics. The range of construction methods includes adhesive methods, sewing and stitching, metallic fastenings and thermal joining methods. The chemical composition of the products is extremely complex. There are a multitude of different materials and tanning and finishing methods present in the products and therefore the potential for a hazardous mix of materials being present is high. Another level of complexity is introduced with post-consumer leather waste as the condition of the waste...

Figure 8.14: Range of wastes produced during distribution and retailing of leather products
products are usually very bad, products like leather shoes can be worn until destruction and usually bacterially contaminated through consumer use. Post-consumer products that are in a poor condition can raise challenges with identifying individual materials and distinguishing leather from faux leather.

When considering the operational characteristics of this waste stream, it is important to consider that although the volume of waste is large, this waste is spread geographically across the globe. Added to this, is the fact that most post-consumer leather waste is currently disposed of in landfills as there are no commercially available collections for waste leather products. Although the post-consumer waste is spread globally there are localised pockets of this waste within the overall spread. It is very likely that there is a high concentration of leather waste products wherever there are urban environments such as

Figure 8.15: A selection of post-consumer leather waste items
cities; however, obtaining data for the geographical location where the most leather is disposed of is not possible at this current time.

Finally, the post-consumer waste stream is the category with the greatest contamination of the leather by other materials, additionally it is the lifecycle stage with the lowest percentage of leather by weight, and this makes the post-consumer waste the lowest value waste stream within the leather lifecycle. Table 8.11 provides a summary of the qualitative characteristics of post-consumer leather waste.

8.3.2 Relational tables: Quantitative and qualitative waste characteristics

This section provides a summary of the quantitative and qualitative attributes of the horizontal waste that were discovered in the previous sections, Tables 8.11 and 8.12 provide this summary.

Patterns within the waste attributes are easier to see if they are illustrated in chart form, Figures 8.16 to 8.18 illustrate the trends within the qualitative characteristics across the lifecycle.

From Figure 8.16 it is clear to see that upon moving from the beginning of the lifecycle to the end of the lifecycle, there is an increasing mix of materials in the waste stream and a decrease in the percentage of leather present. Figure 8.18 illustrates that the condition of the leather within the waste stream deteriorates from good to poor as the lifecycle moves downstream.

<table>
<thead>
<tr>
<th>Quantitative characteristics</th>
<th>Stage of lifecycle</th>
<th>Weight of waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tannery</td>
<td></td>
<td>48%</td>
</tr>
<tr>
<td>Manufacturing</td>
<td></td>
<td>31%</td>
</tr>
<tr>
<td>Distribution and retailing</td>
<td></td>
<td>21%</td>
</tr>
<tr>
<td>Post-consumer</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 8.16: Increasing material mix as lifecycle moves downstream

Figure 8.17: Condition of the waste leather deteriorates as the lifecycle moves downstream
This is to be expected, because at the end-of-life the leather products have been used by consumers and the material within the products inevitably gets worn down. From Figure 8.18 it is clear to see that, the waste becomes dispersed over an increasing geographic region as the lifecycle moves downstream.

8.4 Summary

This chapter presented the work completed for Stage 1 of the CAL framework. The lifecycle stages of leather production and use were presented along with the factors to be considered during waste mapping and characterisation. The leather waste was then mapped and characterised both vertically and horizontally to understand how much waste exists and what its characteristics are. This mapping and characterisation information is used in Chapter 9 for the selection of collection, reprocessing and redistribution strategies for leather waste. Chapter 10 then presents a model that supports economic decisions associated with implementing a circular approach within the leather industry.
CHAPTER 9  RECYCLING AND PROCESSING STRATEGIES

9.1 Introduction

This chapter describes the development of alternative end-of-life scenarios for leather waste which forms the basis of Stages 2 and 3 of the CAL framework. The chapter begins with an introduction to the primary issues involved in end-of-life management, after which, the key steps in the end-of-life processing are described in detail. These include: collection and waste grouping; waste sorting and processing; and redistribution. Using the data gathered in Chapter 8, two novel recycling and processing strategies are developed, and finally, two scenarios for the end-of-life management of leather waste are presented.

9.2 End-of-life management of leather waste

Earlier in this research, the development of an economically viable end-of-life management solution for leather waste was identified as a priority, based on the gap in the knowledge, possible environmental contamination problems, value recovery opportunities and the large quantity of end-of-life waste generated throughout the lifecycle of a leather product.

The end-of-life management of leather waste involves a distinct number of steps to take waste leather products and convert them into useable recycled materials that are suitable for use in other products. These steps are illustrated within the recovery chain diagram in Figure 9.1. End-of-life management begins with the collection of end-of-life leather products or leather material waste from the waste generator and finishes with the redistribution of all outputs from end-of-life processing operations to the appropriate secondary destinations.

9.2.1 Collection and waste grouping

This first step in the end-of-life management process significantly affects the overall effectiveness of the end-of-life scenario. Uncontrolled disposal of leather products from consumers can occur if the transfer of the leather waste to an appropriate reprocessing facility is not facilitated, this can have high environmental impacts. The factors influencing the collection of the end-of-life leather waste are explored in detail in Section 9.3.
9.2.2 Waste sorting and processing

After the leather waste has been collected, there needs to be a level of inspection and sorting to determine whether the materials are suitable for reuse, recycling or disposal. Uncertainty about the materials identity may limit the feasible end-of-life option; consequently, any materials that are unidentifiable will have to be disposed of to landfill. Processing of leather waste may recover materials that are directly reusable or may produce crude materials requiring further processing. Recycled leather waste materials may be reprocessed into useful inputs for the manufacture of other reconstituted leather goods, or as inputs for the manufacture of other products. The options for processing end-of-life leather waste are discussed in greater detail in Section 9.4.
9.2.3 Redistribution

New material flows must be defined during the processing of end-of-life leather products and recovery of materials; these materials require distribution to a new actor in the supply chain. In a closed-loop scenario, redistribution may be back to a leather products manufacturing facility. However, due to the uniqueness of leather, this is, at present, the most unlikely scenario. Demand for virgin leather material will not stop if recycled materials are used; this is because leather is a by-product of the meat industry. Therefore, the drive to use recycled leather in applications where virgin materials are primarily used is based on cost reduction rather than the desire to halt the production of virgin leather material. In an open-loop scenario, recycled materials may be sold for the manufacture of other products, which is far more likely in the case of leather recycling. To conserve resources, it is proposed that most of the material arising from the processing of end-of-life leather waste should be redistributed if possible, with only minimal quantities of material requiring landfill disposal. The economic benefit achieved through the redistribution is likely to play a significant role in the overall economic viability of the end-of-life management process; this will be explored further in Chapter 10.

9.3 Collection methods and waste grouping strategies

This section presents work that defines collection methods and develops waste grouping strategies that could assist the implementation of a circular approach within the leather industry. These strategies are developed based on the need to increase the quality and quantity of recycled materials, which will in turn increase the economic viability of a leather recycling system.

At this stage, it is important to make clear the distinction between waste collection and waste grouping, the following definitions provide clarity. Within this research, waste collection methods are defined as the physical gathering and transportation of waste from the waste generator (tannery, manufacturer, retailer or consumer) to the material recovery/processing facility. On the other hand, waste grouping strategies determine the waste material mix that enters the recycling line for processing and materials recovery. The following sections provide options for leather waste collection and develop two novel strategies for leather waste grouping.
9.3.1 Collection methods

The collection of leather waste at the end-of-life has a big impact on the environmental and economic feasibility of implementing a circular approach within the leather industry. If the collection is not adequately planned and assessed, then, in certain cases, this could lead to greater environmental impact than if the materials were sent to landfill.

Within the research, alternative collection methods for leather waste have been identified. The collection method is dependent on the point in the lifecycle at which the waste is generated. Industrial waste collection is the most practical method of gathering the waste materials and products generated by tanneries, manufacturers, distributors and retailers. Industrial waste collection is common in business-to-business waste services and it involves the provision of skips or other waste receptacles which are stored at the waste-producers site. The waste receptacle is filled by the waste producer and then collected periodically, either when full, or on a fixed schedule, by the waste collection organisation. Due to the amount and frequency of waste generated by tanneries and manufacturers of leather products, having regular waste collections from the premises is often economically feasible and reduces environmental impact.

Collection is more challenging for post-consumer leather waste, the volume of waste from individual households will be significantly lower than that from a manufacturing facility, and the variety of the products will be greater, the practicability of this method is questionable, therefore, alternative collection methods are required. To achieve the aims of this research, four possible collection methods for post-consumer wastes have been identified, these are: kerbside collection; postal returns; localised collection points and retail returns.

Kerbside collection would be most suitable for large items such as leather furniture which are problematic for consumers to transport to a recycling centre. A kerbside collection scheme could be implemented by a local government authority or a charitable organisation. Postal returns would make it more convenient for the consumer to send back leather products, but given the low value of material within leather products, this route may not be economically feasible when postage costs are factored in. The environmental benefit of individual mailings would also have to be evaluated. Localised recycling centres can be used to collect post-consumer leather waste, local government authorities own and manage a range of these types of recycling centres in all counties of the UK. Other types of local recycling centres include recycling ‘banks’ at locations within communities, such as supermarkets or village halls. Finally, retailers can provide in-store facilities for consumers
to return waste leather products. This scheme is best suited to smaller products which can be easily transported by consumers, such as leather footwear or accessories. The cost of the scheme is borne by the retailer and the success is dependent on incentivising the consumer to bring products back at their end-of-life.

9.3.2 Waste grouping strategies

Within the research the author has developed two novel waste grouping strategies which are described further below.

9.3.2.1 Vertical recycling and processing strategy for leather waste

Vertical recycling and processing (VERP) is for recycling leather waste across the lifecycle of a product (for example, waste across the lifecycle of a footwear product), with the aim of producing a revenue improvement through increased material quality (see Figure 8.3). This collection concept has the advantage of a single supplier being able to trace and potentially reduce the environmental impact of their waste products.

However, when leather goods are manufactured and shipped to customers, the supply chain is often global in scale, with component parts of the product often made in different countries and shipped to another country for assembly. This makes the logistics of collecting waste vertically across a product supply chain challenging and potentially more environmentally impactful.

9.3.2.2 Horizontal recycling and processing strategy for leather waste

Horizontal recycling and processing (HORP) is for recycling leather waste at a specific point in the lifecycle across product sectors, for example, leather waste could be collected at the post-consumer stage across all product sectors and industries including footwear, apparel, automotive and furniture. This strategy aims to produce a revenue improvement based on increasing the quantity of leather material recovered (see Figure 8.3). This collection concept has the advantage of increasing the economies of scale by collecting multiple product streams; this makes the collection more viable than having individual collections for single product streams. Another advantage of a horizontal recycling and processing strategy is that waste at specific points in the lifecycle (either post-consumer or manufacturing waste) is likely to be of similar quality. This similarity in waste streams allows for a more streamlined approach to sorting and processing the waste.
Collecting waste horizontally has the advantage of decreasing the distance between waste products that require collection at each point before the post-consumer stage. Tannery waste typically accumulates in areas with high concentrations of tanneries, the same is also true for waste generated during the production of leather goods; it is typically concentrated in areas with large groups of leather goods manufacturers. This means that the geographic spread of waste at a singular point in the supply chain will be lower (except for post-consumer waste); therefore, the transport costs between the point of origin of the waste and the reprocessing point may be lower.

The downside to this approach is that it may not allow individual industries to have full traceability of their waste, and full control over how their waste is managed. This type of collection strategy requires a collaborative scheme similar the ‘Distributor takeback scheme’ that exists in the e-waste industry (Corsini, 2017) to be set up between companies from more than one industry or it requires a scheme to be created by a third-party recycling company to recover waste from multiple industry sectors.

### 9.4 Waste sorting and processing

During Stage 3 of the CAL framework, recycling and material recovery processes are evaluated, considering the waste characteristics identified in Chapter 8, for their applicability to the recovery of end-of-life leather waste.

Within the waste hierarchy (Ghisellini et al., 2016), reusing products that reach the end-of-life is preferred over the recycling of the materials contained within them. It is envisaged that, as the design of leather products become more sustainable in the future, the exploration of opportunities for the repair/remanufacture and reuse of leather products will be increased. However, various characteristics of current leather products determine that any repair or remanufacture operations will be technically challenging or economically infeasible. Therefore, this thesis focusses on material recycling rather than the remanufacture and reuse of end-of-life leather products. The end-of-life processes for leather waste are illustrated in Figure 9.2. An initial sorting process is applied to the end-of-life leather waste, this helps to segregate products and/or materials which are too badly contaminated to be recovered within the recycling process. The sorting process helps to isolate the waste which contains metals from the bulk of the other materials; this will reduce the risk associated with machinery breakage from metal entanglement. Following the segregation of damaged materials and metal-containing materials, the remaining mixed material is available for processing.
Figure 9.2: Overview of alternative processing routes for end-of-life leather waste
Next, the mixed material will undergo fragmentation to reduce the size and liberate dissimilar materials from each other, after which, several material separation processes will be applied to separate material fractions. Once materials have been recovered into the constituent fractions, they may be suitable for direct reuse or they may require further mechanical or chemical processing to prepare them for use in the next application. Finally, these materials are either distributed for use in the same application, higher value (up-cycling) or lower value (down-cycling) applications.

9.4.1 Typical material content in leather waste

Before sorting of leather waste takes place, it is first necessary to understand the typical materials that are present alongside leather within the waste streams. From previous footwear research (Lee and Rahimifard, 2012a), and through experimental work performed for the purposes of this thesis, data has been gathered about the typical material content of leather products across industry sectors. The lab-scale experimental work revealed the most common groups of materials in end-of-life leather products. Typical material content within leather footwear and car seats are shown in Figures 9.3 and 9.4.

![Figure 9.3: Material content within leather car seats](image-url)
There are many similarities between the material content of an item of leather footwear, a piece of leather apparel and a leather car seat. Within this research, the author has identified common materials that are found across leather products, these are listed in Table 9.1. Once the typical materials present within the waste were identified, the characteristics were then used to explore processing technologies required to enable efficient recovery of the materials.

At this stage in implementing a circular approach, initial considerations are given to which technologies would be required to process a specific subset of input waste materials. This is based on the general characteristics of the material and the general attributes of the technology. Further research and detailed experimentation is required to be able to accurately predict the best sequence of technology processes for a combination of mixed waste materials (see future work section in Chapter 13).

Table 9.1: Common materials found in leather products

<table>
<thead>
<tr>
<th>Product</th>
<th>Metal</th>
<th>Leather</th>
<th>Rubber</th>
<th>Foam</th>
<th>Plastics</th>
<th>Textiles</th>
<th>Faux leather</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footwear</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Apparel</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Luxury leather goods (Accessories, briefcases)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automotive interiors and seats</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Furniture</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
9.4.2 Pre-fragmentation processing: Sorting and metal removal

Pre-fragmentation options for end-of-life leather products are considered here in the context of subsequent material separation and recycling processes. The pre-fragmentation processing stage includes: sorting of the waste products and metal detection and removal. To decide if any pre-fragmentation processing is necessary, it is crucial to consider the material composition of the waste along with the required output from the recycling system. If a low-value, low-purity material output is required then it may not be necessary to apply a high-level of sorting to the input waste stream, the converse is also true. Sorting can help to increase the efficiency of the post-fragmentation processing stage by permitting wastes with similar material contents to be grouped and processed together. Subsequently, it has a direct impact on the purity of the output material from the recycling system, and it is critical to consider how waste streams can be best combined to produce an increase in material output quality, as this will increase the revenue generated from the sale of higher quality output materials.

If the leather waste streams contain metal, then it will be necessary to implement a metal detection and removal process. Leather waste originating from the manufacturing and post-consumer stages of the lifecycle is most likely to contain metal. Metal causes a problem with granulation machines (during the fragmentation stage of processing) if it is not removed from the waste; metal can damage the blades of the granulator leading to premature failure and increased maintenance costs. Metal will also contaminate the material stream that is output from the fragmentation process if it is not removed prior to fragmentation.

There are two approaches to detecting and removing metal from leather waste. Metallic components can be detected and removed from the waste stream automatically by using over-band magnets which are mounted above conveyor belts; these magnets remove any ferrous metallic item. Other automated methods include eddy current separators which can be used to detect and remove non-ferrous metal items. Alternatively, manual methods can be used which includes using a hand-held metal detector to scan the waste, after which, the metallic components can then be removed from the leather waste through a manual disassembly of the product (see Figure 9.5). This level of segregation allows for the separation of heavy, hazardous metallic components from a relatively light material fraction which incorporates a mix of other materials.
Detecting and removing metal from waste manually is labour intensive and incurs higher costs over the lifetime of the recycling process; however, it is more accurate than using automated processes. Automated processes can achieve greater throughput of material than manual sorting, but it incurs a greater upfront capital cost and is less accurate overall.

It is important to consider the volume of waste passing through the process when deciding whether to implement a manual or automated metal removal process. If a large volume of the incoming waste stream is likely to have metal encapsulated within it, then a manual process may be too slow, too labour intensive and uneconomical. The level of metal entanglement and encapsulation also needs to be considered when designing a metal removal process. For example, in footwear products, metal can be heavily encapsulated within another material, for example within a rubber sole, which makes detection and extraction of the metal component challenging.

9.4.3 Fragmentation of leather waste

Fragmentation options for end-of-life leather products are considered in the context of subsequent material separation and recycling processes. Figure 9.6 illustrates several fragmentation options considered in the research: shredding and granulation, which both allow for the downsizing and segregation of different material types. However, they produce different sized fragmented particles, see Figure 9.7. In this stage of CAL framework, it is assumed that the leather waste stream being processed requires fragmentation; this may not always be the case. If the waste stream is comprised of 100% leather from a tannery or manufacturing facility, then fragmentation and material recovery may not be required.
Figure 9.6: Shredder and granulator for fragmenting leather waste (Pimco Machine, 2017) and (Franzoi, 2017)

Figure 9.7: (a) shredded (20-50mm) and (b) granulated leather waste (5-20mm) (Lee and Rahimifard, 2012a)
If the waste does require fragmentation then there are several factors which influence the selection of fragmentation technology (shredding or granulation), including:

- Range and number of materials present within the waste stream
- Throughput required for the processing stage
- The desired quality of recovered materials
- Physical size and form of the products in the waste stream

The range and types of materials within the incoming waste stream has an influence on the selection of the fragmentation technology. Generally, if there are a greater number of materials within a waste stream and the required output quality is high, then it will need to be fragmented into smaller particles to successfully liberate different materials from each other during the separation processes. In such cases, achieving good material separation and less post-fragmentation entanglement of materials, requires the use of a granulator. In general, granulation produces particles of materials that are smaller in size than those produced by shredding and should be used for waste streams with a high variety of different materials with a requirement for high-quality output. The disadvantage being that the throughput time will increase because granulation takes longer than shredding.

Conversely, shredders can process a larger volume of material in a shorter amount of time, but this does have an impact on the quality of the recovered materials.

Finally, when deciding which fragmentation process is most appropriate for the incoming waste stream, it is important to consider the overall size and form of products in the waste stream. Waste streams containing products such as leather furniture will be physically larger than waste streams from leather footwear products. This difference in size can determine which technology to use for fragmentation, shredders are generally used for larger wastes and granulators are more suitable for smaller waste products.

### 9.4.4 Post-fragmentation separation

Post-fragmentation separation involves the separation of the granulated or shredded waste particles into distinct material fractions. Methods for achieving this include air-based separation processes such as: vibrating air-tables, zig-zag separators or cyclone separators. Other non-air-based processes include dense media separation processes which use a media (often a liquid such as water) to separate material into two fractions using density of the waste materials as the driving force for separation. There are several factors that influence the selection of post-fragmentation material separation technology. For example,
the material composition of the waste stream has a direct impact on the type of material separation technology. For an air-based separation or a dense media separation process to be effective, there must be a clear difference in densities between input material types. If the density difference is very small (e.g. various polymers) then a dense media separation technology will be more suitable, if the density difference is large, an air-based separation process will yield a better result.

To decide which post-fragmentation processes are suitable for the incoming waste stream, it is necessary to once again consider material mix. Some post-processing technologies are more suited to specific material mixes, for instance, if the waste stream contains light textile material combined with leather materials then it will be necessary to include a process that is capable of separating textile materials from leather materials.

The material content influences how many post-fragmentation separation processes are required; if there are only two materials within the input waste stream then it may be possible to fully separate these materials with a single separation process. If a greater number of materials are present within the incoming waste stream then the number of separation processes increases, this will allow all material fractions to be recovered.

9.4.5 Post-fragmentation material recycling processes

For some of the materials within the end-of-life leather products, such as metal and plastics, there are well-established commercially available recycling processes based on thermal or chemical processes, it is therefore viable to recycle these materials via existing processes and methods. However, limited commercial recycling routes exist for the other materials that are recovered from leather products and novel uses must be found for the recovered materials. For example, the lightweight fraction of recovered material such as foam and textiles are suitable for down-cycling into insulation or underlay products for flooring application. These materials may require further processing either by mechanical or chemical methods, to make them suitable for use in other products. Chapter 11 describes in detail the recycling processes implemented in the case studies.

9.5 Redistribution of recovered materials

Redistribution is the last step in the end-of-life management process for leather waste, as shown in Figures 9.1 and 9.3. Redistribution of recycled materials is only possible if there is a market for the recovered materials, without one, disposal is the only option.
9.5.1 Redistribution of recycled materials

Various options are available for redistribution of recycled materials. Up-cycling is the name given to the use of a recycled material in a high value application, up-cycling may potentially be realised for high value materials such as metals, where metal materials recovered from leather products could be reused in the manufacture of other value-added products. Down-cycling is likely to be realised for materials that are inherently low in value, such as foams and textiles, or materials which are not re-processed to a high enough purity to render them suited to their original or equivalent application. The remaining material which is suitable for neither the original application, up-cycling nor downcycling applications is labelled as residual material and only suitable for disposal.

Due to the specific characteristics of leather, at present downcycling is the most likely scenario for materials that are recovered from a leather recycling system. Demand for virgin leather material will not stop if recycled materials are used; this is because leather is a by-product of the meat industry. Therefore, the drive to use recycled leather in applications where virgin materials are primarily used is based on cost reduction rather than the desire to halt the production of virgin leather material. From the range of materials commonly found within leather products, only the metals, plastics and rubber are likely to be recovered in a pure enough form to be used again in the original or equivalent application. For the foam, textiles and leather, it is highly unlikely to return the material to a form where it could be used in its original application or equivalent. These low value materials are likely to be down-cycled. The largest proportion of the economic benefit from recovering end-of-life materials will come from the redistribution into other applications. Therefore, this step is critical in defining the long-term economic viability of implementing a circular approach in the leather industry.

9.5.2 Disposal options

Without development of a suitable alternative end-of-life process or the existence of suitable markets for the redistribution of recycled materials, disposal of end-of-life leather waste constitutes the only available option open to leather product manufacturers. As discussed in the review in Chapter 3, disposal of biodegradable material to landfill within the EU is increasingly unacceptable, both from a regulatory point of view and based upon public perception. This is especially relevant to leather waste which is constantly under scrutiny for its environment footprint. The chrome tanning substrate provides a real incentive for at least some level of recycling to be carried out and the hazardous nature of
this substance only serves to increase the administrative burden associated with disposal. One of the primary aims of the research presented in the thesis is to support the development of an end-of-life process route for leather waste which minimised the amount of harmful material sent to landfill.

### 9.6 Scenario development for end-of-life management of leather waste

Within this section, two scenarios for the recovery of materials from end-of-life leather waste have been presented (Figure 9.8); they are based on a combination of collection strategies and processing options. These scenarios have been developed based on laboratory-scale feasibility studies conducted by the author of this research. These scenarios will be further assessed in Chapter 11. A comparison of two distinct scenarios was decided to be sufficient to demonstrate the application of the framework. This is consistent with the overall aim of the research which is not to define an optimised end-of-life solution for leather waste, but rather to explore the issues involved in the implementation of a circular approach, and to present an approach by which these issues may be addressed. However, the nature of the framework is such that all combinations of process routes could be compared and evaluated in future research.

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**Figure 9.8**: Alternative end-of-life scenarios for leather waste developed in the thesis
9.6.1 Scenario one: Vertical collection with air-based separation

This scenario comprises a VERP strategy with air-based separation processes; this is illustrated in Figure 9.9. At the collection and sorting stages, wastes from each stage of the lifecycle (tannery, manufacturer and post-consumer) of a singular product are collected and brought together to be processed. The initial step in the processing route is the removal of any items containing metal using a hand-held metal detector and the fragmentation of the waste by granulation.

Figure 9.9: Collection and processing route for scenario one
The granulated materials will then move through a two-step air-based separation process which includes: separation of material in a zig-zag separator and separation of materials via a vibrating air-table process. In this scenario five material streams are produced for redistribution. These comprise the metal fraction, the light foam and textile fraction, the plastics fraction, the heavier rubber fraction, the leather material; any residual material will be disposed of.

9.6.2 Scenario two: Horizontal collection with air-based separation

The second scenario for processing end-of-life leather waste is illustrated in Figure 9.10.
This scenario comprises a HOPR strategy with air-based separation. At the collection and sorting stages, wastes that cut across products, from one stage of the lifecycle, in this case, the post-consumer stage, will be collected and brought together to be processed. The initial step in the processing route is the removal of any items containing metal using an automated metal removal process and the fragmentation of the waste by granulation.

The granulated materials will then move through a two-step air-based separation process which includes: a separation of material in a zig-zag separator and a separation of materials via a vibrating air-table process. In this scenario three material streams are produced for redistribution. These comprise the metal fraction, the rubber fraction and the leather material. The plastics, foam and textile fractions are not targeted for recovery and will be disposed of.

9.6.3 Critical overview of end-of-life scenarios for leather waste

Based on the work presented in the current chapter, initial observations can be made based about the two scenarios based on a comparison of the two process routes, these are summarised in Table 9.2.

Regarding the practical feasibility of the two scenarios, four aspects are identified as being significant. The first is process complexity, and as both scenarios use the same air-based processing methods, the differences between the scenarios therefore lies in complexity in the preceding waste collection and grouping strategies. The complexity level is high in both scenarios; however, different collection strategies present different complexities. Collecting and grouping waste vertically presents the challenge of aggregating all waste associated with a single product across multiple lifecycle points. Whilst aggregating waste horizontally across multiple product sectors at the post-consumer stage presents the challenge of collecting globally dispersed wastes at centralised points for processing.

The second consideration is process availability; this assesses the availability of the selected process technology for the end-of-life scenarios for leather waste. For both scenarios, some process elements are commercially available, such as the granulator. Technology elements, such as the zig-zag separator would need to be adapted to be suitable for use in either scenario and bespoke development of an industrial scale vibrating air-table would be required to make the process suitable for industrial application.
Table 9.2: Factors related to practical implementation of scenarios 1 and 2

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1: Vertical collection with air-based separation</th>
<th>Scenario 2: Horizontal collection with air-based separation</th>
</tr>
</thead>
</table>
| Process complexity    | ● Collection of material across multiple points in lifecycle is complex  
                       |   Four physical processing steps required                  | ● Collection of material across multiple product sectors is complex  
                       |   Four physical processing steps required                  |                                                                       |
| Process availability  | ● Some of the technology elements are commercially available (granulator)  
                       |   ● Some elements require adaption for use in this application (Zig-zag separator)  
                       |   ● Some elements require bespoke development (vibrating air-table)                  | ● Some of the technology elements are commercially available (granulator)  
                       |                                                                       |   ● Some elements require adaption for use in this application (Zig-zag separator)  
                       |                                                                       |   ● Some elements require bespoke development (vibrating air-table)                  |
| Process flexibility   | ● Input material can be in product or material form  
                       |   ● Physical condition of materials is an influencing factor                      | ● Input material can be in product or material form  
                       |                                                                       |   ● Physical condition of materials is a large influencing factor                      |
| Process output        | ● Metal  
                       |   ● Rubber  
                       |   ● Leather  
                       |   ● Textile and foam  
                       |   ● Plastics  
                       |   ● Residual material                                               | ● Metal  
                       |                                                                       |   ● Rubber  
                       |                                                                       |   ● Leather  
                       |                                                                       |   ● Residual material                                               

Process flexibility is the third consideration, with focus on the form of the waste input materials. The physical form and condition (quality) of the leather waste will vary according to where the waste is generated in the lifecycle and how the leather products have been used throughout their lives with consumers. Both scenarios one and two can deal with input materials of varying qualities; however, the quality of the output material will vary in response. Finally, the recycling system output is considered, in terms of the number of different material streams arising from the processed end-of-life leather waste. Both scenarios have the possibility to create identical material types. However, a variation in the purity of the material input will give a variation in the purity of the output material streams. These material outputs can then go on to be used in a variety of next-generation applications.
9.7 Summary

This chapter has explored the key stages in the end-of-life management process, namely: collection methods and waste grouping, material recovery and processing and redistribution of recycled leather materials. The chapter began by developing two novel strategies for grouping leather waste. After which, options for sorting and metal removal from leather waste were discussed. Finally, two scenarios for processing end-of-life leather waste were developed.

The work completed for the final stage of the framework will be presented in Chapter 10, which investigates the economic decision-making that surrounds the implementation of a circular approach within the leather industry and uses the findings from Chapter 9 to develop a cost-model to support those decisions.

It is necessary to define each end-of-life scenario in terms of output and input flows of energy, waste and materials to be able to quantitatively compare and evaluate them. Each output and input flow will have an associated economic impact and data which will support the definition will be collated from various sources. It is expected that initial scoping of new end-of-life scenarios could be achieved by using the estimated or theoretical data from the literature. After which, as processes within the scenarios become more established, more robust data can be generated and utilised to give higher confidence in the output generated by use of the framework and support tool. The alternative end-of-life scenarios are defined quantitatively through the completion of case studies, which are documented in Chapter 11.
CHAPTER 10 ECONOMIC MODEL FOR A CIRCULAR APPROACH IN THE LEATHER INDUSTRY

10.1 Introduction

This chapter presents the work undertaken for Stage 4 of the CAL framework. Work from Stages 1 and 2 are brought together to create a model that evaluates the long-term economic sustainability of the leather industry. The first part of the chapter explores the types of economic decisions that are made throughout the lifecycle of leather and how these decisions can be supported. The second half of the chapter develops a cost model to support the decision-making processes in this area. The cost model will incorporate all costs associated with developing and operating a leather recycling system, this includes: the variable costs of collecting the waste and processing it; and the fixed costs of purchasing capital equipment to establish the recycling system. The model will consider the influences of the waste characteristics, the waste collection strategies and the processing technologies on the cost of implementation. The final part of the chapter will analyse ways in which the cost model could be used to evaluate operational costs and profitability.

10.2 Economic decision-making

A parametric cost model that supports economic decisions has been created, and a set of equations are defined that can evaluate the profitability of a leather recycling system given a set of specific input variables. The steps involved in supporting economic decision-making for leather recycling are illustrated in Figure 10.1.

10.2.1 Stakeholder decisions

The primary consideration for stakeholders involved with leather recycling is related to the economic viability of leather recycling systems. The definition of economic viability in this case depends on the following three considerations:

1. Which stakeholder is making the decision and in what stage in the lifecycle are they active?

2. The stakeholders’ motivation for being involved with recycling of products

3. The type of business strategy that is being used for material recovery and recycling
The interconnectedness of stakeholder motivations and the decisions that they are making about the economics of the recycling system are explored in Figure 10.2.
Figure 10.2: Stakeholders, motivations and economic decisions about recycling (authors own diagram)

It is evident from Figure 10.2 that there are three key decisions regarding economics that are commonly made across the lifecycle of a leather product, these are:

1. Is the increase in sales revenue (gained from the customer’s attraction to ‘green’ leather products and companies) greater than the money spent on participating in the recycling scheme?

2. Does participation in the leather recycling scheme cost less than the current waste disposal method for tanneries, manufacturers or retailers?

3. Is the revenue generated by the sale of recycled leather materials greater than the operational costs of running the leather recycling system?

Analysis of Figure 10.2 it is possible to identify input factors for the decisions listed above, these are:
• The cost of participating in a leather recycling scheme (depends on the type of business strategy used by the recycling company)

• The current waste disposal costs for tanneries, manufacturers and retailers

• The revenue generated from recycling a leather product (by recovering the material and selling it on a secondary market)

• The operational costs of running a leather recycling scheme or system

The next section looks at the ways in which the work within this thesis can use these factors to evaluate the economic viability of a leather recycling system.

10.3 Supporting economic decisions

Upon examination of the three key economic decisions, it is clear to see that the first two decisions represent core business considerations; they are entirely dependent on the costs within each business and the specifics of the recycling business strategy that is used. The selection of a business strategy for recycling depends on the motivations of the waste producer, some manufacturing companies are content to abide by legislation and simply send their waste away for correct treatment, others want to recoup the material from their waste to reuse as raw materials for other products, these different intentions require different relationships between the waste producer and the waste recovery organisation.

The different business strategies are illustrated in Figure 10.3.

Figure 10.3: Common business strategies used by recycling companies
Businesses make decisions on their involvement with certain activities based on a comparative analysis of the costs versus the benefits, and this is required to make the first two decisions in Figure 10.2. Therefore, there is limited novelty in providing another support tool for these decisions. Therefore, the novelty in this research is through the development of a model that provides support for the third key economic decision. A parametric cost model has been developed which will enable recycling companies to evaluate if a leather recycling system is profitable given a set of input criteria. This model will consider how the chosen business strategy impacts the economic effectiveness of the recycling system. This will provide a unique contribution to the leather recycling industry, and it will allow the recycling companies to evaluate if changes made to the recycling system input variables will increase or decrease the profitability of the system.

10.4 Parametric cost model

A cost-benefit analysis (CBA) approach is used to provide an economic metric for the evaluation of alternative recycling scenarios for leather. CBA is used to support decision-making across a broad range of situations and requires all relevant costs (C) and revenues, or benefits (B) to be quantified. Within this thesis the term ‘benefits’ is used to convey only the financial benefits of a recycling system. Quantification of these values is represented in terms of present value (PV), which includes a discount rate (i) which accounts for changes in the monetary value over time (t). The equations used to express the total costs and revenues associated with a given scenario are shown in Equations 10.1 and 10.2 respectively:

\[ PV(C) = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \]  
Equation 10.1

\[ PV(B) = \sum_{t=0}^{n} \frac{B_t}{(1+i)^t} \]  
Equation 10.2

To evaluate recycling scenarios for leather, a parametric cost-benefit model is required that can represent any leather recycling scenario. The model should encompass all costs and revenues arising throughout the recycling process. Therefore, an illustrative parametric cost model has been developed, which can be readapted for other cases with simple modification.

The cost-benefit ratio for leather recycling (CBRL) is defined in Equation 10.3 below:

\[ CBRL = \frac{\sum_{m=1}^{n} C_m}{\sum_{m=1}^{n} B_m} \]  
Equation 10.3
In developing the cost model, and mapping the revenue opportunities together with fixed and variable costs, the specific areas of focus are:

- Waste collection
- Logistics
- Processing
- Redistribution

In Sections 10.4.1 and 10.4.2 economic parameters are defined that represent the revenues, fixed costs and variable costs that are associated with the individual stages of: collection and logistics, and processing and distribution of leather waste respectively, see Figure 10.4. After the economic parameters are defined they will be combined into a series of equations that represent the total revenues, fixed costs and variable costs (Sections 10.4.3 to 10.4.5), after which, these equations will be combined to form a complete cost model for leather recycling (Section 10.4.6).

### 10.4.1 Economic parameters: collection and transportation

In this section, economic parameters are defined for the revenue, fixed costs and variable costs associated with collection of leather and the transportation of leather waste.

#### 10.4.1.1 Revenue

The business strategy used for recycling the leather waste will dictate whether it is possible for recycling companies to charge waste producers to collect their waste. This collection fee generates a revenue stream for the recycling company. The economic parameter defined for this source of revenue is:

Waste collection services, $R_{WCS}$

![Figure 10.4: Structure of the cost model](image-url)
It is important to note that this revenue stream can become a variable cost if the waste is valuable enough for the waste producer to sell their waste to recycling companies. A separate variable is defined below for the variable cost of acquiring the waste.

10.4.1.2 Fixed costs

Fixed costs are defined as: costs which do not vary with the volume of output material produced. To collect waste from waste producers, collection equipment needs to be provided and this collection equipment is the primary source of fixed costs during collection and transportation of waste. The transportation of waste mainly incurs variable costs unless the transportation operation is owned by the recycling company, at which point the fixed costs would be associated with the purchase of waste collection vehicles and equipment. The cost of renting premises or space for collection equipment or temporary storage of waste is another fixed cost. The type of waste collection service provided, either post-consumer or industrial, will dictate the type of collection equipment that will be required and hence the fixed costs of providing the equipment and service.

The economic parameters defined for these fixed costs are:

1. Fixed cost of industrial collection equipment, $CF_{ICE}$
2. Fixed cost of retail collection, $CF_{RC}$
3. Fixed cost of postal collection, $CF_{PC}$
4. Fixed cost of kerbside collection, $CF_{KC}$
5. Fixed cost of localised recycling centres, $CF_{LRC}$
6. Fixed costs of waste transportation vehicles, $CF_{WTV}$
7. Fixed costs of renting/leasing premises, $CF_{PREM}$

For simplicity, it is assumed that the above parameters encompass the total sum of fixed costs associated each method, for instance, a localised recycling centre may have other fixed costs associated with it, including: collection infrastructure, drainage, power, lighting and security amongst other costs.

10.4.1.3 Variable costs

Variable costs are defined as: costs which vary with the volume of output material produced. When considering the variable costs associated with collecting and transporting leather waste, it is important to consider the following:
• The operational characteristics of the waste such as the geographic location and the volume of waste will impact the costs of transporting the waste from the site where it is generated to the site that it will be processed. For instance, if two leather wastes streams are generated, one from a tannery in Ethiopia and one from a footwear manufacturer in the EU, then transporting them both to a processing plant in England will have different economic implications.

• The method used to collect the waste because variable costs associated with an in-store recycling scheme will be different to the variable costs associated with an in-factory waste collection scheme

• The variable transportation costs are impacted by the material or product density in the waste stream because costs associated with transporting bulky leather furniture will be different to costs associated with compact footwear wastes

• What is the volume of waste that is going to be collected? What is the frequency of collection?

• What form will the transportation take? Road, rail, air or sea?

• What is the distance from the collection point to the central waste storage or processing depot?

The variable costs associated with the collection and transportation of leather waste include the cost of providing staff to collect the waste, the cost of fuel for the transportation vehicles and the cost of maintenance and repair of the collection equipment. As mentioned in Section 10.4.1.1, it may be necessary to purchase the waste materials from waste producers depending on the material value; this can also be a variable cost, because it is dependent on the tonnage purchased.

The economic parameters defined for these variable costs are:

1. Variable cost of waste acquisition, $CV_{WA}$
2. Variable cost of collection and transportation staff (labour), $CV_{CTS}$
3. Variable cost of fuel for transportation, $CV_{FT}$
4. Variable cost of maintenance and repair, $CV_{MR}$

It is important to understand that most of these costs are functions of other costs. Maintenance costs for example can be split into planned maintenance activities and reactive or unplanned maintenance. Planned maintenance activities are easy to predict and
factor into the economic model of a recycling system. Reactive maintenance activities are more complicated, and the cost of these activities is a function of the following:

- The cost of replacement parts for equipment
- The hourly rate or call out rate for a maintenance engineer
- The revenue lost due to the downtime of the machine

These costs are represented in Equation 10.4:

\[ CV_{MR} = (\text{cost replacement parts} + (\text{cost per hour for engineer} \times \text{No. of hours repair time}) + (\text{cost per hour of revenue lost} \times \text{No. of hours downtime of machine or system})) \]

\[ CV_{MR} = CV_{RP} + (CV_{ET} \times H_{RT}) + (R_{L-DT} \times H_{DT}) \]  
Equation 10.4

Where:

- \( CV_{RP} = \text{Cost of replacement parts} \)
- \( CV_{ET} = \text{Cost per hour for maintenance engineer} \)
- \( H_{RT} = \text{No. of hours the maintenance engineer took to repair equipment} \)
- \( R_{L-DT} = \text{Revenue lost per hour due to downtime of equipment or system} \)
- \( H_{DT} = \text{No. of hours that the equipment or system was out of action} \)

Given the potential for global marketing of leather products, the variable transportation costs could be significant, and will depend substantially upon the location and number of reprocessing sites available. It is important to note that variables costs all depend on the tonnage of material being collected, processed or disposed of. For instance, when calculating the cost of disposing of materials to landfill, this cost will depend on how many tonnes of materials need to be disposed of. All the parameters for variables costs that are listed in this chapter and subsequent chapters are calculated by multiplying the cost per tonne, for collection, processing or disposal, by the tonnage of material that is being collected, processed or disposed of.

### 10.4.1.4 Summary of economic parameters for collection and transportation

The economic parameters for the collection and transportation stages of the cost model are summarised in Table 10.1.
Table 10.1: Economic parameter for costs and revenue associated with collection and logistics of leather waste

<table>
<thead>
<tr>
<th>Economic parameter name</th>
<th>Revenue</th>
<th>Fixed costs</th>
<th>Variable costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste collection services</td>
<td>$R_{WCS}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Cost of industrial collection equipment</td>
<td>$CF_{ICE}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of retail collection</td>
<td>$CF_{RC}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of postal collection</td>
<td>$CF_{PC}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of kerbside collection</td>
<td>$CF_{KC}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of localised recycling centres</td>
<td>$CF_{LRC}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of waste transportation vehicles</td>
<td>$CF_{WTV}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of renting premises</td>
<td>$CF_{PREM}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of waste acquisition</td>
<td>$CV_{WA}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of collection and transportation staff</td>
<td>$CV_{CTS}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of fuel for transportation</td>
<td>$CV_{FT}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of maintenance and repair</td>
<td>$CV_{MR}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

10.4.2 Economic parameters: processing and redistribution

In this section, economic parameters are defined for the revenue, fixed costs and variable costs associated with processing and redistribution of leather waste.

10.4.2.1 Revenue

Most of the revenue generated from a recycling system is from the sale of the recovered leather materials; however, other sources of revenue are present. It is possible to sell other material fractions that have been recovered from leather products. Materials such as rubber and metals will command a higher price than materials such as foam and textiles, but all materials fractions will generate revenue when sold on the recycled materials market.

Several factors influence the amount of revenue that is generated. These are:

- The next application of the recycled materials. Will the material be used for a high, medium or low value application?
• The purity of the recovered output material. A higher purity output material will command a higher price on a recycled materials market

• The volume of each material fraction recovered

• The types of material recovered from the waste (material content)

As stated, the revenue generated from any of the recycled materials is based on the purity of the materials, and this relationship is non-linear. Therefore, the economic parameters defined for these revenue sources are:

1. Sale of leather materials, $R_{LM}$
2. Sale of other recovered materials (rubber, textiles, metals), $R_{OM}$

10.4.2.2 Fixed costs

During processing and redistribution of recycled materials, the primary fixed costs are those associated with buying the processing equipment. Several factors influence the amount of fixed costs, including the number of processes required in recycling chain, the type of waste that is being processed and the throughput of the recycling system.

The economic parameters defined for these fixed costs are:

1. Cost of metal detection and removal equipment, $CF_{MD}$
2. Cost of fragmentation equipment, $CF_{FG}$
3. Cost of post-fragmentation separation equipment, $CF_{PFSE}$
4. Cost of post-fragmentation processing equipment, $CF_{PFPE}$

10.4.2.3 Variable costs

Variable costs are costs associated with day to day running of the recycling line and they vary with the amount of material that is being processed, these are costs that will occur continually such as labour, consumables or energy, therefore, variable costs will be stated in terms of cost per tonne of material.

Several factors influence the variable costs that are incurred, and these are:

• The throughput of the recycling system
• The number of processes used within the recycling system, the more processes there are, the more energy is required to run them

• The volume of material that is being processed

• The materials composition of the waste stream. For example, a waste stream with a higher percentage of embedded metal will have a higher sorting cost than a waste stream with no metal content

The variable costs associated with creating a leather recycling line are:

1. Cost of labour for sorting waste materials, \( CV_{LS} \)
2. Cost of energy for equipment, \( CV_{EE} \)
3. Cost of labour for operating the processing equipment, \( CV_{LP} \)
4. Cost of consumables for use during processing, \( CV_{CC} \)
5. Cost of redistribution (shipping) of recovered materials, \( CV_{GRD} \)
6. Costs of disposing of unrecoverable materials (landfill costs), \( CV_{DIS} \)

Cost of energy for processing equipment

It is important to note that many of the costs listed above are functions of other costs. For instance, the cost of energy required to operate the processing equipment is a function of the following things:

• Throughput rate of the recycling system (in tonnes per hour)
• The standing rate fee that a company will pay on an annual basis to their energy supplier
• The price per kwh for the energy that the company uses

These costs are represented in Equation 10.5:

Running cost = (energy consumption x energy cost/throughput)

\[ CV_{EE} = \frac{CV_{sc}/24}{T_s} + \left( U_{EPE} \times \frac{CV_{kwh}}{T_s} \right) \]

Equation 10.5

Where:
\( CV_{SC} \)
\( = \text{Cost of standing charge imposed by energy company in pounds per day (24 hrs)} \)

\( U_{EPE} = \text{Power rating for equipment in kW} \)

\( CV_{kwh} = \text{Cost per kwh of energy from energy supplier (£/kwh)} \)

\( T_S = \text{System throughput in tonnes per hour (T/h)} \)

Cost of labour for operating processing equipment

Cost of labour for operating the process equipment is a function of the following things:

- Basic pay rate (age dependent if minimum wage is used)
- National insurance contributions
- Holiday provision
- Statutory pay provision
- Pension pay provision
- No. of hours that the employee is contracted to perform

These costs are represented in Equation 10.6:

\[
CV_{LP} = H_{EW} \times CV_{BR} \left( 1 + \frac{ENIC+HP+SPP+PPP}{100} \right) \quad \text{Equation 10.6}
\]

Where:

\( CV_{LP} = \text{Cost of labour for operating processing equipment per annum} \)

\( H_{EW} = \text{hours worked by the employee per annum} \)

\( CV_{BR} = \text{basic rate of pay per hour} \)

\( ENIC = \text{Employers National Insurance Contributions (% of basic rate)} \)

\( HP = \text{Holiday Provision (% of basic rate)} \)

\( SPP = \text{Statutory Pay Provision (% of basic rate)} \)

\( PPP = \text{Pension Pay Provision (% of basic rate)} \)

**10.4.2.4 Summary of economic parameters for processing and redistribution**

The economic parameters for the processing and redistribution stages of the cost model are summarised in Table 10.2.
Table 10.2: Economic parameters for costs and revenue associated with processing and redistribution of leather waste

<table>
<thead>
<tr>
<th>Economic parameter name</th>
<th>Revenue</th>
<th>Fixed costs</th>
<th>Variable costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sale of leather materials</td>
<td>$R_{LM}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sale of other recovered materials (rubber, textiles, metals)</td>
<td>$R_{OM}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of metal detection and removal equipment</td>
<td>$CF_{MD}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of fragmentation equipment</td>
<td>$CF_{FG}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of post-fragmentation separation equipment</td>
<td>$CF_{PFSE}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of post-fragmentation processing equipment</td>
<td>$CF_{PFPE}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of labour for sorting waste materials</td>
<td>$CV_{LS}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of energy for equipment</td>
<td>$CV_{EE}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of labour for operating the processing equipment</td>
<td>$CV_{LP}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of consumables for use during processing</td>
<td>$CV_{CC}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of redistribution (shipping) of recovered materials</td>
<td>$CV_{CRD}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costs of disposing of unrecoverable materials (landfill costs)</td>
<td>$CV_{DIS}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

10.4.3 Equation for revenue/ benefits

The equation presented in this section will combine the economic parameters for all revenue streams from Sections 10.4.1 and 10.4.2, along with a new variable outlined below to create an equation that represents the total revenue for the recycling system.

There is one more financial benefit associated with the development and implementation of a leather recycling solution, which is the benefit realised by not sending material to landfill. For every tonne of material that is not sent to landfill, this represents a saving for the waste producer. This benefit will be given the economic parameter $R_{LDF}$ and will be included in the cost model. The total benefits associated with any leather recycling scenario, $B_{leather}$, are calculated as the sum of all revenues generated by the sale of the materials recovered from the recycling process, fees charged to collect waste materials and the savings made from not sending materials to landfill (as depicted in equation 10.7).

$$B_{leather} = R_{WCS} + R_{LM} + R_{OM} + R_{LDF}$$

$$B_{leather} = R_{WCS} + (LM_{weight} \times LM_{value}) + (OM_{weight} \times OM_{value}) + (T_{AL} \times L_{TAX})$$

Equation 10.7
Where,

\[ LM = \text{leather materials} \]
\[ OM = \text{other materials} \]
\[ T_{AL} = \text{Material averted from landfill (tonnes)} \]
\[ L_{TAX} = \text{Cost per tonne of sending material to landfill (£/T)} \]

10.4.4 Equation for fixed costs

The equation presented in this section combines the economic parameters for fixed costs from Sections 10.4.1 and 10.4.2 to create an equation that represents the total fixed costs for the system.

This gives a parametric equation for the fixed costs, \( CF \), associated with a leather recycling system, as depicted in Equation 10.8.

\[
CF = CF_{ICE} + CF_{RC} + CF_{PC} + CF_{KC} + CF_{LRC} + CF_{WTV} + CF_{PREM} + CF_{MD} + CF_{FG} + CF_{PFSE} + CF_{PPPE}
\]

Equation 10.8

The fixed costs form one half of the total costs associated with a leather recycling system, the other associated costs are the variable costs and an equation for these will be defined in the next section.

10.4.5 Equation for variable costs

The equation presented in this section will combine the economic parameters for all variable costs from Sections 10.4.1 and 10.4.2 to represent the total variable costs for the system.

This gives a parametric equation for the variable costs, \( VC \), associated with a leather recycling system, as depicted in Equation 10.9.

\[
CV = CV_{WA} + CV_{CTS} + CV_{FT} + CV_{MR} + CV_{LS} + CV_{EE} + CV_{LP} + CV_{CC} + CV_{GRD} + CV_{DIS}
\]

Equation 10.9

When equations 10.4 to 10.6 are substituted into Equation 10.9 it becomes:
\[ CV = CV_{WA} + CV_{CTS} + CV_{FT} + (CV_{RP} + (CV_{ET} \times H_{RT}) + (R_{L-DF} \times H_{DT})) + CV_{LS} + \]
\[
\left( \frac{CV_{sc}}{24} \right) + \left( \frac{CV_{kwh}}{T_S} \right) + (H_{EW} \times CV_{BR} \left( 1 + \frac{ENIC+HP+SPP+PPP}{100} \right)) + CV_{CC} + CV_{CRD} + CV_{DIS}
\]

Equation 10.10

The next section will bring together the equations from this section and Sections 10.4.3 and 10.4.4 together to form a complete cost model, which can be used to evaluate the economics of implementing a circular approach in the leather industry.

10.4.6 Final parametric cost-benefit model

This section brings together the equations from the last three sections which represent the revenue and the fixed and variable costs associated with creating a leather recycling system. Together, these equations form a complete parametric cost model for the implementation of a circular approach in the leather industry. Equations 10.3 to 10.12 form the complete cost model and are summarised below:

\[ CBR_{leather} = \frac{\sum_{m=1}^{n} C_m}{\sum_{m=1}^{n} P_m} \quad \text{Equation 10.3} \]

\[ B_{leather} = R_{WCS} + (LM_{weight} \times LM_{value}) + (OM_{weight} \times OM_{value}) + (T_{AL} \times L_{TAX}) \quad \text{Equation 10.4} \]

\[ CF = CF_{ICE} + CF_{RC} + CF_{PC} + CF_{KC} + CF_{LRC} + CF_{WTV} + CF_{PREM} + CF_{MD} + CF_{FG} + CF_{PFSE} + CF_{PFPE} \quad \text{Equation 10.8} \]

\[ CV = [CV_{WA} + CV_{CTS} + CV_{FT} + (CV_{RP} + (CV_{ET} \times H_{RT}) + (R_{L-DF} \times H_{DT})) + CV_{LS} + \]
\[
\left( \frac{CV_{sc}}{24} \right) + \left( \frac{CV_{kwh}}{T_S} \right) + (H_{EW} \times CV_{BR} \left( 1 + \frac{ENIC+HP+SPP+PPP}{100} \right)) + CV_{CC} + CV_{CRD} + CV_{DIS} \]

Equation 10.10

\[ \text{Profitability of the system} = B_{leather} - [CF_{ICE} + CF_{RC} + CF_{PC} + CF_{KC} + CF_{LRC} + CF_{WTV} + CF_{PREM} + CF_{MD} + CF_{FG} + CF_{PFSE} + CF_{PFPE}] - [CV_{WA} + CV_{CTS} + CV_{FT} + (CV_{RP} + (CV_{ET} \times H_{RT}) + (R_{L-DF} \times H_{DT})) + CV_{LS} + \]
\[
\left( \frac{CV_{sc}}{24} \right) + \left( \frac{CV_{kwh}}{T_S} \right) + (H_{EW} \times CV_{BR} \left( 1 + \frac{ENIC+HP+SPP+PPP}{100} \right)) \]
By combining Equations 10.8, 10.10 and 10.4 it is possible to calculate the cost-benefit ratio, as shown in Equation 10.12 below:

\[
\frac{\text{Cost}}{\text{benefit}} \text{ ratio (CBR}_{\text{leather}}) =
\]

\[
= CF_{ICE} + CF_{RC} + CF_{PC} + CF_{KC} + CF_{LRC} + CF_{WTV} + CF_{PREM} + CF_{MD} + CF_{FG} + CF_{PFSE}
\]

\[
+ CF_{PFPE} \right) + W_m \left[ CV_{WA} + CV_{CTS} + CV_{FT} + \{CV_{RP} + (CV_{ET} \ast H_{RT})
\]

\[
+ (R_L- DT \ast H_{DT}) \right) \right) + CV_{LS} + \left( \frac{CV_{SC}}{T_s} + \left( U_{EPE} \ast \frac{CV_{RWH}}{T_S} \right) \right) + (H_{EW})
\]

\[
* CV_{BR} \left( 1 + \frac{ENIC + HP + SPP + PPP}{100} \right) \right) + CV_{CC} + CV_{CRD} + CV_{DIS}
\]

\[
/ R_{WCS} + (L \text{M}_{\text{weight}} * L \text{M}_{\text{value}}) + (O \text{M}_{\text{weight}} * O \text{M}_{\text{value}}) + (T_{AL} * L_{TAX})
\]

Equation 10.12

10.5 Summary

The first part of this chapter explored the economic decisions that are made during the development of recycling systems and how these decisions can be supported through the creation of a parametric cost model.

The next part of the chapter described in detail the costs and revenue streams associated with recycling systems, including fixed and variable costs. These costs were then used to formulate a parametric cost model for the complete leather recycling system. Once the parametric model was formed, consideration to how it could be used by recycling organisations was presented. Chapter 11 presents the application of the parametric cost model to two case studies.
CHAPTER 11  CASE STUDIES

11.1 Introduction

This chapter presents two case studies that have been selected to demonstrate how the research reported within the thesis can be applied. The chapter begins by giving an overview of the case studies which is followed by a description of the steps taken to complete them. After this, the results from each case study are presented and analysed and conclusions are drawn about the validity of the framework and economic model in supporting the implementation of a circular approach within the leather industry.

11.2 Overview of selected case studies

During the case study investigations, two examples are used to demonstrate how the framework and cost model reported within the thesis can be applied to the management of leather waste. The first study is used to evaluate the economic feasibility of a VERP strategy for leather waste and aims to improve the economic viability of leather recycling through improved quality by collecting wastes vertically across the lifecycle of a product. The second case study is used to evaluate the economic feasibility of a HORP strategy, which aims to improve the economic feasibility of leather recycling through economy of scale by collecting leather waste horizontally across a range of product sectors. An overview of both case studies is shown in Figure 11.1.

![Figure 11.1: Visualisation of the first and second case studies](image-url)
11.3 Case Study 1

The purpose of this case study is to demonstrate the application of the framework and economic support tool to the concept of vertically grouping and processing leather waste. For the purposes of this case study, waste generated by a leather tannery will be studied. This company produces finished leather hides and manufactures leather products together in the same factory, due to confidentiality reasons the tannery does not wish to be named and from this point forward the tannery will be referred to as ‘Tannery X’.

This case study will attempt to answer the following question:

- Is it economically effective for Tannery X to collect and process their own waste horizontally across the lifecycle of their production processes?

11.3.1 Implementation of case study 1

The first step in implementing the case study was to apply Stages 1 to 3 of the CAL framework to: characterise the waste streams, define the collection and waste grouping strategy and define the leather processing scenario, these steps will be described in Sections 11.3.2 to 11.3.3. The application of Stages 1 to 3 of the framework generated data and assumptions which are detailed in Section 11.3.4. These data and assumptions were used to enable the application of the Stage 4 of the framework: the cost model, as described in Section 11.3.5.

A cost-benefit spreadsheet in excel was generated to support the parametric CBA described in Chapter 10, and again to generate graphical representations of the results. After the economic model was applied, the results were analysed and the feasibility of the strategy was assessed, this analysis is presented in Section 11.3.6. The largest costs associated with the recycling system were then identified and recommendations were given for amendments to the strategy that could improve the economic viability and optimize the cost-benefit ratio. Conclusions were drawn from the analysis and these are presented in Section 11.5.

11.3.2 Characterisation of waste streams for case study 1

The waste stream considered in this case study consists of wastes from the tanning and finishing of leather hides along with wastes from the production of leather goods within Tannery X factory. A schematic of the waste produced by Tannery X is shown in Figure 11.2,
it illustrates the range of leather wastes produced during the tanning and finishing operations, data and waste samples were provided to the author during a visit to Tannery X.

The following assumptions underline the characteristics of the waste stream that are identified as being relevant to the end-of-life management process:

- The waste streams arise from a single factory site
- In total, 8.5 tonnes of leather waste is available for processing per day on average, which, at 260 working days per year, equates to 2210 tonnes per year of leather waste per annum
- The waste consists of leather hide processing waste from the tanning stage of ‘wet-blue’ onwards, no putrescible waste from earlier in the tanning process is considered within this analysis

![Characterise wastes generated by Tannery X per day](image)

Figure 11.2: Characterisation of wastes generated by Tannery X
• The individual waste streams shown in Figure 11.2 are segregated at source within the factory and are collected in skips at the location where they are initially generated, before sending them to landfill. Tannery X currently owns these skips.
• The waste streams from the ‘tanned but unfinished’ stages of the production are all single-material waste streams; there are no contaminant materials present in this stream.

11.3.3 Definition of end-of-life scenario for case study 1

The end-of-life process route developed as Scenario 1 is represented graphically in Figure 9.9 of the thesis and is defined in detail in this section.

11.3.3.1 COLLECTION AND SORTING

Collection and sorting is conducted at the site where the end-of-life wastes are generated. No additional transportation is required to move the wastes to the location where the first recycling process step (i.e. sorting) takes place. Wastes are sorted according to their material content and level of finishing. Wastes that are 100% leather will be segregated from mixed-material wastes, after which they will be fragmented and processed separately.

11.3.3.2 PROCESSING

Metal detection and removal is not required in this case study because the tannery and manufacturing wastes generated by Tannery X do not contain metal. The processing route for case study 1 has three principal process steps and these are:

1. Fragmentation
2. Material separation via zig-zag separator
3. Material separation via vibrating air-table

The fragmentation process used for this waste will be granulation. Granulation of materials is a proven technique for fragmenting plastic materials at industrial scale. Granulation of leather wastes, both material and product, has been proven at a laboratory scale. However, specific data from the process trials are not available for quantifying energy and other process requirements. Therefore, data generated by the previous work at Centre for SMART on footwear recycling (Lee and Rahimifard, 2012a) are re-utilised. The post-fragmentation separation processes used are zig-zag separator, followed by air-table separation, the outputs from which are leather, foam and textiles.
11.3.3 REDISTRIBUTION

Four redistribution scenarios for leather wastes and mixed wastes are possible; they are outlined below in Table 11.1.

For the medium and low value applications, the purity and physical properties of the leather recovered from the mixed waste is not suitable for applications where virgin material would be used, hence the recovered material is down-cycled compared to virgin leather. The definition of scenario one is summarised in Figure 11.3, the tonnage figures represent the amount of waste generated per day for each of the waste categories.

Table 11.1: Four distribution scenarios for leather wastes and mixed wastes

<table>
<thead>
<tr>
<th>Value of recovered material</th>
<th>Description of recovered material</th>
<th>Visual representation of recovered material</th>
</tr>
</thead>
<tbody>
<tr>
<td>High value</td>
<td>Leather off-cuts suitable for direct re-use in leather products</td>
<td><img src="image" alt="High Value Material" /></td>
</tr>
<tr>
<td>Med-high value</td>
<td>100% granulated leather (finished or unfinished) OR mixed material of 80-95% leather content this is suitable to be reformed into e-leather</td>
<td><img src="image" alt="Med-High Value Material" /></td>
</tr>
<tr>
<td>Med-low value</td>
<td>Mixed material of 70-80% leather content, this is suitable to be applied to mop up chemical spills.</td>
<td><img src="image" alt="Med-Low Value Material" /></td>
</tr>
<tr>
<td>Low value</td>
<td>Mixed material (textile, foam and leather) with leather content of less than 70%, this is suitable to be reused as low-grade insulation material or underlay for various types of flooring</td>
<td><img src="image" alt="Low Value Material" /></td>
</tr>
</tbody>
</table>
11.3.4 Data and assumptions for case study 1

Sections 11.3.2 and 11.3.3 provided high-level data that define the waste streams and end-of-life scenario that are evaluated in case study 1. These data are developed from real data and assumptions and collated from various sources. More detailed data regarding the economic attributes of the process steps described are required to apply the evaluation methods to the scenarios; this data is presented in the next section. But first a series of assumptions are defined:

- Tannery X are going to process and redistribute the waste that they generate in-house, they will not have an external contractor collect and process the waste
- Tannery X already have equipment (waste skips) for collecting the various wastes that they generate around the factory
• Tannery X already own the equipment (fork lift trucks) needed to move the waste receptacles around the factory
• The ‘mixed offcuts’ category of waste contains 95% leather and 5% other materials
• The materials within the input waste streams have a low proportion of contamination, as these are not worn or dirty like post-consumer wastes are likely to be (the quality is high).
• The processing equipment will only be run from Monday to Friday, the factory is closed at the weekend
• The input waste materials are only run through the processing line once at an average throughput of 0.5 tonnes per hour
• The fragmentation and air-separation processes run at 100% efficiency, no material will be lost from any of these processes, therefore the weight of material input to process is equal to the weight of material output from process
• The recovery efficiency for the combined separation processes is 95%, therefore for every tonne of leather input to the system, 5% of this leather will not be recovered and will be captured within the ‘other material’ fraction. This separation efficiency is based on experimental trials that were conducted for the purposes of this research.
• The movement of the recovered material from the process to the redistribution station will be an additional duty for the employee who drives the forklift truck who would usually be moving the waste ready for distribution to landfill. Therefore, no extra human resources are required here.
• The new employees for operating the process equipment will be over 25 years of age; hence, the higher rate of living wage will apply. The employer will need to make pensions contributions of minimum 1% of salary; this means that the true cost for each employee is £9.21 per hour (Essential recruitment, 2017).
• Employees will work for five days per week, and will do an 8-hour shift once per day
• No post-separation processing is required, all materials are sold as in the form that they are recovered
• Transportation of redistributed materials will be a bought-in service and the locations to distribute all output materials to are 20 miles from the Tannery X factory
• None of the recovered materials are sent to landfill, all materials are sold on to be used within other industries
### 11.3.4.1 Data to support evaluation of economic feasibility

Quantification of all costs and benefits arising during the end-of-life management of leather is required to facilitate the evaluation of the economic feasibility of leather recycling using CBA. Cost data to support the case study is obtained from various sources.

**Data for revenue of different grades of material**

To perform the cost-benefit analysis it is necessary to know the price that the recycled leather material of different grades will command on the secondary materials market. At present, due to the infancy of the recycled leather market, this data does not exist. Therefore, assumptions were made about the value of the materials based on data from previous work on footwear recycling (Lee and Rahimifard, 2010); this data is displayed in Table 11.2.

**Data for costs of setting up the system and ongoing processing costs**

Setting up the recycling system involves purchasing equipment and operating the recycling line requires employees. The costs per hour of hiring employees on the living wage are detailed in Table 11.3 and capital costs for processing equipment and energy requirements are approximated in Table 11.4. This data was acquired from previous work completed on footwear recycling and updated with energy prices that are reflective of the market in 2017.

<table>
<thead>
<tr>
<th>Redistribution scenario</th>
<th>Recycling process</th>
<th>Recovered materials and applications</th>
<th>Revenue (£/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High grade leather</td>
<td>None required</td>
<td>Primary material types, Off-cuts of leather suitable for direct re-use in leather products.</td>
<td>£226</td>
</tr>
<tr>
<td>Medium-high grade mixed material</td>
<td>Granulation</td>
<td>100% granulated leather (finished or unfinished) OR mixed material of 80-95% leather content this is suitable to be reformed into e-leather</td>
<td>£180</td>
</tr>
<tr>
<td>Med-low grade mixed material</td>
<td>Granulation, separation</td>
<td>Mixed material of 70-80% leather content, this is suitable to be applied to mop up chemical spills.</td>
<td>£140</td>
</tr>
<tr>
<td>Low grade mixed material</td>
<td>Granulation, separation</td>
<td>Mixed material (textile, foam and leather) with leather content of less than 70%, this is suitable to be reused as low-grade insulation material or underlay</td>
<td>£82</td>
</tr>
</tbody>
</table>
Table 11.3: Hourly rate for recycling line employees (Essential recruitment, 2017).

<table>
<thead>
<tr>
<th>Pay rate</th>
<th>Basic rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>£7.50</td>
<td></td>
</tr>
<tr>
<td>Actual ENIC Provision @ 8.40%</td>
<td>£0.63</td>
</tr>
<tr>
<td>Holiday Provision @ 12.07%</td>
<td>£0.91</td>
</tr>
<tr>
<td>Statutory Pay Provision @ 1.00%</td>
<td>£0.08</td>
</tr>
<tr>
<td>Pension Pay Provision @ 1.00%</td>
<td>£0.08</td>
</tr>
<tr>
<td><strong>Total charge rate per hour</strong></td>
<td><strong>£9.21</strong></td>
</tr>
</tbody>
</table>

Table 11.4: Summary of approximate capital and running costs for processing equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Power rating (kw)</th>
<th>Capital cost (approximate, £, per unit of equipment)</th>
<th>Running costs* (£/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granulator</td>
<td>20</td>
<td>25000</td>
<td>2.02</td>
</tr>
<tr>
<td>Zig-zag separator/air cascade</td>
<td>4</td>
<td>20000</td>
<td>0.42</td>
</tr>
<tr>
<td>Air-table</td>
<td>4</td>
<td>24000</td>
<td>0.42</td>
</tr>
</tbody>
</table>

*Running cost = (Power Rating x energy cost/throughput), where energy cost is 11.12pence/kwh and standing charge is 22.75pence per day for 365 days, and throughput of the system is 0.5tonnes/hour (BusinessElectricityPrices.org.uk, 2017).

Data for redistribution costs

Redistribution of the recovered materials involves packaging up the materials and transporting them to a new location. The costs involved with these processes are associated with the packaging materials and the transportation/haulage of the materials. The output materials from the granulation and the separation processes will be packaged in 1-tonne building sacks and they will be loaded onto a curtain-sider haulage vehicle with a forklift truck, which Tannery X already own, ready for redistribution. The sacks will not be returned to Tannery X after use. Overall, 2210 tonnes of material will need to be packaged up for redistribution. Assuming one builder sack is required for every tonne of material, plus a 5% contingency for bags that get damaged. This means that 2321 sacks will be required at an average cost of £2.46 each (Sackmarket, 2017), this gives total costs for building sacks as £ 5709.66. The haulage of the redistributed materials is carried out by a third-party haulage contractor. The haulage market was reviewed, and the data and assumptions were gathered, Table 11.5 illustrates how a haulage price per tonne of material was calculated.
Table 11.5: Haulage costs for redistributing materials

<table>
<thead>
<tr>
<th>Assumptions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Miles to each redistribution location</td>
<td>20</td>
</tr>
<tr>
<td>Gross vehicle weight (tonnes)</td>
<td>32</td>
</tr>
<tr>
<td>Weight carried per load (tonnes)</td>
<td>21.5</td>
</tr>
<tr>
<td>Trips that haulier can make per day</td>
<td>2</td>
</tr>
<tr>
<td>Miles covered per day</td>
<td>80</td>
</tr>
<tr>
<td>Material hauled per day (tonnes)</td>
<td>43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost calculations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Haulier fee for 1 standard day</td>
<td>£285.00</td>
</tr>
<tr>
<td>80 miles at 115.4 pence per mile</td>
<td>£92.32</td>
</tr>
<tr>
<td>Drivers bonus and additional overtime per day</td>
<td>£15.00</td>
</tr>
<tr>
<td>Weighbridge costs</td>
<td>£30.00</td>
</tr>
<tr>
<td>Total costs for 1 day</td>
<td>£422.32</td>
</tr>
<tr>
<td>Target margin for haulage company (5%)</td>
<td>£21.12</td>
</tr>
<tr>
<td>Desired revenue for haulage company for 1 day @40 tonnes</td>
<td>£443.44</td>
</tr>
<tr>
<td>Desired rate and quotation per tonne (assuming 20 tonnes per load)</td>
<td>£10.31</td>
</tr>
<tr>
<td>Cost per annum for 2220 tonnes of material</td>
<td>£22,790.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Schedule considerations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number days required to haul 2210 tonnes</td>
<td>51</td>
</tr>
<tr>
<td>System output produced by Tannery X every day (tonnes)</td>
<td>8.5</td>
</tr>
<tr>
<td>System output produced by Tannery X every 5 days (tonnes)</td>
<td>42.5</td>
</tr>
</tbody>
</table>

Therefore, every week the haulier will remove 43 tonnes material from Tannery X factory site, the material will be stored under cover on Tannery X site until it is collected.

11.3.5 Application of the economic cost model

To apply the cost model to this case study and assess the economic viability of the horizontal waste collection and grouping strategy, it was first necessary to calculate all revenues, fixed costs and variable costs associated with the case study. Data and assumptions detailed in Sections 11.3.2 and 11.3.4 are used as the basis for these values.

The parametric models defined in equations 10.3 to 10.12 are used to construct an economic evaluation of the implementation of a circular approach in the leather industry based on scenario 1 (i.e. horizontal model). Firstly, Equations 10.4, 10.8 and 10.10 were used to calculate the total fixed costs, variable costs and revenues for this case study.
Table 11.6 presents details of the running costs of the processing equipment and revenue generated from the sale of the redistributed materials, generated by a spreadsheet developed using Equations 10.4 to 10.8, as outlined below.

\[ B_{leather} = R_{WCS} + (LM_{weight} \cdot LM_{value}) + (OM_{weight} \cdot OM_{value}) + (TAL \cdot L_{TAX}) \]

Equation 10.4

\[ CF = CF_{ICE} + CF_{RC} + CF_{PC} + CF_{KC} + CF_{LRC} + CF_{WTV} + CF_{PREM} + CF_{MD} + CF_{FG} + CF_{PFSE} + CF_{PPPE} \]

Equation 10.8

\[ CV = [CV_{WA} + CV_{CTS} + CV_{FT} + \{CV_{RP} + (CV_{ET} \cdot H_{RT}) + (R_{L-DT} \cdot H_{DT})\} + CV_{LS} + \left\{\frac{CV_{sc}}{24 T_s} + (U_{EPE} \cdot \frac{CV_{kwh}}{T_s})\right\} + (H_{EW} \cdot CV_{BR} \left(1 + \frac{ENIC+HP+SPP+PPP}{100}\right)) + CV_{CC} + CV_{CRD} + CV_{DIS} \]

Equation 10.10

For the purposes of this case study, there are no costs and revenues associated with the waste collection and transportation stages of the recycling system. Therefore, the only costs and revenues are associated with the processing and redistribution stages of the recycling system and they are summarised in Table 11.7.
### Table 11.6: Calculation of running costs for the processing equipment and revenues from redistributed materials per annum

<table>
<thead>
<tr>
<th>Tonnage of waste for processing</th>
<th>Wet blue first offcuts</th>
<th>Wet blue shavings</th>
<th>Wet blue buffing dust</th>
<th>Second shaving and offcuts</th>
<th>Perforation holes</th>
<th>Lab test samples</th>
<th>Cutting room offcuts</th>
<th>Mixed product offcuts</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste generated per day (tonnes)</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0.5</td>
<td>0.25</td>
<td>0.5</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Waste generated per year (260 working days) (tonnes)</td>
<td>520</td>
<td>520</td>
<td>260</td>
<td>520</td>
<td>130</td>
<td>65</td>
<td>130</td>
<td>65</td>
<td>2210</td>
</tr>
<tr>
<td>Leather material recovered for redistribution (tonnes)</td>
<td>520</td>
<td>520</td>
<td>260</td>
<td>520</td>
<td>130</td>
<td>65</td>
<td>130</td>
<td>61.75</td>
<td>2206.75</td>
</tr>
<tr>
<td>Total low-value material recovered from system (tonnes)</td>
<td>3.25</td>
<td>3.25</td>
<td>2.60</td>
<td>3.25</td>
<td>2.60</td>
<td>2.60</td>
<td>3.25</td>
<td>3.25</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Running costs</th>
<th>£2.02</th>
<th>£2.02</th>
<th>£2.02</th>
<th>£2.02</th>
<th>£2.02</th>
<th>£2.02</th>
<th>n/a</th>
<th>£2.02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granulator running costs per tonne</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>£0.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Revenue from selling materials</th>
<th>Medium-high</th>
<th>Medium-high</th>
<th>Medium-high</th>
<th>Medium-high</th>
<th>Medium-high</th>
<th>Medium-high</th>
<th>High</th>
<th>Medium-high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value for different quality brackets (£226, £180, £82)</td>
<td>£180.00</td>
<td>£180.00</td>
<td>£180.00</td>
<td>£180.00</td>
<td>£180.00</td>
<td>£180.00</td>
<td>£266.00</td>
<td>£180.00</td>
</tr>
<tr>
<td>Total revenue for redistributed High and Med-high quality materials</td>
<td>£93,600.00</td>
<td>£93,600.00</td>
<td>£46,800.00</td>
<td>£93,600.00</td>
<td>£23,400.00</td>
<td>£11,700.00</td>
<td>£29,380.00</td>
<td>£11,115.00</td>
</tr>
<tr>
<td>Total revenue generated by selling 'other materials' (Low value bracket at £82 per tonne)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>£266.50</td>
<td>£266.50</td>
</tr>
</tbody>
</table>

| Money saved by not sending waste to landfill | £44,772.00 | £44,772.00 | £22,386.00 | £44,772.00 | £11,193.00 | £5,596.50 | £11,193.00 | £5,596.50 | £190,281.00 |

160
Table 11.7: Costs and revenues per annum for the processing and redistribution stages of the recycling system presented in case study 1

<table>
<thead>
<tr>
<th>Economic parameter name</th>
<th>Revenue</th>
<th>Fixed costs</th>
<th>Variable costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sale of leather materials (High and med-high quality)</td>
<td>£403,195</td>
<td></td>
<td>See Table 11.6</td>
</tr>
<tr>
<td>Sale of low-quality materials</td>
<td>£266.50</td>
<td></td>
<td>See Table 11.6</td>
</tr>
<tr>
<td>Cost of metal detection and removal equipment</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Cost of fragmentation equipment</td>
<td>£25,000</td>
<td></td>
<td>See Table 11.4</td>
</tr>
<tr>
<td>Cost of post-fragmentation separation equipment</td>
<td>£44,000</td>
<td></td>
<td>See Table 11.4</td>
</tr>
<tr>
<td>Cost of post-fragmentation processing equipment</td>
<td>n/a</td>
<td></td>
<td>No post-separation processing occurs in this case study, materials are sold in the form which they are recovered (either granulated or leather offcuts)</td>
</tr>
<tr>
<td>Cost of labour for sorting waste materials</td>
<td></td>
<td>£19,156.80</td>
<td></td>
</tr>
<tr>
<td>Cost of energy for equipment/running costs</td>
<td></td>
<td>£4256.20</td>
<td>See Table 11.6, includes annual standing charge and cost per kwh</td>
</tr>
<tr>
<td>Cost of labour for operating the processing equipment</td>
<td></td>
<td>£19,156.80</td>
<td>True cost of 1 x employee per hour = £9.21, 8 hours per day, 260 days per year. This cost represents half the cost of each employee; the other half of their role will be to sort the waste materials.</td>
</tr>
<tr>
<td>Cost of consumables for use during processing</td>
<td></td>
<td>£5,708.43</td>
<td>See Section 11.3.4.1 for calculation of this cost</td>
</tr>
<tr>
<td>Cost of redistribution of recovered materials</td>
<td></td>
<td>£22,790.55</td>
<td>Haulage costs and assumptions detailed in Table 11.5</td>
</tr>
<tr>
<td>Costs of disposing of unrecoverable materials (landfill costs)</td>
<td></td>
<td>£0.00</td>
<td>£86.10 per tonne (GOV UK, 2017), a lower rate of landfill tax is £2.70 per tonne but this is reserved for: (A lower band is applied to inert waste that contains no biodegradable material)</td>
</tr>
</tbody>
</table>
After the fixed costs, variable costs and revenues were identified, equations 10.11 and 10.12 were used to calculate the profitability and cost-benefit ratio for this case study. Table 11.8 presents the results of these calculations.

**Profitability of the system**

\[ \text{Profitability of the system} = B_{\text{leather}} - \left[ CF_{\text{ICE}} + CF_{\text{RC}} + CF_{\text{PC}} + CF_{\text{KC}} + CF_{\text{LRC}} + CF_{\text{WTV}} + CF_{\text{PREM}} + CF_{\text{MD}} + CF_{\text{FG}} + CF_{\text{PPFE}} + CF_{\text{PPPE}} \right] - \left[ CV_{\text{WA}} + CV_{\text{CTS}} + CV_{\text{FT}} + \{ CV_{\text{RP}} + (CV_{\text{ET}} \times H_{\text{RT}}) + (R_{\text{L-DT}} \times H_{\text{DT}}) \} + CV_{\text{LS}} + \left( \left( \frac{CV_{\text{sc}}/24}{T_{\text{s}}} + (U_{\text{EPPE}} \times \frac{CV_{\text{rwh}}}{T_{\text{s}}}) \right) \right) + (H_{\text{EW}} \times CV_{\text{BR}} \left( 1 + \frac{\text{ENIC+HP+SPP+PPP}}{100} \right)) + CV_{\text{CC}} + CV_{\text{CRD}} + CV_{\text{DIS}} \]\n
Equation 10.11

\[ \frac{\text{Cost}}{\text{benefit}} \text{ ratio (CBR}_{\text{leather}}) = \]

\[ = CF_{\text{ICE}} + CF_{\text{RC}} + CF_{\text{PC}} + CF_{\text{KC}} + CF_{\text{LRC}} + CF_{\text{WTV}} + CF_{\text{PREM}} + CF_{\text{MD}} + CF_{\text{FG}} + CF_{\text{PPSE}} + CF_{\text{PPPE}} ) + W_{\text{m}}\{ CV_{\text{WA}} + CV_{\text{CTS}} + CV_{\text{FT}} + \{ CV_{\text{RP}} + (CV_{\text{ET}} \times H_{\text{RT}}) \} + (R_{\text{L-DT}} \times H_{\text{DT}}) \} + CV_{\text{LS}} + \left( \left( \frac{CV_{\text{sc}}/24}{T_{\text{s}}} + (U_{\text{EPPE}} \times \frac{CV_{\text{rwh}}}{T_{\text{s}}}) \right) \right) + (H_{\text{EW}} \times CV_{\text{BR}} \left( 1 + \frac{\text{ENIC+HP+SPP+PPP}}{100} \right)) + CV_{\text{CC}} + CV_{\text{CRD}} + CV_{\text{DIS}} \] / \[ R_{\text{WCS}} + \left( L_{\text{M} weight} \times L_{\text{M value}} \right) + \left( O_{\text{M weight}} \times O_{\text{M value}} \right) + (T_{\text{AL}} \times L_{\text{TAX}}) \]

Equation 10.12

<table>
<thead>
<tr>
<th>Cost-benefit results for case study 1</th>
<th>Benefits</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Revenue generated per annum</td>
<td>£403,461.50</td>
<td></td>
</tr>
<tr>
<td>Total fixed costs for year 1</td>
<td>£69,000.00</td>
<td></td>
</tr>
<tr>
<td>Total variable costs per annum</td>
<td>£71,068.78</td>
<td></td>
</tr>
<tr>
<td>Ratio of fixed to variable costs</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>Money saved by avoiding landfill (Based on 100% diversion of waste from landfill)</td>
<td>£190,281.00</td>
<td></td>
</tr>
<tr>
<td><strong>Total annual benefit</strong></td>
<td>£593,742.50</td>
<td>£140,068.78</td>
</tr>
<tr>
<td><strong>Total annual costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual profit of the system</td>
<td>£263,392.72</td>
<td></td>
</tr>
<tr>
<td>Cost-benefit ratio (Inc. landfill avoidance benefit)</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>Cost-benefit ratio (Exc. landfill avoidance benefit)</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

Table 11.8: Results of the profitability calculations and the cost-benefit ratio calculations for year 1 only (fixed costs decrease from year 2 onwards)
11.3.6 Analysis of economic evaluation results for case study 1

The results from the economic evaluation for case study one are presented in the economic viability dashboard in Figure 11.4 (a), with revenues and landfill avoidance benefits displayed as positive values and costs displayed as negative values. It can immediately be seen from Figure 11.4 (a) that the revenue generated from the sale of the recycled materials is the main contributing factor to the performance of the system. The costs associated with the system are marginal in comparison with the revenues recovered from recycled materials. For this case study, the fixed costs are higher than the variable costs, with a ratio of 1.03 (see Table 11.8). This is explained by the high initial outlay of capital for purchasing equipment when compared to the low running costs associated with the equipment. The cost-benefit ratio provides a single figure result for the economic feasibility assessment. A low economic impact is represented by a low cost-benefit ratio. For this case study, the cost-benefit ratio is 0.35 not including the landfill avoidance benefit and 0.24 when including the landfill avoidance benefit (see Table 11.8), indicating that an overall economic benefit is feasible and/or very likely. Hence, based on costs of £71,854.89 from year 2 onwards (the fixed costs of buying equipment don’t apply in year 2), and using the cumulative profit each year it is possible to calculate that this system will take less than a year to make a profit (see Table 11.9).

<table>
<thead>
<tr>
<th>Year</th>
<th>Revenue per year (£)</th>
<th>Cost per year (£)</th>
<th>Profit (£)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>593,742.50</td>
<td>140,854.89</td>
<td>452,887.61</td>
<td>Profit realised in less than 1 year</td>
</tr>
<tr>
<td>2</td>
<td>593,742.50</td>
<td>71,854.89</td>
<td>974,775.22</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>593,742.50</td>
<td>71,854.89</td>
<td>1,496,662.83</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>593,742.50</td>
<td>71,854.89</td>
<td>2,018,550.44</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>593,742.50</td>
<td>71,854.89</td>
<td>2,540,438.05</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>593,742.50</td>
<td>71,854.89</td>
<td>3,062,325.66</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>593,742.50</td>
<td>71,854.89</td>
<td>3,584,213.27</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>593,742.50</td>
<td>71,854.89</td>
<td>4,106,100.88</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>593,742.50</td>
<td>71,854.89</td>
<td>4,627,988.49</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>593,742.50</td>
<td>71,854.89</td>
<td>5,149,876.10</td>
<td></td>
</tr>
</tbody>
</table>
To maximise the economic effectiveness of a recycling system, most of the costs should be associated with directly producing the recycled materials, indirect costs, such as transport and consumables, should be kept to a minimum. On analysis of the direct and indirect costs for this case study, it is clear that with a ratio of 1.1, the direct costs are higher. This means that only 52% of the costs are spent on directly converting waste into recycled materials, direct costs and indirect costs are compared visually in Figure 11.4 (b).

The chart in Figure 11.4 (c) presents an analysis of the largest group of costs, these are associated with the purchase of capital equipment (only applicable to the first year) and the running costs for the system, the second largest expenditure is associated with paying employees to operate the equipment, and transport unsurprisingly contributes the least to the cost profile for the system. Finally, analysis of the result for the quality of the material output from the system indicates that the medium quality material is generated in the largest volume, and only a small percentage of the material is high quality and will command the highest price on the recycling materials market, as shown in Figure 11.4 (d). In this context, it is also helpful to note the revenue profile for system output materials. The chart in Figure 11.4 (e) shows the total revenue achieved for each output material stream, with medium quality generating (92.7%) of the revenue.
Figure 11.4: Economic viability dashboard for case study 1 (for year 1)
11.4 Case study 2

The results from the first case study indicate that if a manufacturer of leather products wanted to develop an in-house system to recycle their leather waste it would be economically viable; however, case study 1 did not consider any post-consumer waste.

Therefore, a second case study in this thesis simulates the development of a recycling system for post-consumer leather waste. The purpose of this case study is to demonstrate the application of the CAL framework and its associated economic support model for the concept of horizontally grouping and processing leather waste. For the purposes of this case study, the post-consumer waste generated from leather car seats and leather footwear will be investigated. This case study will attempt to answer the following question:

- Is it economically effective for a recycling company to collect and process post-consumer leather waste vertically across different product sectors?

11.4.1 Implementation of case study 2

The implementation of case study 2 followed the same process as described in Section 11.3.1. The only difference is that in case study 2 there were two waste streams to characterise and two sets of assumptions and data to gather.

11.4.2 Characterisation of waste streams for case study 2

The waste streams studied within this case study consist of leather seats from end-of-life vehicles and footwear products that have reached the end-of-life after consumers no longer need them. The following assumptions underline the characteristics of the waste streams that are identified as being relevant to the end-of-life management process:

- The waste streams arising from consumers in the United Kingdom will be included in this study.
- In total 1129 tonnes of post-consumer leather car seat waste is available for processing per annum, which represents 17% of the vehicles seats dismantled by UK automotive dismantlers per annum (See Table 11.10).
- In total 750 tonnes of post-consumer footwear is available for processing per annum, which represents 10% of all leather used in footwear in the UK per annum (FAO, 2013).
- The waste consists of post-consumer leather waste which is tanned and finished and of mixed quality, no putrescible leather waste is considered within this analysis.
Table 11.10: Tonnage of leather available from automotive sector on annual basis

<table>
<thead>
<tr>
<th>Annual volume of leather available for recovery from automotive sector in UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of vehicles processed by dismantlers per year in UK, (Eurostat, 2017)</td>
</tr>
<tr>
<td>No. of vehicles with leather seats @17% (UNIDO, 2010)</td>
</tr>
<tr>
<td>Average weight of leather per vehicle seat (kg)</td>
</tr>
<tr>
<td>Average number/equivalent number of seats per vehicle</td>
</tr>
<tr>
<td>Total leather in vehicle (kg)</td>
</tr>
<tr>
<td>Total leather available for recovery in UK (kg)</td>
</tr>
<tr>
<td>Total leather available for recovery in UK (tonnes)</td>
</tr>
</tbody>
</table>

11.4.3 Definition of end-of-life scenarios for case study 2

The end-of-life process route developed as Scenario 2 is represented graphically in Figure 9.10 of the thesis and is defined in detail in this section.

11.4.3.1 COLLECTION AND SORTING

The post-consumer wastes associated with end-of-life leather car seats is collected from a different location than the post-consumer waste associated with end-of-life leather footwear.

Collection and sorting is conducted at locations that are different from the waste-generation locations. Waste is generated by consumers when their footwear products come to the end of life or when they decide to dispose of their vehicle. Collection of the leather car seats takes place at an end-of-life vehicle processing centre/dismantler.
Collection of the leather footwear will take place via the placement of portable recycling banks that are placed at supermarket sites.

Transport is required to move both waste streams between the waste collection site and the waste processing site. Automotive car seats and leather footwear waste are both transported to the same processing site where they are sorted separately before being combined for processing. Sorting of the footwear will identify any shoes that are damaged or worn beyond recognition, or too dirty to process. These footwear pieces will be disposed of to landfill.

11.4.3.2 PROCESSING

After both waste streams have been sorted, then metal will be removed from the waste, both the car seat cover and the footwear contain metal elements. The car seat covers and the footwear containing metal will be manually processed to remove the visible metal. It is important to note that scenario 2 specifies that an automatic metal detection process be applied to the waste for vertical waste processing. However, this case study concentrates wastes from two industries only, and so a manual process is applied. If waste from more than two industries were included in the case study, then the automated metal detection and removal would be applicable.

Further confirmation for a manual metal-removal process was found during laboratory-scale trials on leather seats from the automotive industry, this work was carried out as part of an undergraduate student project (Coates, 2017). The trials concluded that it only requires two manual cuts to the vehicle seat to liberate 90% of the leather from the metal frame of the seat (see Figure 11.5); this makes it unnecessary to shred the whole seat. The vehicle seat covers will be removed from the metal frame at the site of the end-of-life vehicle dismantlers; this evaluation does not consider the costs incurred by the vehicle dismantler to remove the seats and covers from the vehicles.

If metal is detected in any of the waste footwear or automotive seats and no visible metal can be found the materials will be disposed of to landfill, this is because metal that is severely embedded is too time consuming to remove. After the metal detection, the process route is the same as was described in Section 11.3.3.2.
11.4.3.3 Redistributions

Four redistribution scenarios for leather wastes and mixed wastes are possible; they are outlined below in Table 11.11.

Table 11.11: Four distribution scenarios for leather wastes and mixed wastes

<table>
<thead>
<tr>
<th>Value of recovered material</th>
<th>Description of recovered material</th>
<th>Visual representation of recovered material</th>
</tr>
</thead>
<tbody>
<tr>
<td>High value</td>
<td>Leather off-cuts suitable for direct reuse in leather products</td>
<td>![Image of high value material]</td>
</tr>
<tr>
<td>Med-high value</td>
<td>100% granulated leather (finished or unfinished) OR mixed material of 80-95% leather content this is suitable to be reformed into e-leather</td>
<td>![Image of Med-high value material]</td>
</tr>
<tr>
<td>Med-low value</td>
<td>Mixed material of 70-80% leather content, this is suitable to be applied to mop up chemical spills.</td>
<td>![Image of Med-low value material]</td>
</tr>
<tr>
<td>Low value</td>
<td>Mixed material (textile, foam and leather) with leather content of less than 70%, this is suitable to be reused as low-grade insulation material or underlay for various types of flooring</td>
<td>![Image of Low value material]</td>
</tr>
</tbody>
</table>
For the medium and low value applications, the purity and physical properties of the leather recovered from the mixed waste is not suitable to be used in applications where virgin material would be used, hence the recovered material is down-cycled compared to virgin leather.

### 11.4.4 Data and assumptions for case study 2

Sections 11.4.2 and 11.4.3 provided high-level data that define the waste streams and end-of-life scenario that are evaluated in case study 2. These data are developed from real data and assumptions and collated from various sources. More detailed data regarding the economic attributes of the process steps described are required to apply the evaluation methods to the scenarios; this data is presented in the next section. But first a series of assumptions are defined:

- A recycling company is going to be formed to collect, process and redistribute the waste from end-of-life automotive seats and end-of-life post-consumer footwear
- The recycling company that will be formed will supply collection skips to end-of-life vehicle dismantlers to collect the leather car seat covers and recycling ‘banks’ will be provided to supermarkets to enable the collection of post-consumer footwear. According to (Bomford, 2017), supermarket sites collect most of the material and are more cost effective
- The leather vehicle seat covers will be provided to the recycling company free of charge, the only cost to the recycling company will be the provision of the skip in which to collect the covers
- The materials within the input waste streams have a high proportion of contamination and are worn or dirty out due to use by the consumers. Hence, a proportion of the material will be rejected from the recycling system at the sorting stage; this material will be sent straight to landfill
- The processing equipment will only be run from Monday to Friday, the factory is closed at the weekend
- The input waste materials are only run through the processing line once at an average throughput of 0.5 tonnes per hour
- The fragmentation and air-separation processes run at 100% efficiency, no material will be lost from any of these processes, the weight of material input to process is equal to the weight of material output from process
The recovery efficiency for the combined separation processes is 95%, therefore for every tonne of leather input to the system, 5% of this leather will not be recovered and will be captured within the ‘other materials’ fraction. This separation efficiency is based on experimental trials that were conducted for the purposes of this research.

The new employees for operating the process equipment will be over 25 years of age; hence, the higher rate of living wage will apply (The employer will need to make pensions contributions of minimum 1% of salary, this means that the true cost for each employee is £9.21 per hour (Essential recruitment, 2017).

Employees will work for five days per week, and will do an 8-hour shift once per day.

No post-separation processing is required, all materials are sold as in the form that they are recovered.

Transportation of redistributed materials will be a bought-in service and the locations to distribute all output materials to are 50 miles from the recycling factory.

11.4.4.1 Data to support evaluation of economic feasibility

Quantification of all costs and benefits arising during the end-of-life management of leather is required to facilitate the evaluation of the economic feasibility of a leather recycling strategy using CBA. Cost data to support the case study is available from various sources.

Data for revenue of different grades of material

The data used within case study 2 for the value of the recovered materials is the same data that was outlined in Table 11.2 in Section 11.3.4.1.

Data for collection and transportation costs

To enable collection of the end-of-life vehicle seat covers and end-of-life footwear skips and recycling banks will need to be provided. A summary of the costs of providing these items is displayed in Table 11.12. Transportation costs for the collection of the end-of-life vehicle seat covers and end-of-life footwear are summarised in Table 11.13 to Table 11.15.

Data for costs of setting up the system and ongoing processing costs

The data used within case study 2 for the costs of setting up and operating the recycling system are detailed in Table 11.16.
Data for redistribution costs

The data used within case study 2 for the costs of packaging for the recovered materials is the same as the data used in case study 1. The same average price, of £2.46, for a 1-tonne building sack is used again in case study 2. The haulage costs used within this case study are different from those for case study 1, this is because more transportation is required and the assumed mileage to the redistribution locations is different. The haulage of the redistributed materials is carried out by a third-party haulage contractor. The haulage market was reviewed, and the data and assumptions were gathered, Table 11.17 displays the haulage costs for redistribution of the recovered materials.

Table 11.12: Costs for provision of skips and recycling banks for collection of end-of-life vehicle seat covers and post-consumer footwear

<table>
<thead>
<tr>
<th>Waste type to be collected</th>
<th>Number of collection locations</th>
<th>Cost of providing waste collection bins and recycling banks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>175</td>
<td>£40,250</td>
</tr>
<tr>
<td>Footwear</td>
<td>350</td>
<td>£350,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>£390,250</strong></td>
</tr>
</tbody>
</table>

Table 11.13: Haulage costs for collecting automotive seat waste from dismantlers

<table>
<thead>
<tr>
<th>Assumptions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Miles to each redistribution location</td>
<td>50</td>
</tr>
<tr>
<td>Gross vehicle weight (tonnes)</td>
<td>32</td>
</tr>
<tr>
<td>Weight carried per load (tonnes)</td>
<td>21.5</td>
</tr>
<tr>
<td>Trips that haulier can make per day</td>
<td>2</td>
</tr>
<tr>
<td>Miles covered per day</td>
<td>200</td>
</tr>
<tr>
<td>Material hauled per day (tonnes)</td>
<td>43</td>
</tr>
<tr>
<td><strong>Cost calculations</strong></td>
<td></td>
</tr>
<tr>
<td>Haulier fee for 1 standard day</td>
<td>£285.00</td>
</tr>
<tr>
<td>80 miles at 115.4 pence per mile</td>
<td>£92.32</td>
</tr>
<tr>
<td>Drivers bonus and additional overtime per day</td>
<td>£15.00</td>
</tr>
<tr>
<td>Weighbridge costs</td>
<td>£30.00</td>
</tr>
<tr>
<td>Total costs</td>
<td>£422.32</td>
</tr>
<tr>
<td>Target margin for haulage company (5%)</td>
<td>£21.12</td>
</tr>
<tr>
<td>Desired revenue for haulage company for 1 day @43 tonnes</td>
<td>£443.44</td>
</tr>
<tr>
<td>Desired rate and quotation per tonne (assuming 21.5 tonnes per load)</td>
<td>£10.31</td>
</tr>
</tbody>
</table>

Therefore, for 1129 tonnes of redistributed materials, total costs per year would be £11639.99
Table 11.14: Haulage costs for collecting footwear waste from recycling banks

<table>
<thead>
<tr>
<th>Assumptions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Miles to each redistribution location</td>
<td>15</td>
</tr>
<tr>
<td>Gross vehicle weight (tonnes)</td>
<td>32</td>
</tr>
<tr>
<td>Weight carried per load (tonnes)</td>
<td>21.5</td>
</tr>
<tr>
<td>Trips that haulier can make per day</td>
<td>4</td>
</tr>
<tr>
<td>Miles covered per day</td>
<td>120</td>
</tr>
<tr>
<td>Material hauled per day (tonnes)</td>
<td>86</td>
</tr>
</tbody>
</table>

Cost calculations

- Haulier fee for 1 standard day: £285.00
- 80 miles at 115.4 pence per mile: £92.32
- Drivers bonus and additional overtime per day: £15.00
- Weighbridge costs: £30.00
- Total costs: £422.32
- Target margin for haulage company (5%): £21.12
- Desired revenue for haulage company for 1 day @ 86 tonnes: £443.44
- Desired rate and quotation per tonne (assuming 21.5 tonnes per load): £10.31
- Total cost for 725 tonnes of collected material are: £7474.75

Table 11.15: Total costs for collecting end-of-life automotive and footwear waste

<table>
<thead>
<tr>
<th>Waste</th>
<th>Cost of collection per annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>£11639.99</td>
</tr>
<tr>
<td>Footwear</td>
<td>£7474.75</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>£19114.74</strong></td>
</tr>
</tbody>
</table>

Table 11.16: Summary of approximate capital and running costs for processing equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Power rating (kw)</th>
<th>Capital cost (approximate, £, per equipment unit)</th>
<th>Running costs* (£/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic separator</td>
<td>3</td>
<td>15000</td>
<td>0.32</td>
</tr>
<tr>
<td>Detect and eject chute</td>
<td>1</td>
<td>8000</td>
<td>0.11</td>
</tr>
<tr>
<td>Granulator</td>
<td>20</td>
<td>25000</td>
<td>2.02</td>
</tr>
<tr>
<td>Zig-zag separator/air cascade</td>
<td>4</td>
<td>20000</td>
<td>0.42</td>
</tr>
<tr>
<td>Air-table</td>
<td>4</td>
<td>24000</td>
<td>0.42</td>
</tr>
</tbody>
</table>

*Running cost = (Power rating x energy cost/throughput), where energy cost is 11.12pence/kwh and standing charge is 22.75pence per day for 365 days, and throughput of the system is 0.5tonnes/hour (BusinessElectricityPrices.org.uk, 2017).
Table 11.17: Haulage costs for redistributed materials

<table>
<thead>
<tr>
<th>Assumptions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Miles to each redistribution location</td>
<td>20</td>
</tr>
<tr>
<td>Gross vehicle weight (tonnes)</td>
<td>32</td>
</tr>
<tr>
<td>Weight carried per load (tonnes)</td>
<td>21.5</td>
</tr>
<tr>
<td>Trips that haulier can make per day</td>
<td>2</td>
</tr>
<tr>
<td>Miles covered per day</td>
<td>80</td>
</tr>
<tr>
<td>Material hauled per day (tonnes)</td>
<td>43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost calculations</th>
<th></th>
</tr>
</thead>
<tbody>
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</thead>
<tbody>
<tr>
<td>Desired rate and quotation per tonne (assuming 21.5 tonnes per load)</td>
<td>£10.31</td>
</tr>
</tbody>
</table>

| Therefore, for 1579 tonnes of redistributed materials, total costs per year would be | £16,279.49 |

11.4.5 Application of the economic cost model

To apply the cost model to this case study and assess the economic viability of the horizontal waste collection and grouping strategy, it was first necessary to calculate all revenues, fixed costs and variable costs associated with the case study. Data and assumptions detailed in Sections 11.4.2 and 11.4.4 are used as the basis for these values.

The parametric models defined in equations 10.4, 10.8 and 10.10 are used to construct an economic evaluation of the implementation of a circular approach in the leather industry. Firstly, equations 10.4 to 10.6 were used to calculate the total fixed costs, variable costs and revenues for this case study. Table 11.18 presents details of the running costs of the processing equipment and revenue generated from the sale of the redistributed materials, generated by a spreadsheet developed using Equations 10.4 to 10.8, as outlined below.

\[ B_{\text{leather}} = R_{WCS} + \left( L_{\text{weight}} \times L_{\text{value}} \right) + \left( O_{\text{weight}} \times O_{\text{value}} \right) + \left( T_{\text{AL}} \times L_{\text{TAX}} \right) \]
Equation 10.4

\[ \mathbf{CF} = \mathbf{CF}_{\text{ICE}} + \mathbf{CF}_{\text{RC}} + \mathbf{CF}_{\text{PC}} + \mathbf{CF}_{\text{KC}} + \mathbf{CF}_{\text{LRC}} + \mathbf{CF}_{\text{WTV}} + \mathbf{CF}_{\text{PREM}} + \mathbf{CF}_{\text{MD}} + \mathbf{CF}_{\text{FG}} + \mathbf{CF}_{\text{PPSE}} + \mathbf{CF}_{\text{PPPE}} \]

Equation 10.8

\[ \mathbf{CV} = [\mathbf{CV}_{\text{WA}} + \mathbf{CV}_{\text{CTS}} + \mathbf{CV}_{\text{FT}} + \{\mathbf{CV}_{\text{RP}} + (\mathbf{CV}_{\text{ET}} \times H_{\text{RT}}) + (R_{\text{L-DT}} \times H_{\text{DT}})\} + \mathbf{CV}_{\text{LS}} + \left(\frac{\mathbf{CV}_{\text{sc}}}{24} + (U_{\text{EPE}} \times \frac{\mathbf{CV}_{\text{kwH}}}{T_{\text{s}}})\right) + (H_{\text{EW}} \times \mathbf{CV}_{\text{BR}} \left(1 + \frac{\text{ENIC} + H_{\text{P}} + \text{SPP} + \text{PPP}}{100}\right)) + \mathbf{CV}_{\text{CC}} + \mathbf{CV}_{\text{CRD}} + \mathbf{CV}_{\text{DIS}}]\]

Equation 10.10

The costs and revenues for the waste collection and transportation stages of the recycling system presented in this case study are summarised in Table 11.19, and the costs and revenues for the processing and redistribution stages of the recycling system presented in this case study are summarised in Table 11.20.
Table 11.18: Calculation of running costs per annum for the processing equipment and revenues from redistributed materials

<table>
<thead>
<tr>
<th>Tonnage of waste for processing</th>
<th>Automotive</th>
<th>Footwear</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste that requires processing after sorting (tonnes)</td>
<td>1016</td>
<td>563</td>
<td>1,579</td>
</tr>
<tr>
<td>Med-low value material recovered from system (tonnes)</td>
<td>942</td>
<td>0</td>
<td>942</td>
</tr>
<tr>
<td>Total low-value material recovered from the system (tonnes)</td>
<td>637</td>
<td></td>
<td>637</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Running costs</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total metal detection and removal running cost</td>
<td>£426.76</td>
<td>£236.25</td>
<td>£663.01</td>
</tr>
<tr>
<td>Total Granulator running costs</td>
<td>£2,052.52</td>
<td>£1,136.25</td>
<td>£3,188.77</td>
</tr>
<tr>
<td>Total Zig-zag separator/ air cascade running costs per tonne</td>
<td>£426.76</td>
<td>£477.23</td>
<td>£903.99</td>
</tr>
<tr>
<td>Air-table running costs per tonne</td>
<td>£426.76</td>
<td>£236.25</td>
<td>£663.01</td>
</tr>
<tr>
<td>Total running costs for process equipment per year</td>
<td>£2,906.05</td>
<td>£1,849.73</td>
<td>£5,418.78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Revenue from selling materials</th>
<th>Medium low</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value bracket for leather materials</td>
<td>£140.00</td>
<td>£82.00</td>
</tr>
<tr>
<td>Total revenue for redistributed leather materials</td>
<td>£131,840.10</td>
<td>£52,224.57</td>
</tr>
<tr>
<td>Total revenue generated by selling Low value output material</td>
<td>£0</td>
<td>£0</td>
</tr>
</tbody>
</table>

| Money saved by not sending waste to landfill | n/a | n/a | £0.00 |
Table 11.19: Costs and revenues for the collection and transportation stages of the recycling system presented in case study 1, for year 1

<table>
<thead>
<tr>
<th>Economic parameter name</th>
<th>Revenue</th>
<th>Fixed costs</th>
<th>Variable costs</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste collection services</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>No waste collection fees are applicable, the waste is given for free</td>
</tr>
<tr>
<td>Cost of industrial collection equipment</td>
<td>£40,250</td>
<td>n/a</td>
<td></td>
<td>This represents the cost of providing a 1000L waste container to vehicle dismantlers to collect automotive seat covers</td>
</tr>
<tr>
<td>Cost of retail collection</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
<td>No retail collection occurring</td>
</tr>
<tr>
<td>Cost of postal collection</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
<td>No postal collection occurring</td>
</tr>
<tr>
<td>Cost of kerbside collection</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
<td>No kerbside collection occurring</td>
</tr>
<tr>
<td>Cost of localised recycling centres</td>
<td>£350,000</td>
<td>n/a</td>
<td></td>
<td>This cost represents the costs of providing one footwear recycling bank to 350 supermarkets sites</td>
</tr>
<tr>
<td>Cost of waste transportation vehicles</td>
<td>n/a</td>
<td>n/a</td>
<td>No waste transportation vehicles required, haulage to be contracted out</td>
<td></td>
</tr>
<tr>
<td>Cost of waste acquisition</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
<td>In this case study, the recycling company does not pay anything to acquire the waste from the waste producer, the waste is given free of charge</td>
</tr>
<tr>
<td>Cost of collection and transportation staff</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
<td>No collection and transportation staff required for the collection of waste. The costs of transport staff are included within the haulage company costs</td>
</tr>
<tr>
<td>Cost of fuel for transportation</td>
<td>n/a</td>
<td>£19,115</td>
<td></td>
<td>This represents haulage costs for collecting wastes from the waste collection points</td>
</tr>
<tr>
<td>Cost of maintenance and repair of collection equipment</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
<td>Not applicable</td>
</tr>
<tr>
<td>Cost of renting premises</td>
<td>£40,000</td>
<td></td>
<td></td>
<td>This rate includes rental and business rates for an 8000sqft industrial warehouse</td>
</tr>
</tbody>
</table>
Table 11.20: Costs and revenues for the processing and redistribution stages of the recycling system presented in case study 1, for year 1

<table>
<thead>
<tr>
<th>Economic parameter name</th>
<th>Revenue</th>
<th>Fixed costs</th>
<th>Variable costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sale of leather materials</td>
<td>£131,840.10</td>
<td>See Table 11.18</td>
<td></td>
</tr>
<tr>
<td>Sale of other recovered materials (textiles, foams)</td>
<td>£52,224.57</td>
<td>See Table 11.18</td>
<td></td>
</tr>
<tr>
<td>Cost of metal detection and removal equipment</td>
<td>£23,000.00</td>
<td>This cost includes a magnetic separator and a detect and eject chute</td>
<td></td>
</tr>
<tr>
<td>Cost of fragmentation equipment</td>
<td>£25,000.00</td>
<td>See Table 11.16</td>
<td></td>
</tr>
<tr>
<td>Cost of post-fragmentation separation equipment</td>
<td>£44,000.00</td>
<td>See Table 11.16</td>
<td></td>
</tr>
<tr>
<td>Cost of post-fragmentation processing equipment</td>
<td>n/a</td>
<td>No post-separation processing occurs in this case study; materials are sold in the form which they are recovered.</td>
<td></td>
</tr>
<tr>
<td>Cost of labour for sorting waste materials</td>
<td>£19,156.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of energy for equipment/running costs</td>
<td>£5,418.78</td>
<td>Includes annual standing charge for energy and cost per kwh for energy</td>
<td></td>
</tr>
<tr>
<td>Cost of labour for operating the processing equipment</td>
<td>£19,156.80</td>
<td>True cost of 1 x employee per hour = £9.21, 8 hours per day, 260 days per year. This cost represents half the cost of each employee, the other half of their role will be to sort the waste materials and feed them into the system.</td>
<td></td>
</tr>
<tr>
<td>Cost of consumables for use during processing</td>
<td>£3,883.36</td>
<td>£2.46 per sack, with 1579 sacks required</td>
<td></td>
</tr>
<tr>
<td>Cost of redistribution (shipping) of recovered materials</td>
<td>£16,279.49</td>
<td>Haulage costs and assumptions are detailed in Table 11.17</td>
<td></td>
</tr>
<tr>
<td>Costs of disposing of unrecoverable materials (landfill costs)</td>
<td>£25,864.44</td>
<td>£86.10 per tonne (GOV UK, 2017), a lower rate of landfill tax is £2.70 per tonne but this is reserved for: (A lower band is applied to inert waste that contains no biodegradable material)</td>
<td></td>
</tr>
</tbody>
</table>
After the fixed costs, variable costs and revenues were identified, equations 10.11 and 10.12 were used to calculate the profitability and cost-benefit ratio for this case study. Table 11.21 presents the results of these calculations.

**Profitability of the system**

\[
B_{leather} = \left[ CF_{ICE} + CF_{RC} + CF_{PC} + CF_{KC} + CF_{LRC} + CF_{WTV} + CF_{PREM} + CF_{MD} + CF_{FG} + CF_{PFSE} + CF_{PFPE} \right] - \left[ CV_{WA} + CV_{CTS} + CV_{FT} + \{ CV_{RP} + (CV_{ET} \times H_{RT}) \} + CV_{LS} + \left( \frac{CV_{sc}/24}{T_s} \right) + (U_{EPE} \times \frac{CV_{kwh}}{T_s}) \} + (H_{EW} \times CV_{BR} \left( 1 + \frac{ENIC + HP + SPP + PPP}{100} \right)) + CV_{CC} + CV_{CRD} + CV_{DIS} \]

Equation 10.11

\[
\text{Cost-benefit ratio (CBR}_{leather} = \]

\[
= CF_{ICE} + CF_{RC} + CF_{PC} + CF_{KC} + CF_{LRC} + CF_{WTV} + CF_{PREM} + CF_{MD} + CF_{FG} + CF_{PFSE} + CF_{PFPE} + W_{m}[CV_{WA} + CV_{CTS} + CV_{FT} + \{ CV_{RP} + (CV_{ET} \times H_{RT}) \} + CV_{LS} + \left( \frac{CV_{sc}/24}{T_s} \right) + (U_{EPE} \times \frac{CV_{kwh}}{T_s})} + (H_{EW} \times CV_{BR} \left( 1 + \frac{ENIC + HP + SPP + PPP}{100} \right)) + CV_{CC} + CV_{CRD} + CV_{DIS} \]

/ \left( R_{ WCS} + (LM_{weight} \times LM_{value}) + (OM_{weight} \times OM_{value}) + (T_{AL} \times L_{TAX}) \right)

Equation 10.12

Table 11.21: Results of the profitability calculations and the cost-benefit ratio calculations for year 1 only (fixed costs decrease from year 2 onwards)

<table>
<thead>
<tr>
<th>Cost-benefit results for case study 1</th>
<th>Benefits</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Revenue generated per annum</td>
<td>£184,064.67</td>
<td></td>
</tr>
<tr>
<td>Total fixed costs for year 1</td>
<td></td>
<td>£522,250.00</td>
</tr>
<tr>
<td>Total variable costs per annum</td>
<td></td>
<td>£108,874.67</td>
</tr>
<tr>
<td>Ratio of fixed to variable costs</td>
<td>N/a</td>
<td>4.8</td>
</tr>
<tr>
<td>Money saved by avoiding landfill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Based on 100% diversion of waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>from landfill)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total annual benefit</td>
<td>£184,064.67</td>
<td></td>
</tr>
<tr>
<td>Total annual costs</td>
<td></td>
<td>£631,124.67</td>
</tr>
<tr>
<td>Annual profit of the system</td>
<td></td>
<td>-£447,060.00</td>
</tr>
<tr>
<td>Cost-benefit ratio (Inc. landfill</td>
<td></td>
<td>3.43</td>
</tr>
<tr>
<td>avoidance benefit)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
11.4.6 Analysis of economic evaluation results for case study 2

The result from the economic evaluation for case study one is presented in Figure 11.6 (a), with revenues and landfill avoidance benefits displayed as positive values and costs displayed as negative values. It can immediately be seen from Figure 11.6 (a) that the fixed costs is the main contributing factor to the performance of the system. The costs associated with the system are marginal in comparison with the revenues recovered from recycled materials. For this case study, the fixed costs are higher than the variable costs, with a ratio of 4.8 (see Table 11.21). This is explained by the high initial outlay of capital for purchasing equipment when compared to the low running costs associated with the equipment.

The cost-benefit ratio provides a single figure result for the economic feasibility assessment. A low economic impact is represented by a low cost-benefit ratio. For this case study, the cost-benefit ratio is 3.43 (see Table 11.21) indicating that a significant overall economic loss occurs. It is common to make a loss in the first year of operation due to the large capital outlay equipment; however, even in the second year when the fixed costs have reduced to £40,000 for rent of premises, the revenue generated from the sale of materials is not great enough to cover the costs of the system. Hence, based on costs of £154,205.61 from year 2 onwards (the fixed costs of buying equipment do not apply in year 2), and using the cumulative profit each year it is possible to calculate that this system will take 17 years to make a profit (see Table 11.22). To maximise the economic effectiveness of a recycling system, most of the costs should be associated with directly producing the recycled materials, indirect costs, such as transport and consumables, should be kept to a minimum.

On analysis of the direct and indirect costs for this case study, it is clear to see that with a ratio of 0.18, the indirect costs are much higher. This means that only 18% of the costs are spent on directly converting waste into recycled materials, direct costs and indirect costs are compared visually in Figure 11.6 (b). The chart in Figure 11.6 (c) shows that the largest group of costs are associated with the purchase of capital equipment and the running costs for the system, the second largest expenditure is associated with rental for commercial premises, with employees to operate the equipment and transport at similar values. Finally, analysis of the result for the quality of the material output from the system indicates that the low-quality material is generated in the largest volume, with no high-quality material generated at all, as shown in Figure 11.6 (d). In this context, it is also helpful to note the revenue profile for system output materials. Figure 11.6 (e) shows the total revenue achieved for each output material stream, with the most revenue generated from the sale of the medium-low quality material (72%).
Table 11.2: Payback period for case study 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Revenue per year</th>
<th>Cost per year</th>
<th>Profit</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>£184,064.67</td>
<td>£636,455.61</td>
<td>-£452,390.94</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>£184,064.67</td>
<td>£154,205.61</td>
<td>-£422,531.88</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>£184,064.67</td>
<td>£154,205.61</td>
<td>-£392,672.82</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>£184,064.67</td>
<td>£154,205.61</td>
<td>-£362,813.76</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>£184,064.67</td>
<td>£154,205.61</td>
<td>-£332,954.70</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>£184,064.67</td>
<td>£154,205.61</td>
<td>-£303,095.64</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>£184,064.67</td>
<td>£154,205.61</td>
<td>-£273,236.58</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>£184,064.67</td>
<td>£154,205.61</td>
<td>-£243,377.52</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>£184,064.67</td>
<td>£154,205.61</td>
<td>-£213,518.46</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>£184,064.67</td>
<td>£154,205.61</td>
<td>-£183,659.40</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>£184,065.67</td>
<td>£154,205.61</td>
<td>-£153,799.34</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>£184,066.67</td>
<td>£154,205.61</td>
<td>-£123,938.28</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>£184,067.67</td>
<td>£154,205.61</td>
<td>-£94,076.22</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>£184,068.67</td>
<td>£154,205.61</td>
<td>-£64,213.16</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>£184,069.67</td>
<td>£154,205.61</td>
<td>-£34,349.10</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>£184,070.67</td>
<td>£154,205.61</td>
<td>-£4,484.04</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>£184,071.67</td>
<td>£154,205.61</td>
<td>£25,382.02</td>
<td>First year of profit</td>
</tr>
<tr>
<td>18</td>
<td>£184,072.67</td>
<td>£154,205.61</td>
<td>£55,249.08</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>£184,073.67</td>
<td>£154,205.61</td>
<td>£85,117.14</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>£184,074.67</td>
<td>£154,205.61</td>
<td>£114,986.20</td>
<td></td>
</tr>
</tbody>
</table>
Figure 11.6: Economic viability dashboard for case study 2 (for year 1 only)
11.5 Summary of findings from case studies

The case studies reported in this chapter demonstrate the application of the CAL framework (introduced in Chapter 7), to the end-of-life management of leather waste. In the first study, the framework is used to evaluate the economic feasibility of a VERP strategy for leather waste, which aims to improve the economic viability of leather recycling by collecting wastes vertically across the lifecycle of a product. The second case study is used to evaluate the economic feasibility of a HORP strategy for leather waste, which aims to improve the economic feasibility of leather recycling by collecting leather waste horizontally across a range of product sectors. Together, therefore, the case studies demonstrate the flexibility of the framework regarding the mode of application.

The results from the case studies show that applying the framework helps to identify and characterise the wastes streams that arise from Tannery X factory processes, additionally, it helps to identify the fixed costs, variable costs and revenues associated with each aspect of the recycling system. Finally, by applying the framework, four levels of value can be assigned to the materials fractions that are recovered from the recycling system. The diversion of 100% of the waste materials from landfill shows that the application of the framework allows for the identification of alternative destinations for waste leather materials. This provides an economic benefit by eliminating landfilling costs; consequently, it provides an environmental benefit because 100% of the chromium and finishing chemicals contained with the waste leathers are diverted from landfill.

Finally, on evaluation of the results, it can be concluded that capital equipment is the largest expenditure category, with transportation contributing the least to the cost profile, this is because the wastes are collected and processed within the same factory. This would differ if the collection and processing locations were separately geographically, as highlighted by case study 2.

Similarly, case study 2 demonstrates the application of the framework for the implementation of the second scenario proposed by this research i.e. the horizontal model for leather recycling. The results from this study show that, based on current undeveloped markets for recycled materials from leather products, this strategy is not economically viable. The system outlined in case study 2 would make a significant loss in the first year and it would continue to make a loss from year 2 onwards until year 17 when it would start to make a profit. The reasons for this are twofold: firstly, the revenue generated from the sale of materials in case study two is 60% lower than the revenue generated within the first
case study, and secondly, the landfill avoidance benefit is not realised by the recycling company in case study 2 and hence it is not included in the overall cost-benefit analysis. However, if this strategy involved the waste collector charging the waste producer for the collection of the waste, it may become viable, this would depend on the fee that was charged to collect the waste.

With regards to post-consumer waste, it is not entirely clear who would receive the economic benefit from not sending post-consumer leather waste to landfill. For the automotive waste, this benefit would be realised by the end-of-life vehicle dismantlers, as they would no longer be sending the same volume of shredder residue to landfill, hence saving money on landfill tax. For the footwear waste, it is slightly more complicated. Assumptions have been made within this thesis that consumers will choose to put their end-of-life leather footwear into the general waste stream to be collected by their local authority. In this instance, the landfill avoidance benefit would be realised by the waste collection authorities across the United Kingdom. This creates questions about who should pay for the recycling of these leather products, if multiple organisations are benefitting from the landfill avoidance revenue then there may be reason to suggest that the recycling should be funded as part of a joint scheme by the UK government and leather product manufacturers.

The results show that applying the framework helps to identify and characterise the wastes streams that arise from Tannery X factory processes, additionally, it helps to identify the fixed costs, variable costs and revenues associated with each aspect of the recycling system. Finally, by applying the framework, four levels of value can be assigned to the materials fractions that are recovered from the recycling system and identification of alternative destinations for waste leather materials can be achieved.

Finally, on evaluation of the results, it can be concluded that capital equipment for collection and processing of wastes is the largest expenditure category; with transportation costs double that from the first case study. This is to be expected because the wastes are collected and processed at two different locations, hence transport costs increase.

The findings from the case studies provide interesting insights about the economic viability of alternative end-of-life scenarios. The case studies show that the framework presented in this thesis provides a useful support tool for the development of end-of-life management solutions for leather waste which are economically beneficial.
CHAPTER 12 CONCLUDING DISCUSSION

12.1 Introduction

This chapter presents the significant findings and knowledge gained from the research. The principal research contributions are defined at the start of the chapter, after which the original research objectives and scope, defined in Chapter 2, are discussed against the findings.

12.2 Research contributions

The research in this thesis has investigated the implementation of a circular approach within the leather industry. The principal contributions from the research can be summarised as follows:

I. Identification of specific requirements arising during the end-of-life phase of leather lifecycle, to ensure that the environmental problems associated with incorrect disposal are reduced.

II. Investigation of the opportunities presented for leather recovery and recycling based on a systematic mapping and characterisation of waste properties.

III. Definition of alternative practical solutions for the end-of-life management of leather waste, based on a mixture of existing and novel waste management technologies and capability.

IV. Creation of an economic model for predicting the cost effectiveness of leather recycling systems based on a range of input factors based on two novel recycling strategies.

V. Demonstration of the application of a novel economic model, to support decision-making with respect to the development of an end-of-life management solution for leather waste.

12.3 Concluding discussion

The following sections present the results of the research aligned with the original research objectives and scope.
12.3.1 Review of the status of the leather industry and current disposal options for leather products along with waste management and recycling technologies from published literature

To establish context for the research, it was necessary to undertake a literature review. Two specific areas of literature were identified as being of particular relevance to the research: the review of leather use and recycling as reported in Chapter 3 of the thesis, and a review of recycling and material recovery processes and technologies as reported in Chapter 4.

Together, these review chapters identify that there has been a significant increase in the diversification of leather products, along with an increase in the complexity of the geometry and material mix of leather products on a global scale. The research shows that the EU landfill directive and targets for reduction of biodegradable material sent to landfill will pose a practical obstacle to existing disposal practices for leather products. While leather does not fit under the traditional definition of ‘biodegradable’, as it is specifically designed to not biodegrade for a long period of time, the legislation will still apply and waste producers will have to conform. In addition, leather waste creates several environmental problems if disposed of incorrectly, including: skin diseases and pollution of both land and water.

Based on this evidence, the need for a systematic approach towards managing leather waste across the product lifecycle to successfully meet future challenges has been highlighted. It was clear from the literature review that end-of-life management of leather waste has not been considered with any rigour, and as such, this gap in existing knowledge justifies the need for the research presented in this thesis.

12.3.2 Develop a framework that supports the implementation of a circular approach within the leather industry

Due to the complexities mentioned in Section 12.3.2 and in the absence of an existing comprehensive end-of-life management solution for leather waste, the research investigates various possible practical solutions. It was identified that these potential solutions should be evaluated to establish their economic viability. A framework was developed carefully to ensure that a systematic approach was taken to solve this complex problem. The framework provides a four-stage approach to develop alternative end-of-life scenarios which can be evaluated in terms of their economic viability.
This research therefore enables a holistic consideration of the end-of-life management options for leather waste, using a framework provides a comprehensive approach in addressing the need for an economically viable end-of-life solution for leather waste.

12.3.3 Develop a waste-flow map for leather and define waste streams in terms of the quantitative and qualitative characteristics

The analysis of leather waste across its lifecycle identified the fact that the quantity and quality of the waste depends very much on the lifecycle stage at which it is generated. Despite commonalities in material between the waste streams across the lifecycle, there exist significant variations in physical characteristics between leather material waste and leather product waste. These variations in physical characteristics of the waste have an impact on the technical feasibility of recycling processes, and hence, may influence the decisions and actions necessary to ensure viable processing of the waste through the lifecycle. Economic priorities for recycling differ between the different waste streams, considering the breakdown in inherent value for each waste stream.

Leather material undergoes significant change in physical properties as the lifecycle progresses; this impacts the choice of recycling processes and hence the economic sustainability. This identifies the need for strategic approach to identify where to best target recycling initiatives in the leather lifecycle, and how to maximise recovery of materials.

12.3.4 Develop recycling and processing strategies for the recovery of leather waste

Within the research it was assumed that the size of the end-of-life leather waste stream did not justify the development of bespoke process technologies, and as such existing infrastructure should be adopted where possible. This led to the development of two end-of-life scenarios, based on existing process capability.

The strategy of mixing low quality waste with high-quality waste has been proven in other industries, namely, the plastics industry. This provides the basis for the vertical recovery and recycling strategy. It is economically infeasible to develop individual recycling and processing lines for each type of leather product; therefore, the strategy of horizontal mixing of the waste has been proposed to increase the feasibility of the recycling of post-consumer leather waste being economically viable. This works shows how products with
similar material content can be clustered to provide the economy of scale for a single recycling line to process different product and material types.

The secondary use of recycled leather material is under-developed, with a distinct lack of data surrounding the value of different purities of recycled leather material on the open market. It was not the intention of this research to present an optimised strategy for recycling and processing, but rather to use the end-of-life scenarios as a vehicle for developing and validating the evaluation methodology.

12.3.5 Develop a cost model to support economic decisions regarding the implementation of a circular approach in the leather industry

The economic viability of leather recycling and processing solutions depends on a range of considerations that are linked and need to be analysed in an integrated manner, this includes: volume of waste, quality, frequency, geographical distribution and material mix.

CBA is a recognised methodology and has proved to be a useful tool for the evaluation of economic viability which is commonly applied to the evaluation of end-of-life management solutions. The results generated from CBA are heavily influenced by the scope of the model used in the evaluation process and the quality and completeness of the input data; hence, the limitations of the methods proposed by this research are clearly acknowledged in this thesis.

Data availability was one of the biggest challenges encountered throughout the completion of the thesis; this is due to the novelty of the research area. As this area is explored in greater depth by the leather industry, and as more high-quality, comprehensive data becomes available, opportunities for development of a more detailed and accurate CBA model will arise. Noting these challenges, the results obtained from the CBA presented in the thesis are valid in relation to the current leather market.

12.3.6 Demonstrate the validity of the research concepts, framework and tools through case studies

To demonstrate the framework for the implementation of a circular approach within the leather industry, and the evaluation methodology developed in the research, two case studies were carried out. The primary objective of the case studies was to apply the framework in a systematic manner to support economic decision-making related to the selection of the most appropriate recycling and processing strategy for leather waste. The
case studies were specifically selected to demonstrate application of the evaluation methodology in a vertical approach (case study 1) and in a horizontal approach (case study 2).

### 12.4 Implementing a circular approach within the leather industry

The principle research questions, presented at the beginning of this thesis are: How can flexible waste recovery strategies assist the implementation of a circular approach within the leather industry? And: How can a circular approach improve the economic viability of leather recycling systems? These questions have been supported by a comprehensive review of the literature, which identifies end-of-life management as a notable challenge, driven by environmental and legislative concerns. As reported in the thesis, the exploration of end-of-life management of leather waste across the lifecycle extends the existing body of knowledge, by applying proven approaches and principles to leather industry waste.

Three categories of challenges and opportunities arising during the end-of-life management of products were identified: economic, environmental and legislative. Ever-increasing legislative control on end-of-life management presents a challenge to the current disposal practices for leather waste, while environmental challenges exist in ensuring that the least amount of environmental burden is caused when the wastes arising from end-of-life products are processed.

When developing commercial solutions for the management of end-of-life leather waste, economic challenges and opportunities are of greater significance. The costs of developing the end-of-life management system can be offset by the recovery of revenue from recycled material streams. The requirement to be able to evaluate economic performance is therefore necessary to support decision-making. The research therefore enables the challenges and opportunities in end-of-life management of leather waste to be analysed, by providing a comprehensive evaluation methodology which systematically assesses the economic viability of different end-of-life scenarios for leather waste.

Traditionally, an end-of-life product is regarded as a waste problem which must be dealt with in an appropriate manner; this is a reactive approach to end-of-life management of products. However, a proactive approach to end-of-life management is increasingly being prompted, with end-of-life considerations being incorporated into product design. The output from the framework supports the evaluation of the reactive end-of-life scenarios defined in the thesis; however, the knowledge gained during the application of the
framework provides a deeper understanding of the issues associated with the end-of-life management of leather waste. Thus, where the framework is applied in a reactive manner to leather waste, the knowledge gained can inform future proactive design decisions regarding end-of-life management. Therefore, the framework provides a comprehensive and transparent evaluation methodology which can support both a proactive as well as reactive optimisation of the lifecycle impacts of the leather industry.

12.5 Constraints and limitations to the research

The research reported in the thesis has been successful in addressing the original aims and objectives; however, several weaknesses in the work are acknowledged.

While this is undoubtedly a research area with great novelty, the absence of literature addressing the end-of-life management of leather waste is concerning; there is a possibility that research has been conducted by individual system developers but not disseminated. It is acknowledged that the preservation of commercial advantage is a necessity for any business that is undertaking research into leather recovery; this restricts and hinders the development of practical solutions to the problem.

The lack of practical and industrial data, with which to validate the theories presented in the thesis, is a particular weakness within the research; much of the research presented in the thesis is based on a combination of synthesised data and assumptions. With this in mind it is noted that the evaluation methodology, and in particular the cost-benefit analysis model, could in the future be further developed to allow a more thorough evaluation of economic viability at the end-of-life. While the validation of the cost model included a limited amount of sensitivity analysis, a higher level of confidence in and understanding of the results generated would be provided by a more systematic and extensive sensitivity analysis. Finally, it is noted that a sophisticated cost-modelling software tool along with a user-friendly interface would be beneficial to the future research.
CHAPTER 13  CONCLUSIONS AND FURTHER WORK

13.1 Introduction

This chapter summarises the principal research conclusions proposed by the thesis and identifies some interesting opportunities for extension of the work.

13.2 Research conclusions

The research presented within the thesis leads to the following conclusions:

I. The challenges imposed by incoming legislation and the consumer environmental concerns can be viewed as a burden to the end-of-life management of leather waste; however, opportunities exist in value recovery from recycled materials. If managed correctly, the leather waste can be viewed as a resource-rich asset which offers potential for contributing reducing the environmental impact and cost of managing the waste across its lifecycle. This highlights the need for systematic approach to leather recycling.

II. Variation in physical characteristics of the leather waste across lifecycle creates a strong need for strategic recycling and processing, to maximise the material and value recovery. Different strategies are required to contend with the variation in material properties across the lifecycle. Horizontal and vertical strategies for recycling and processing leather waste have different economic profiles and lend themselves to be applied by different groups of stakeholders within the recycling chain.

III. Economic viability is an essential consideration when deciding between alternative end-of-life recycling and processing strategies for leather waste. The complex decisions involved in developing an end-of-life management solution require a systematic approach to be adopted when evaluating economic viability. A holistic framework to define and evaluate alternative end-of-life scenarios for leather waste is essential to support this decision-making process.

IV. Existing waste management infrastructure can in part support the challenges regarding the processing of end-of-life leather waste; however, opportunities for improving overall economic performance would be realised by optimisation of material separation and recycling processes. It would be beneficial for leather product manufacturers to consider end-of-life management during product
conception and design, in particular, considerations around the current capabilities and limitations of existing recycling technologies.

V. CBA has proved to be a suitable tool for the economic evaluation of end-of-life strategies for leather waste; however, lack of quality data regarding the value of recycled leather materials on the secondary materials market hinders the effectiveness of this evaluation.

VI. The case studies show that a reduction in waste sent to landfill can relieve the waste producer of the legislative burden that would otherwise apply. The results from the case studies also show that the availability and quality of relevant data limits all evaluation methods. Uncertainties regarding the value of recycled materials on the secondary materials market lead to uncertainties in the development of end-of-life scenarios for leather waste. The absence of repeated process trials results from which to draw high-quality data leads to a requirement for the economic viability assessment to be based on assumptions rather than facts. However, considering all of this, the author believes that the benefits of the proposed leather recycling scenarios outweigh the shortcomings. The conceptualisation of many highlighted challenges paves the way for proactive measures to be taken to prevent and reduce leather waste across the lifecycle.

13.3 Future work

There are several routes for further developing the research documented in this thesis, aspects of interest to the author are described below.

13.3.1 Further practical work to explore alternative end-of-life processes for leather waste

It was not the intention of this research to provide an optimised end-of-life solution for leather waste, but rather to develop a framework by which such a solution could be identified and evaluated. Therefore, the end-of-life processing trials were limited to several laboratory-scale trials of novel processes. However, despite this, the research has identified that leather waste provides some interesting challenges with respect to recycling and material separation at the end-of-life. Further research into end-of-life processes would be beneficial in supporting the development of optimised processing routes for leather waste. Further research would also help to generate accurate data to support a deeper understanding of the economic and environmental impacts associated with the end-of-life stage of the leather lifecycle.
13.3.2 Consideration of additional performance parameters at end-of-life and integration of factors into a multi-criteria evaluation methodology

13.3.1 Economic impact has been identified within this thesis as the principal performance parameter associated with the various decisions surrounding end-of-life management of leather waste. However, it is acknowledged that concerns about environmental impact and legislative risk may grow in significance over time. The author believes that these issues may become increasingly significant in directing end-of-life management priorities, as material recycling becomes not just as an economic consideration but also an environmental necessity. Therefore, it is suggested that the consideration of these issues, and the development of a multi-criteria decision-making tool which evaluates economic, environmental and legislative impacts simultaneously would be beneficial to the future of this research to ensure that end-of-life management priorities continue to be relevant in future climates.

13.3.3 Further development of the framework for end-of-life management and the decision-support tool

The issues which are addressed within this research associated with end-of-life management are not unique to leather. It is the author’s opinion that the CAL framework for end-of-life management of leather provides a systematic approach for exploring and evaluating these end-of-life issues and is applicable to other waste streams. It is believed that both the framework and the evaluation methodology could further be developed to support end-of-life decisions within wider industrial applications.
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APPENDIX A

THE CHALLENGES IN ACHIEVING A CIRCULAR ECONOMY WITHIN LEATHER RECYCLING

This paper was presented at the 23rd International CIRP conference on LifeCycle Engineering in Berlin, 22nd-24th May 2016.