The realisation of end-of-life product recovery to support a zero waste to landfill approach in footwear industry

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The Realisation of End-of-Life Product Recovery to Support
a Zero Waste to Landfill Approach in Footwear Industry

by

Theodoros Staikos

A Doctoral Thesis
Submitted in Partial Fulfilment of the Requirements
for the Award of Doctor of Philosophy of
Loughborough University

Wolfson School of Mechanical and Manufacturing Engineering
July 2007

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Acknowledgements

First and foremost, I would like to express my honest gratitude to my academic supervisor Dr. Shahin Rahimifard for offering me support and guiding me throughout the entire development of my research work.

I would also like to thank my office mates, especially Gareth Coates, Chris Edwards, Muhammad Abu Bakar, Yusri Yusof, Abeer Pharaon and Simon Collins for interesting and fruitful discussions regarding research as well as everything about life.

Finally, I dedicate this thesis to my family. To my parents Dimitris and Vasiliki Staikos and my brother Paschalis for their unconditional support and love for all these years.
Synopsis

This thesis reports on the research undertaken to investigate the realisation of end-of-life product recovery in footwear industry, and to develop a systematic approach in considering the various factors that influence the selection of the most appropriate end-of-life treatment options for post-consumer shoes. The principle objective of this research is to generate knowledge and generic solutions to facilitate the application of product recovery and recycling procedures in footwear industry.

The research contribution is divided into three major parts. The first part provides an overview of recent advancements in footwear sector and reviews the most relevant research in the area of end-of-life product recovery and multi-criteria decision making techniques. The second part investigates a novel methodology for the end-of-life product recovery in footwear industry. The application of this methodology is supported by a multi-criteria decision making model and software tool to aid the selection of the most appropriate end-of-life treatment option for post-consumer shoes. The third part of the thesis explores the applicability of the research concepts through the development of case studies based on two distinctly different types of shoes. The results from these case studies have shown a wide range of potential markets that can be established for the various recycled materials that can be obtained from post-consumer shoes. These results also indicated that a small increase in the cost of recovery process can lead to generation of high quality shoe recycled materials which could have potentially valuable applications in various industries.

In summary, the research has concluded that the methodology, the multi-criteria decision making model and tool investigated by this research can provide invaluable support for the implementation of shoe recovery and recycling procedures in footwear industry. Throughout this research it has also become evident that the idealistic vision of “zero waste to landfill” in footwear industry cannot be achieved only by consideration of end-of-life management options and necessitates the proactive involvement of shoe manufacturers through improvements in shoe design and material selection.
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AHP</td>
<td>Analytic Hierarchy Process</td>
</tr>
<tr>
<td>BCR</td>
<td>Benefit/Cost Ratio</td>
</tr>
<tr>
<td>CBA</td>
<td>Cost Benefit Analysis</td>
</tr>
<tr>
<td>DfE</td>
<td>Design for Environment</td>
</tr>
<tr>
<td>ECM</td>
<td>Environmental Conscious Manufacturing</td>
</tr>
<tr>
<td>EDIP</td>
<td>Environmental Design of Industrial Products</td>
</tr>
<tr>
<td>EF-DST</td>
<td>End-of-Life Footwear Decision Support Tool</td>
</tr>
<tr>
<td>EoL-PR</td>
<td>End-of-Life Product Recovery</td>
</tr>
<tr>
<td>EoL</td>
<td>End-of-Life</td>
</tr>
<tr>
<td>EPR</td>
<td>Extended Producer Responsibility</td>
</tr>
<tr>
<td>ETS</td>
<td>End-of-Life Treatment of Shoes</td>
</tr>
<tr>
<td>IPP</td>
<td>Integrated Product Policy</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
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<tr>
<td>LCI</td>
<td>Life Cycle Inventory</td>
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<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
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<tr>
<td>MCDM</td>
<td>Multi-Criteria Decision Making</td>
</tr>
<tr>
<td>MCS</td>
<td>Men's Casual Shoe</td>
</tr>
<tr>
<td>PR</td>
<td>Product Recovery</td>
</tr>
<tr>
<td>WFB</td>
<td>Women's Fashion Boot</td>
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Chapter 1

Introduction

The development of the industry is one of the main driving forces for the economic growth of the society, resulting in improvements in the standards of living and quality of life of the population. However, the considerable growth in the scale of industrial production and consumption has resulted in the significant increase of pollution and waste worldwide. Nowadays, it is commonly accepted that a balance between industrial growth and protection of the environment is needed in the view of further economic development for the whole society. The identification of these environmental considerations has led to the concept of sustainable development, which takes into account the trade-off between continuous economic growth, social justice and the reduction of impact on the environment (WCED 1987). Under these conditions, the various industrial sectors are under increasing pressure to reduce their current level of material consumption, minimize their harmful releases to air, water and land as well as manage their products at the end of their useful life. These pressures are promoting a fundamental “ecological transformation” of the industrial sector to deal with industrial pollution and waste whilst also opening up new market opportunities for innovative environmental organisations and companies (Jamison, 2001).

Manufacturing of high-volume consumer products producing an enormous amount of post-consumer waste, most of which are currently end up in landfills around the world. As a result, most industrial sectors have been targeted by environmental legislations in order to provide solutions in accordance with the principles of sustainable development. Suggestions to reduce the generation of end-of-life waste do not only comprise the optimisation and efficiency of the design and production phase inside the factory, but also the introduction of product recovery and recycling procedures at the end-of-life phase. There is at present, a varying level of product recovery and recycling applications within many industrial sectors which are often developed on an “ad hoc” basis and mainly due to
the hidden economic value within used products. These recycling applications ranging from the automotive sector with a well-established recovery chain and the electrical/electronic sector with rapidly growing recovery activities to apparel and footwear sectors with a very limited recycling activity. However, it should be noted that it is not automatically a sound policy to recover and recycle end-of-life products and it is not automatically sensible to recycle in a certain way.

The footwear industry is a manufacturing sector which utilises a wide variety of materials and processes to produce a range of distinctly different products, from sandals to more specialised safety footwear. Over the last 20 years, the footwear sector has placed significant effort in improving material efficiency, as well as eliminating the use of hazardous materials during the production phase. However, the environmental gains made in production are being overtaken by the considerable increase in the demand for footwear products. Worldwide footwear consumption is doubled every 20 years, from 2.5 billion pairs in 1950 to more than 19 billion pairs of shoes in 2005 (World Footwear 2007). Footwear industry’s response to this increasing problem of end-of-life shoe waste has been negligible. In fact, the only established form of recycling, or more accurately reuse, activity in the footwear sector is the collection and distribution of worn or unwanted second hand shoes from developed countries to developing countries. Only one major shoe manufacturer, Nike, has been taken measures to manage its post-consumer waste through its well-known “Reuse-A-Shoe” recycling scheme, the only product take-back and recycling programme currently established by a shoe manufacturer. However, forthcoming environmental legislations as well as increasingly environmental consumer demands expected to challenge the way the global footwear industry is dealing with its end-of-life waste. Take-back and producer responsibility initiatives aim to affect the footwear sector similarly to other consumer goods sectors such as packaging, automotive and electrical and electronic. In addition, the emergence of mass customization as one of the main trends in today’s footwear market is changing the way footwear products are designed, manufactured, delivered and recycled. Mass customization represents a new trend that aims to apply the efficiency and scale economy of mass production in the manufacturing of small batches of diversified and personalised products (Boer et al. 2004). In fact, mass customization reduces the amount of end-of-life shoe waste generated by producing on demand rather than to stock and hence avoiding over production waste.
In this context, the research assertion of this thesis is that in a rapidly growing mass-production/consumption/disposal society, which generates an enormous amount of end-of-life waste, there is a essential need to develop product recovery and recycling procedures for post-consumer products in order to prevent material resources of being landfilled, reduce the consumption of raw materials and, finally, capture the hidden value of recyclable materials in used products. Product recovery and recycling is a crucial element in attempting to reach the vision of “Zero Waste to Landfill”, which remains one of the major challenges of the 21st century in many industrial sectors. To determine, however, the feasibility of an end-of-life product recovery application a comprehensive examination is required to ensure that recycling would provide environmental benefits and to examine which treatment option is the most appropriate based on a wide range of considerations including environmental, economic and socio-technical factors.

The research reported in this thesis aim to investigate the variant end-of-life options for footwear products and to generate a multi-criteria decision making model to aid the selection of the most appropriate product recovery and recycling treatment option for a particular end-of-life footwear product. To achieve this aim the following tasks will be undertaken:

i) An overview of market trends, materials, construction processes and environmental concerns in the footwear sector will be performed, together with an evaluation of current end-of-life product recovery and recycling practices adopted in other industrial sectors.

ii) A systematic end-of-life product recovery methodology will be investigated to enable the best decision possible to be made and to determine the most appropriate set of treatment actions for particular types of post-consumer shoes.

iii) The scope of the traditional end-of-life assessment and selection processes will be expanded to include a parallel consideration of environmental, economic and socio-technical aspects, through the development of a multi-criteria approach to support the decision making process.
Chapter 1

This thesis is divided into three major sections: research background and review, theoretical and experimental research, and research conclusions as illustrated in Figure 1.1. Section I, the research background and review, consists of five chapters and provides the context, objectives, scope and methodology of the research in addition to an appraisal of the relevant research publications and background knowledge to the research. Chapter 1 is the main introduction to the research work and presents the layout of the thesis. Chapter 2 outlines the context and assertion of the research together with a description of the research objectives and scope. Chapter 3 provides a literature survey of relevant research in the area of end-of-life product recovery, waste management and multi-criteria decision making. An extensive review of the footwear sector is outlined in Chapter 4 including a discussion on environmental issues and current reuse and recycling activities in the sector. Chapter 5 is the last in Section I and describes the research methodology undertaken in this thesis.

Section II, the theoretical and experimental research, comprises of five chapters which identify novel contributions to research made over the period of the PhD programme. This section commences with Chapter 6 which defines the potential waste management options in footwear industry and describes the creation of a waste management model for end-of-life footwear products. Chapter 7 describes the various stages of the End-of-Life Treatment of Shoes (ETS) methodology for post-consumer shoes. The multi-criteria decision making model for environmental, economic and socio-technical considerations is described in Chapter 8 while Chapter 9 outlines the design and development of the decision support software tool for identifying the most appropriate end-of-life treatment option. Finally, Chapter 10 describes the application of research results through two case studies.

Section III, the last section of the thesis namely research conclusions, consists of two chapters. Chapter 11 discusses the main research issues highlighted within this thesis in order to formulate research conclusions while Chapter 12 summarises the final conclusions of the thesis and provides a list of suggested research areas for the possible continuation of this research.
Figure 1.1: Thesis Structure
Chapter 2

2 Research Context and Scope

2.1 Introduction

This chapter describes the scope and context of the research reported in this thesis. The first section provides the context in which the research is undertaken. The latter sections identify the aim and objectives of the research, together with the specific scope of the work carried out in meeting each of the objectives.

2.2 Research Context

Manufacturers, governmental agencies, local and national authorities as well as the general public have come to recognise the importance of environmental quality. However, some environmental topics are of particular importance for most of people since affecting the quality not only of the overall environment but also of their own lives. One of these hot topics is the rapid increase in post-consumer (end-of-life) waste generation which is the result of many years of unsustainable production and consumption patterns around the world.

The need for the treatment of end-of-life products is unavoidable, no matter how well the product is designed or used. End-of-life product recovery procedures, however, are currently applied only in limited industrial sectors, which is mainly driven due to economic value of the recovered materials. It is argued that in order to make a desired environmental impact the number of product recovery and recycling applications has to be significantly increased and ideally be implemented in every manufacturing application.

The selection of an appropriate end-of-life treatment option, however, it is not always an easy process. Trade-offs are always present and a comprehensive analysis is often needed to determine the most suitable approach. In particular, practising recycling should not
result in a greater environmental impact than landfilling or even incineration. It makes sense to treat end-of-life products only if environmental, economic and socio-technical considerations are such that recycling is a preferable option. Hence, the selection process must achieve a reasonable balance between these considerations. A more comprehensive method should, therefore, be employed for selecting an appropriate end-of-life treatment option for a product (or product family). Such method must have the capacity to consider many criteria, which include a number of environmental, economic and socio-technical aspects.

To achieve such multi-disciplinary approach, three main domains of expertise have been examined throughout the thesis which are list below and depicted in Figure 2.1:

- Environmental Conscious Manufacturing
- Waste Management
- Multi-Criteria Decision Making

![Figure 2.1: Interrelation between the Different Areas of Research](image)
2.3 Aims and Objectives

The large amount of end-of-life waste produced every year, the pressures to divert waste from landfills as well as the hidden value of recyclable materials in post-consumer products provide the impetus for this research. The overall aim of this research is to investigate the variant end-of-life options for footwear products and to generate a multi-criteria decision making model to aid the selection of the most appropriate product recovery and recycling treatment option for a particular post consumer footwear product.

The major objectives to achieve the aim of the research can be defined as follows:

i) to review relevant research work on product recovery, waste management, environmental conscious manufacturing and multi-criteria decision making together with an extensive review of the footwear sector.

ii) to generate an end-of-life product recovery methodology tailored to the specific requirements of the footwear sector.

iii) to develop a multi-criteria decision making model for a parallel consideration of the main aspects influencing the selection of the most appropriate end-of-life treatment option for post-consumer shoes.

iv) to design and specify a decision support software tool to aid the selection of end-of-life treatment options for post-consumer shoes.

v) to demonstrate the validity and applicability of the research concepts and tools through case studies.

2.4 Scope of Research

The scope of the research is in line with the research objectives defined above, and are described below.
2.4.1 Review of relevant literature and footwear sector

An extensive review of relevant literature within the area of product recovery, waste management, environmental conscious manufacturing and multi-criteria decision making needs to be undertaken to provide a background on the research problem, present some of the main considerations in the field and define the major concepts upon which the research will be based. Furthermore, an analysis of various activities and practices in footwear sector will be conducted in order to gather information regarding materials and processes used to produce shoes as well as to investigate current reuse and recycling practices in the footwear sector and their environmental implications.

2.4.2 Generation of an end-of-life product recovery methodology for footwear products

The identification of the most appropriate end-of-life product recovery option often depends on the nature of the product itself and whether the objective is to minimise environmental impacts or maximise economic benefits. Therefore, there is clearly a need to identify a systematic method of considering all these criteria in an attempt to reach decisions that are environmentally acceptable, economically justified and socio-technically feasible. In this context, the generation of an end-of-life footwear product recovery methodology will be investigated in this research which aims to assist shoe designers, shoe manufacturers and recovery and recycling operators in determining appropriate end-of-life scenarios for post-consumer shoes. This methodology would enable the definition of alternative end-of-life treatment scenarios to a level of detail that will allow environmental, economic and socio-technical criteria to be calculated, analysed and compared.

2.4.3 Development of a multi-criteria decision making model for post-consumer shoes

In any product recovery and recycling application, there are a number of possible options with different environmental impacts, economical implications and socio-technical requirements. Hence, there is a need for a decision making process to assess and evaluate these criteria and provide support in decision making. The research will design and generate a multi-criteria decision making model for post-consumer shoes which aims to provide an integrated approach to evaluate a number of related quantitative and qualitative
product recovery and waste management factors that influence the selection of the most appropriate end-of-life treatment option for post-consumer shoes.

2.4.4 Design and development of a decision support software tool

The determination of the most suitable (in environmental, economic and socio-technical terms) manner in which to treat post-consumer shoe waste is a complex process involving the consideration of a wide range of materials, construction methods and recycling processes. Therefore, this research will design, specify and develop a prototype end-of-life decision support software tool for footwear products to facilitate the implementation of the multi-criteria decision making model for identifying optimal treatment options for post-consumer shoes.

2.4.5 Demonstrate the validity of the research concept though case studies

In order to assess the validity and applicability of the research concepts and to highlight the value of the proposed end-of-life product recovery methodology and its associated decision support model and software tool, a number of cases studies will be identified and undertaken. Industrial and experimental data will be used to populate the models to provide a comprehensive assessment of alternative end-of-life treatment options. These case studies will provide a benchmark against which the suitability of various end-of-life product recovery procedures for post-consumer footwear products can be investigated and measured.
Chapter 3

3 Review of Environmental Conscious Manufacturing, Waste Management and Multi-Criteria Decision Making

3.1 Introduction

This chapter provides a review of relevant research work to the scope of this thesis. It briefly presents some of the main considerations as well as defines the three major concepts upon which this research has been build upon, namely environmental conscious manufacturing, waste management and multi-criteria decision making.

3.2 The Concept of the Environment

The word ecology derives from the Greek word oikōς, which means household or, in a more abstract translation, everything in proper order. In this context, household can be regarded as a synonym for our global environment. Therefore, ecology is the science of the relationship between living things and their environments (Dictionary 2007). Ecology is also used as a synonym for the natural environment or environmentalism and, hence, ecologic or ecological is often taken in the sense of environmentally friendly.

Until the 1960s, the ecological or environmental concept was not a major concern. As Dryzek (1997) notes, "the environment did not exist as a concept in politics and policy making in any country until the 1960s". Environmental policies were just beginning to take hold and discourses on such a subject were not common. This situation changed with the emerged of the environmentalist or ecology discourse that came to surface during the late 1960's and early 1970's as a part of a social movement against the industrial society and its waste (Jameson 2001). These movements changed the attitude of the whole society concerning environmental problems. In addition, an entire range of environmental concerns have facilitated this transformation in the public opinion. As Hajer (1995)
Chapter 3 reveals, "a collection of claims and concerns brought together by a great variety of actors, from sociologists, engineers, and economists, environmental experts, politicians, and activists, altogether contribute with their ideas and theories to the ecological transformation of the society".

3.3 Environmental Conscious Manufacturing

Environmental Conscious Manufacturing (ECM) is "concerned with developing methods for manufacturing new products from conceptual design to final delivery and ultimately to the end-of-life (EoL) disposal such that the environmental standards and requirements are satisfied" (Gupta and Gungor 1999). The major objective of ECM is to minimise the environmental load of manufacturing activities by conserving energy and natural resources while protecting the natural environment. It should be noted that ECM is also referred as Environmental Benign Manufacturing, and Sustainable Manufacturing in some parts of the world.

3.3.1 Origins of Environmental Conscious Manufacturing

The evidences of the ecological transformation of the society, at least in the developed world, are numerous and can be found in all the three pillars or institutions that constitute a stable society, the State, the Civil Society and the Market. The establishment of the ecological transformation of the society can be analysed using the following model, which adding the sector of Industry as an integral part of the society (Scott 2001). There is an interconnection between Industry and the three institutions which resulting to pressures against Industry, as depicted in Figure 3.1. If we put this model in our context, it can be argued that environmental pressure coming from the State, the Civil Society and the Market follow-on changes in the Industrial sector.
Figure 3.1 Interconnections between industry and the three institutional pillars of the society (Scott 2001)

On the State level, several events and developments show a change in the way of thinking of the decision-makers towards more responsible and accountable environmental laws and regulations. From the first piece of environmental legislation that passed through the European Union (EU) in 1967 until today, numerous environmental laws and regulations came into effect. On the other part of the Atlantic Ocean, several initiatives became known in the environmental policy field. The most important of them include the first laws against toxic waste and their management along with the establishment of the Environmental Impact Assessment (EIA) process (Welford and Gouldson 1993). All the above-mentioned developments have led to the commonly acceptable notion of Sustainable Development, as seen in the influential United Nations report *Our Common Future* published in April 1987 by a team led by the Norwegian Prime Minister Gro Harlem Brundtland. According to this report sustainable development was loosely defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). A more practical definition of Sustainable Development talks about the "three pillars of sustainability" (Environment, Economy and Social aspects) which often summarized by the catchy phrase "People, Planet, Profit" or "Triple Bottom Line" (Klöpffer 2003). Although there seems to be an agreement about the three pillars, there is not such global consensus about the relative weights of these aspects. Industrialized countries tend to emphasize the environmental and social aspects, whereas developing countries give highest priority to
economic development. Currently, according to Faber et al. (2005), more than 50 definitions and operationalisations of sustainability exist in the literature. Convincingly, it can be argued that the development of the Sustainable Development concept practically constitutes the establishment of the ecological transformation of the society in the level of the State.

Similar developments can be found on the Civil Society domain which show that the awareness of the public about environmental issues have been improved over the years. Initially, a number of scientific publications following with the media coverage of environmental degradation and disasters raised the awareness of the people for the global and local limits to environmental exploitation and modification. One of the publications that opened the eyes of many, during the 1960’s, was Rachel Carson’s book *Silent Spring*, which speaks about the effects of the use of pesticides such as DDT (Carson 1962). This was one of the first publications to address environmental concerns at the level accessible to general readers. Furthermore, several accidents or disasters that happen over the past fifty years have helped make us aware of the deterioration of the global environmental. Early on in the 1950’s there was the mercury poisoning of the Minimata Bay in Japan, which announced the coming of the global environmental crisis, while in the 1960’s there was the ecological devastation of Vietnam and the countless discoveries of waste and pollution in fields and factories around the world (Jameson 2001). In the 1970’s the environmental crisis started to hit closer to home with the Seveso disaster in Italy in 1976, when a factory exploded and a dioxin cloud contaminated a densely populated area in the outskirts of Milan (Mitchell 1996). Soon after came the nuclear accident at the Three-Miles Island in USA in 1979, which brought a new phase of anti-nuclear movement around the world. It led, for example, directly to the Swedish government’s decision to hold a referendum on the future of nuclear energy, and gave a serious push for the development of alternative forms of energy in other countries (Jameson 2001). In 1984, there was an explosion at the Union Carbide chemical plant in Bhopal in India, killing and blinding tens of thousands of people in the surrounding area. The Bhopal disaster was, perhaps, the first example of a global environmental catastrophe, which led to a lengthy legal dispute between American and Indian officials, and offered an initial example of the ways in which environmental problems were exported from the Northern industrial countries to less-developed countries in the Southern hemisphere (Mitchell 1996). In 1986, there was an accident at the nuclear energy facility at Chernobyl in Ukraine,
spreading radioactivity across northern and central Europe. Again, the international character of the crisis was brought home and raised the awareness and concern of the public for the use of both chemicals and nuclear energy. It was during that period of time that many European countries cancel their plans for building up nuclear power plants as a consequence of the public debate and pressure against these developments (Jameson 2000). During the 1980's also, people saw a need for environmental representation in the decision-making processes, leading to the strengthening of green parties throughout regions such as Germany, Scandinavia as well as within the European Parliament (Burchell 2002). Media coverage of environmental degradation and disasters, publications, scientific discoveries, green parties, and even rising awareness among the public and consumers of products all comprise evidences of the ecological transformation that happen in the civil society and have led up to the emergence of a new ecological lifestyle and consumption habits, where economic concerns are no longer the only consideration.

Finally, on the Market level radical changes emerged with the view to adopt and adjust the changes that described above in the other sectors. This situation has generated new ideas, theories and methodologies especially in the area of cleaner production, waste prevention and environmental management. In recent years, Corporate Social Responsibility (CSR) has emerged as an increasingly important feature of the market philosophy. According to the European Commission (2002), CSR is defined as “a concept whereby companies integrate social and environmental concerns in their business operations and in their interaction with their stakeholders on a voluntary basis”. CSR urges companies to make decisions based not only on financial factors but also based on the social and environmental consequences of their activities (European Commission 2002). This approach is closely linked with the principles of sustainable development.

Table 3.1 below summarises some of the developments that establish the concept of ecological transformation of the society.
3.3.2 Future Trends in Environmental Conscious Manufacturing

The adjustments that occurred, and described in the previous chapter, have showed a shift in the way the market, the state and the civil society deal with environmental issues. These pressures have also prompted the industrial sector to modernize its activities according to the ecological transformation concept. While unlimited production without regard to pollution and waste used to be the way industry worked, the activities, during the last fifty years, have encouraged industry to start looking at its impacts on the environment. For many years, however, the mentality of the industry was still to treat environmental pollution through “end of pipe” solutions, meaning the treatment of wastes and pollution streams with traditional means of combating pollution leaving the original product and process unaffected (Welford and Gouldson 1993).

Over the last decade, however, a growing number of environmental life cycle-based concepts and tools have been developed to facilitate the management and monitoring of sustainable practices in manufacturing (Alting and Legarth 1993). These concepts and tools provide an expanded view of environmental management in order to look at the entire system from “cradle to grave”. International trends are demonstrating that life cycle-based concepts and tools such as Life Cycle Assessment (LCA), Industrial Ecology and Design for Environment (DfE) and here to stay (Fava and Cooper 2004). Finally, with the launch of the Integrated Product Policy (IPP) by the European Commission (2003), new challenges have been put forward to incorporate life-cycle thinking into policies for the improvement of the environmental performance of product systems.

Table 3.1: Ecological Transformation of the Society (Jamison 2001)

<table>
<thead>
<tr>
<th>State</th>
<th>Market</th>
<th>Civil society</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainable Development</td>
<td>Corporate Social Responsibility</td>
<td>Ecological Lifestyles</td>
</tr>
<tr>
<td>Responsive Regulation</td>
<td>Environmental Management</td>
<td>Public Participation</td>
</tr>
<tr>
<td>Ecological Procurement</td>
<td>Cleaner Production</td>
<td>Green Consumption</td>
</tr>
</tbody>
</table>
3.3.2.1 Life-Cycle Based Concepts and Tools

In order to design, manufacture, use and dispose a product which is environmentally benign, the whole life cycle of the product should be investigated. The gains made in production efficiency are being overtaken by the overall increase in the demand for products and services, the so-called rebound effect (UNEP 2002). The challenge of the rebound effect can only be tackled through life-cycle approaches that take into consideration the production, consumption and end-of-life phases of a product life-cycle covering all processes required: extraction and processing of raw materials, manufacture, transport and distribution, use, reuse and maintenance, recycling and final disposal. All decisions should be made based upon an analysis of its consequences on the total life-cycle.

For this reason, life-cycle-based tools and approaches were developed to avoid problem shifting from one life cycle stage to another, from one geographic area to another and from one environmental medium to another. It does not make any sense at all to improve one part of the system in one country, in one step of the product life cycle, or in one environmental section, if this improvement has negative consequences for other parts of the system, which may outweigh the advantages achieved. In other words, a systems approach has to be taken into consideration. Westkamper et al. (2000) state that “life-cycle based approaches are the essential requirement and the key element in achieving the movement towards sustainable development”. Life-cycle based thinking expands the traditional focus on manufacturing processes to incorporate various aspects associated with a product over its entire life-cycle (Hauschild, 2004). In this respect, IPP has been proposed by the European Commission (2003a) to “considers a product’s life-cycle and aims for a reduction of its cumulative environmental impacts, from the cradle to the grave”. The main objective of IPP is to direct environmental policy attention from merely production processes towards comprising also consumption-related emissions and waste by using a toolbox of policy instruments and life-cycle based tools.

Such a life-cycle-based tool is the concept of Industrial Ecology (IE), currently identified as a broad umbrella of concepts rather than a unified theoretical construct. As such, it is described and presented in different ways by different authors. In general, the concept “requires that an industrial system be viewed not in isolation from its surrounding
systems, but in concert with them" (Graedel and Allenby, 2003). The idea is that no firm exists in a vacuum but is linked to thousands of other transactions and activities and to their environmental impacts. Design for Environment (DfE), on the other hand, has a more narrow meaning. DfE ensures that all relevant environmental considerations and constrains are integrated into a firm’s product design process. Sun et al (2003) examined academic research in the DfE area and attempted to identify future trends to further realise DfE in industry. Other closely related tools, all based on a cradle to grave approach, have also been developed and used to analyse products and their interactions with the environment. Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) are such representative tools. The major difference between them is that LCA is an analytical tool for specifying product chains while MFA is used for specifying material or even substance chains (Lewis and Gertsakis 2001). Although, in recent years, LCA has become as much a way of thinking as a tool or methodology, the term LCA has stricter application as a specific and internationally standardised methodology, according to the ISO 14040 standards, for assessing environmental burdens from product systems (ISO 1997). LCA and the related research is discussed in more details in Section 8.5.1.

3.4 Waste Management

According to the Directive 2006/12/EC (2006), waste management is defined as “the collection, transport, recovery and disposal of waste, including the supervision of such operations and after-care of disposal sites”. Waste management practices differ significantly for developing and developed nations, for urban and rural areas, and for household, industrial, and commercial producers. This thesis discuss waste management practices in a European perspective and mainly focus on waste management of end-of-life consumer products.

3.4.1 Trends in Waste Generation and Management

Waste generation in the European Union is currently estimated at about 1.3 billion tonnes per year, approximately 3.5 tonnes per capita per year. This includes waste from manufacturing (338 million tonnes), from mining and quarrying (377 million tonnes), from the construction sector (286 million tonnes), municipal solid waste (182 million tonnes) and hazardous waste (27 million tonnes) (European Commission 2003b). In
addition significant amounts of waste are produced by agriculture, forestry, fishery, and the service and public sectors; however, there are no good estimates of the quantities. Contribution of various waste types on the total amount of waste generated in the EU is depicted in Figure 3.2 In general, waste generation in the EU is increasing at rates comparable to economic growth. For example, both GDP and municipal solid waste grew by 19% between 1995 and 2003 (European Commission 2005). These upward trends in waste generation are expected to continue, in particular generation of post-consumer waste. Post-consumer waste is simply the garbage that people routinely discard, either in a litter bin, or by recycling, incinerating or pouring down the drain. Post-consumer waste is distinguished from pre-consumer waste, which is the reintroduction of manufacturing scrap (such as trimmings from leather production, etc.) back into the manufacturing process. Pre-consumer waste is commonly used in manufacturing industries, and is often not considered recycling in the traditional sense.

According to the recently published Directive 2006/12/EC (2006), waste should only be landfilled when the use of better waste treatment option is not possible. However, in many countries landflling still is the most common practice of waste treatment.
Based on the latest EU figures, municipal waste is disposed of through landfills (49%), recycling and composting (33) and incineration (18%) (European Commission 2005). However, there are wide disparities between Member States, ranging from those which recycle least (90% landfilling) to those which are more environmental friendly.

Figure 3.3 presents the mix of different waste management methods used in various European countries. The figure shows that some progressive European countries (e.g. Netherlands, Belgium) have already in place methods to reduce the growth in waste volumes and move waste management up the waste hierarchy while others are still throw waste in holes in the ground (landfill sites) or burn it (incineration). However, while recycling and incineration are increasing in the EU, the absolute amounts of waste landfilled are not decreasing because of the growth in total waste generation. For example, the amount of post-consumer plastic waste going to landfill increased by 21.7% between 1990 and 2002 in the EU, regardless of the considerable effort devoted to plastic recycling during this period (European Commission 2005).

![Figure 3.3: Waste Management Method in different European Countries (Strategy Unit 2002)](image-url)
In the UK, in particular, the amount of waste landfilled has remained almost stable between 1999 and 2003 despite a rapid development in the amount of waste recycled (CIWM 2005). Hence, it can be concluded that although the proportion of recycled waste has been increasing, this has been offset almost completely by an increase in waste generation.

3.4.2 Market Pressures and Waste Generation

According to Porter (2004), to meet the needs of market and customer demands, manufacturing companies must continually introduce new products to keep consumers coming back for more. Today's consumer demands a larger variety of products on different price levels including products for specialized markets. To be competitive, manufacturing companies must face two key challenges: being quick to market changes and staying relevant in order to identify or establish consumer trends and get to the market first (Kahn, 1998). These market challenges lead obviously to a shorter product life-cycle, and an even increasingly shorter product development cycle.

A shorter product life-cycle means that more and more products are being produced over the years which lead to a higher level of post-consumer waste when these products reach the end of their functional life (EC, 1999). Figure 3.4 presents some of the pressures that manufacturing industries are facing, leading to increased waste generation at the end-of-life phase.
3.4.3 The Waste Hierarchy Concept

The last thirty years have seen a radical change in the way that waste is managed. Firstly, the environmental impacts of waste management are increasingly under control. Legislative requirements are in place, and their enforcement is improving. Secondly, the economics of waste management have changed. Particular waste streams that companies would have had to pay to be taken away a decade ago, are now being sold in a global commodities market. Thirdly, business innovation has transformed the technology available for the handling and management of waste which makes recycling and product recovery a feasible option (Monkhouse and Farmer 2003). According to the European thematic strategy on recycling of waste (European Commission 2005) "the long-term goal is to become a recycling society that seeks to avoid waste and uses waste as a resource". To achieve this goal and, hence, secure a higher level of environmental protection, the European Commission has set up basic principles upon which its approaches to waste management are based.

Based on the EU principles on waste management, "Member States must prohibit the abandonment, dumping or uncontrolled disposal of waste" as well as "they shall promote waste prevention, recycling and processing for reuse" (Directive 2006/12/EC 2006). A waste hierarchy, therefore, set out the order in which waste management should be considered based on environmental impact, as depicted in Figure 3.5.

![Waste Hierarchy Diagram](image)
Following this hierarchy, reduction of waste is the top priority of waste management solutions. Reduction of waste, which is also referred to as waste minimisation, aims to reduce or generate less waste, in the first place, through efficient use of materials, better design and reduced operational costs (Monkhouse and Farmer 2003). The second preferred option is to reuse products and materials with minimal processing. Reuse includes any operation by which components and products are used for the same purpose for which they were conceived in the first place. Recycling is the third preferred option. Through recycling, materials send back into the process by additional processing in order to recover value from waste. When waste is being recycled, the value extracted from raw materials should be maximised while the energy needed for recycling should be less than that for extracting new raw materials. Energy recovery from waste is a process by which energy contained in the waste is extracted in the form of fuel or electric, which can be then used as a power source for various applications. Techniques currently used to recover energy from waste are varied and include incineration, anaerobic digestion, gasification and pyrolysis (McLanaghan 2002). Finally, disposal of waste in landfills is considered as the worst waste management option, although in many countries still is the most common form of waste treatment.

It should be mentioned, however, that the waste hierarchy concept has its own limitations. Firstly it is too simplistic to be applied in real life situations and secondly does not incorporate the sustainability dimension for reaching judgements about the preferred option within the waste hierarchy. Although the European Commission presented this hierarchy under its sustainable development initiative, sustainable development is seen to have a number of dimensions; such as social, ethical, economic and environmental. It is therefore not clear on which of many possible criteria the hierarchy is based on. Is reuse always better than recycling? Is incineration (energy recovery) a better waste management option than landfilling? According to a recent vote by the Members of the European Parliament (MEPs), the principle of a five-stage waste hierarchy will be laid down in a piece of draft EU legislation for the first time with the revision of the 1975 Waste Framework Directive (Materials Recycling Week 2007a). In fact, MEPs agreed that deviations from the hierarchy should only be allowed when backed by established and publicly available scientific criteria. The waste hierarchy concept, in reality, is used as a communication tool to highlight the range of alternative options for waste management. It should, therefore, only be regarded as a general guideline to determine waste
management options, including waste minimisation, recycling and reuse. In order to identify the best waste management option for a particular product, a detailed assessment is needed that will take into consideration sustainability factors such as social, environmental and economic indicators.

3.4.4 “Zero Waste to Landfill” Approach

The developed world is stuck in a linear model of the economy, meaning resources are extracted, turned into goods, consumed, and finally disposed. According to Biffaward (2006), most products stay in the economy for less than six months before they become waste. “Zero waste to landfill” is the expression of the desire in some countries, regions or organisations to move away from this linear model of resource use. The concept of “zero waste to landfill” represents the new versus the old waste command.

In fact, zero waste means going further than maximising recycling, to stopping things being discarded, through waste prevention. It means focusing at product policy to persuade consumers to buy products that have less non-recyclable or hard-to-recycle items. “Zero waste to landfill” initiatives are mainly voluntary. However, pricing is crucial, and councils have been finding ways to put landfill costs up, including imposing landfill taxes, closing smaller sites, and using regulations to mandate the pre-sorting of waste going to landfill. New Zealand is often credited as the first country to declare a zero waste goal, which means a goal of “zero waste to landfill” over a period of five to 15 years while increase recycling to 100 per cent of waste (New Zealand 2007). However, the zero waste movement is by no means just about municipal solid waste recycling since companies are also embracing the zero waste approach. In December 1999, Toyota UK set a target to send “zero waste to landfill” by 2005. It achieved this target in 2004 and continues to reduce its overall environmental impact. By sending zero manufacturing waste to landfill, Toyota has made significant savings in initial material purchase, handling, treatment and disposal of waste while it has also eliminated its exposure to increases on the landfill tax (IEMA 2004). Additionally, the super market chain ASDA has also committed to “zero waste to landfill” by 2010, and in addition, all of the products sold under the ASDA brand will be redesigned with the aim of reducing the weight and volume of packaging by at least 10 per cent (ASDA 2006). Finally, Wates Construction recently announced that it intends to eliminate its landfill waste by 2010, as it attempts to
lead a green revolution in the construction industry responsible for a third of UK waste volume (Wates Construction 2006).

3.4.5 Review of EU Waste Policy and Legislations

The adoption of the EU Waste Framework Directive 75/442/EEC (1975) was the first piece of legislation that intended to provide a common framework for waste policy, and sought to define a set of measures applicable to all Member States. This directive was followed by other EU directives on toxic waste, waste oils, shipment of hazardous waste, etc. At this first phase of waste policy development, there was a tendency to focus on end-of-pipe solutions to the problems associated with waste. However, since the 1990's, the EU waste policy focus has shifted towards more proactive approaches and has been a considerable increased in the number of policy measures using the principle of producer responsibility (Monkhouse and Farmer 2003).

In general, waste policy in the European Union is based on four key principles (European Commission 2003b):

i) Prevention Principle. The EU policy promotes better resource efficiency by shifting toward more sustainable patterns of production and consumption.

ii) Producer Responsibility and Polluters Pay Principle. The producers and distributors of waste are responsible for the entire life-cycle of their products and have to carry the expenses caused during this time. This means that producers and distributors are responsible for the final treatment or disposal of goods and its packaging.

iii) Precautionary Principle. Potential problems for the environment or human health should be anticipated and measures must be taken.

iv) Proximity Principle. Waste should be deposited or treated as near to its source as possible.

Based on these principles, the EU waste legislation can be divided into three main categories, as depicted in Figure 3.6:
Horizontal legislations, which establish the overall framework for the management of waste in the EU, including definitions and general principles.

- Legislations on waste treatment operations, including disposal, such as landfill and incineration directives
- Legislations on specific waste streams, which has been motivated by the growing waste volume and complexity of specific waste streams such as packaging and end-of-life vehicles directives.

In particular, the implementation of the Landfill Directive 99/31/EC (1999) and the increasing cost of landfilling are expected to be major drivers for the future development of waste management policies which promote the diversion of waste towards products and materials recycling. Currently in the UK, landfill tax rises by £3 each year, but was revealed that from April 2007 it will rise by £8 per year until 2010-11 (Materials
Recycling Week 2007b). This would mean that landfill tax will rise above £48 per tonne by 2010, exceeding £35 per tonne, which is the rate suggested as providing the tipping point for making landfill uneconomic by taking gate fees to £50-£60 per tonne.

In this context, very important also are the landfill restrictions introduced by the Directive, in particular the reduction in the amount of biodegradable waste going to landfill and prohibition of the landfilling of certain waste types such as tyres. Members of the European Parliament (MEPs) have voted, recently, for a revised EU Waste Framework Directive, which would succeed the 1975 Waste Framework Directive. MEPs adopted a non-binding “thematic strategy” for waste which aims to ban the landfill of paper, glass, textiles, plastic and metal by 2015 and ensure that no recyclable waste is landfill by 2020 (Materials Recycling Week 2007a). In the near future, however, the EU waste policy focus is likely to move away from the existing priority waste stream approach to looking at materials, regardless of whether these come from packaging, end-of-life vehicles or other waste streams. According to (Monkhouse and Farmer 2003), targets for reuse and recycling may therefore be set on for paper, plastic, leather etc, rather than looking at these materials from different sources.

3.4.5.1 The Principle of Producer Responsibility

In most countries, managing end-of-life waste has long been the responsibility of governmental agencies and local authorities. Once products reach the end of their functional lives, manufacturers play no role in collection, recycling or disposal of those end-of-life products. But in 1991, the first so-called product take-back or producer responsibility legislation was introduced by the German government which changed the whole concept of sustainable waste management. In an effort to relieve local authorities and municipalities from rising waste management costs, the 1991 Packaging Ordinance required manufacturers and distributors in Germany to take back packaging from consumers and ensured that a specified percentage of it is recycled (Fishbein 1996). However, manufacturers and distributors could meet their obligations by joining a “producer responsibility organization” that handled collection and arranges for recycling and product recovery of the end-of-life waste products. This concept of broadening manufacturer’s responsibility for products beyond their useful life into the post-consumer
Chapter 3

phase is called Extended Producer Responsibility (ERP) or just Producer Responsibility (PR) and is also concerned about closing the loop with respect to materials use and waste management at the end-of-life stage (Hanisch 2000).

According to OECD (2001), "producer responsibility is an environmental policy approach in which a producer’s responsibility for a product is extended to the post-consumer stage of a product’s life cycle". Although there are variations on the producer responsibility concept, generally the concept impose a fee that is paid by manufacturers or retailers for targeted products, and establish specific take-back goals for each targeted material or product system. This concept based on the idea that if manufacturers pay for the post-consumer impacts of their products, they will design them differently to reduce end-of-life waste while increase recovery and recycling targets for materials and products (Palmer and Walls 2002).

The principle of producer responsibility was first introduced into the EU waste policy with the 1994 Packaging Directive and since then has spread to other industrialised countries (Directive 94/62/EC 1994). In 2000, the European Commission has passed a Directive requiring its Member States to institute a producer responsibility program for end-of-life vehicles (ELV) (Directive 2000/54/EC 2000). Furthermore, an additional Directive for Waste Electronics and Electrical Equipment (WEEE) is expected to be adopted soon by all EU Member States (Directive 2002/96/EC 2002). Additionally, local councils and authorities around Europe urging manufacturers to take responsibility and pay the cost of the increasing amount of post-consumer waste send to landfill. In the case of disposable nappies, the British Local Government Association (LGA) board chairman, stated that “it is high time that nappy manufacturers were made to take full responsibility for the life cycle of their products. It’s totally unacceptable that the council tax payer is picking up the bill for landfilling disposable nappies” (Materials Recycling Week 2007c). However, this is not only a European phenomenon as, for example, ToJo (2001) presents Japan’s Extended Producer Responsibility legislation which covering four large electric home appliances (TV sets, refrigerators, air conditioners and washing machines). Lindhqvist and Lifset (2003) and Forslid (2005) state that producer responsibility procedures are providing a stable source of financing to offset the cost disadvantages of recycling versus energy recovery and disposal while Mayers et al. (2005) suggests that the EU should revise the scope of consideration of the WEEE Directive in order to ensure that product
life-cycle impacts are addressed. The paper states that, in particular, specific environmental objectives and operating standards for treatment and recycling processes should be investigated as an alternative to mass-based recycling and recovery targets.

Furthermore, over the last years, voluntary producer responsibility programs have also emerged in some setting, for some materials, and within some industries. Voluntary take-back programs in many ways reflect those created through legislative initiatives. Individual companies or specific industries set up procedures to recover end-of-life products, either direct by the manufacturer or through a designated collection network. Costs are borne either by an individual firm or through a fee system established by the sponsoring industry. Gattuso et al. (2002) provide a list of examples of such voluntary producer responsibility activities introduced by major manufacturers such as Dell, IBM, Hewlett Packard and Nike.

3.4.6 End-of-Life Product Recovery

When a product reaches the end of its functional life, it can be recovered in a variety of ways. Understanding and developing methods for the end-of-life management of products by means of material and product recovery are extremely crucial considering the amount of post consumer waste generated. In a world of limited resources and disposal capacities, end-of-life product recovery (EoL PR) is key in supporting a growing population at an increasing level of consumption. It should be mentioned that EoL PR has been approached from a wide array of disciplines including operations management, engineering, economics, marketing and logistics. A review from all this perspectives is beyond the scope of this thesis. As such, the review is focusing on engineering and operations management literature.

End-of-life product recovery (EoL PR) procedures have resulted in the emergence of new activities and actors, which require accomplishing recovery processes at the end of the product's functional life, including collection of end-of-life products, inspection/separation, reprocessing, and redistribution of recovered products and finally disposal of waste. All these flow of materials and products between different actors involved in the various stages of end-of-life product recovery, constitute the so-called product recovery chain (Rahimifard et al. 2002). Figure 3.7 gives a graphical
representation of the activities within a product recovery chain together with traditional supply chain activities.

3.4.6.1 Definitions of End-of-Life Product Recovery

One definition of End-of-Life (EoL), proposed by Rose (2000), is "the point in time when the product no longer satisfies the initial purchaser". This definition allows for reuse in addition to recycle as possible end-of-life treatment options. Other definitions start from the last user, but do not include reuse and service as potential end-of-life strategies. Hence, the definition of Rose, which captures the situation where consumer preferences change more rapidly than the product wears out, has been adopted throughout this thesis. On the other hand, as Gupta and Gungor (1999) defined, product recovery "aims to minimise the amount of waste send to landfill be recovery materials and parts from old or outdated products by means of recycling and remanufacturing (including reuse of parts and products)". In addition, many categorisations exist in the literature regarding product recovery activities.

![Diagram of Product Recovery Chain](image)

**Figure 3.7: Product Recovery Chain (Fleischmann 2001)**
Thierry et al. (1995) present a categorisation of product recovery options into repair, refurbish, remanufacture, cannibalise and recycling while Johnson and Wang (1995) define the product recovery process simply as a combination of remanufacture, reuse and recycling. Another alternative definition was presented by Fleischmann et al. (1997) which categorise product recovery simply into material recovery and added value recovery. However, Gupta and Gungor (1999), Moyer and Gupta (1997), Brennan et al. (1994), and US EPA (1997), simply classify the recovery of end-of-life products into two major categories:

- Material Recovery (Recycling) and
- Product Recovery (Remanufacturing).

Both end-of-life recovery options imply collection of the product, reprocessing activities and, finally, redistribution of the recovered product. However, the main difference of the two options is in the reprocessing activities. Material recovery or recycling aims to recover the material content of retired products by performing the necessary reprocessing activities. These mostly includes disassembly, sorting and chemical operations for separation and processing of materials (Spengler, 1997). The main objective of recycling is to minimise the amount of waste send to landfill and maximise the amount of materials returned back into the production cycle. The economic value of end-of-life products is the main reason for several established infrastructures for recycling operations along the industry.

On the other hand, remanufacturing preserves the product’s identity and performs the required operation in order to bring the product to a desired level of quality. Lund (1996) defines remanufacturing as “an industrial process in which used or discarded products are restored to like-new condition”. Fleischmann et al. (1997) present a series of industrial processes of bringing end-of-life products back to “as new” condition by performing operations such as disassembly, overhaul and replacement. Guide and Srivastava (1997) present a typical product and part flow in a remanufacturing environment while examines the differences between conventional production systems and remanufacturing systems.
Different methodologies have also been developed in order to find a balance between the time and money invested in recovery operations and value gained from the recovered or remanufactured products and materials. Johnson et al. (1995) suggest a methodology which aims to identify a preferred sequence of disassembly steps while maximise the value gained from recovery products. Hentschel et al. (1995) present an approach to recycling system planning for used products at their end-of-life phase while Krikke et al. (1998) propose a model to evaluate recovery strategies without violating the physical and economical feasibility constrains. Gungor and Gupta (1997) present a methodology to evaluate different disassembly strategies so that the best one could be chosen. Finally, Rahimifard et al. (2004) suggested a novel systematic five-stage methodology, called PRIME, to support product end-of-life management in different manufacturing applications based on an integrated view for a product supply and recovery chain.

Disassembly issues have also gained a lot of attention in the literature due to its role in end-of-life product recovery (Jovanne 1993, Brennan 1994, Gupta and Taleb 1994). If a product, instead of being disposed, remanufactured or (partially) recycled, it usually involves disassembly operations. Disassembly may be defined as a series of actions that separates a product in subassemblies and/or components, making a product partially (product not completely disassembled) or completely (product is fully disassembled) disassembled. Some approaches to disassembly distinguish between destructive and non-destructive disassembly. Feldmann and Scheller (1994) further subdivide destructive disassembly into partially destructive 1, and partially destructive 2. The former implies minimal destruction due to removal, for example, of labels or screws while the latter normally implies severe modifications on the original component (e.g. shredding). However, as Alting and Legarth (1995) conclude, a high percentage of products are not recovered because of the significant disassembly cost. This is mainly because, in the past, research was more production oriented without taking into consideration the life cycle aspects of the product. Finally, other related area of research related to product recovery is also inventory control and production planning for recycling and remanufacturing environments (Srivastava and Guide 1997, Fleischmann et al. 1997, Korugan and Gupta 1998).
3.4.6.2 Drivers of End-of-Life Product Recovery

The reasons for developing end-of-life product recovery activities are mainly hidden economic value of end-of-life waste, market requirements and, last but not least, legislative pressures. Fleischmann, (2001) adds also asset protection to the list of product recovery drivers. To begin with, EoL PR has to be economically attractive in order to be successful. Recovery is often cheaper than purchasing new products or virgin materials. However, in view of low raw material prices, economic attractiveness often relies in the recovery of added manufacturing value rather than on mere materials recovery (Fleischmann, 2001). For example, Xerox corporation, through its Xerox Green World Alliance recycling program, has saved millions of dollars in annual logistical, inventory and raw material costs by disassembling and reusing used cartridges and toner bottles (Xerox 2007). However, there may be exceptions, such as precious metal recycling where currently the price of gold is trading at around $650 per ounce and spot platinum at around $1,256 per ounce, which makes recycling of these precious metals a very profitable business (Materials Recycling Week 2007d).

Market requirements refer to the role of EoL PR in improving a company’s market position. Growing competition may force companies to recover their end-of-life products, but end-of-life product recovery is mainly an important element for building a “green (environmental)” corporate image. However, Thierry et al (1995) described the case of a multinational copier manufacturer (CopyMagic) which managed to improve its “green image” by offering remanufactured products but has had to put much effort in its marketing operations to convince its customers that the quality of remanufactured products is indeed “as good as new”. Finally, according to Fleischmann, (2001), taking back used products may be seen as a service element, taking care of the customer’s waste disposal needs.

Legislative pressure is another driver for EoL PR that is of growing importance. Over the last years, environmental policy makers have increasingly turned their attention to the environmental impacts of end-of-life products in several countries. Producer responsibility (PR), as previously described, is becoming a key element of public environmental policy, under which producers are responsible for ensuring that their products are collected from customers and recycled when their functional life has ended.
Finally, asset protection has also been mentioned as another motive for companies to implement EoL PR procedures. In this way, companies seek to prevent sensitive components or materials from leaking to secondary markets or competitors. For example, the aircraft engine industry is protecting valuable sources of columbium and titanium metal scrap to be used for such applications as heat-resisting and combustion equipment, jet engine components and rocket subassemblies (Sibley 2004). Also, according to Fleischmann, (2001), potential competition between original virgin products and recovered products is avoided in this way.

3.4.6.3 Current Practice on End-of-Life Product Recovery

A considerably amount of case studies with EoL PR systems have been reported in the literature, addressing various issues in a product recovery context. According to Kopicki et al. (1993), EoL PR systems can usually take two forms: closed and open loop systems. In a closed loop system post consumer products are returned to the original equipment manufacturer, which refurbish, reuse or recycle them into new products. In an open loop system manufacturers assume responsibility for collecting and finding markets for their end-of-life products, but do not use the materials themselves.

Economically-driven EoL PR processes applied extensively in the automotive industry, where developed automobile recycling centres exist around the world (Isaacs and Gupta 1997, Krupp 1993). Also, according to Mayers (2005) and Moyer and Gupta (1997), established recovery processes could be found in the consumer electronics industry. Besides the recycling of high valuable end-of-life products, other materials such as plastics are also being recovered mainly due to environmental impacts and legislative pressures (Ambrose et al. 2002) and (Pohlen and Farris 1992). On the other hand, examples of remanufacturing operations typically can be found in automotive, electronics and tire manufacturing (Ferrer 1997a, Ferrer 1997b, Harmozi 1997).
3.5 Multi-Criteria Decision Making

Sustainability, as previously defined, is the linking between economic, environmental and social concerns. Assessments based on sustainability criteria are needed to address the economic, social and environmental trade-offs within different alternative options, in order to complement complex decision-making processes. This means that a multi-criteria approach need to be applied that will take into account these particular sustainability dimensions. Decision analysis can provide answers to such problems especially through the domain of multi-criteria decision making.

3.5.1 Background on Decision Making Analysis

Decision making is the process of making decisions. The objective of decision making is to achieve a good decision outcome that is desired by decision makers (Keeney and Raiffa 1976). However, because of uncertainty, there is no guaranty that a decision making process will always produce a good outcome. Hence, a distinction must be made between a good decision and a good decision outcome. According to Merkhofer (1999), the decision outcome refers to the consequences of the decision while a good decision, on the other hand, is produced by a quality decision making process. The characteristics of a quality decision making process include that it involves the appropriate people, identifies good alternatives, collects the right amount of information, is logically sound, uses resources efficiently and produces choices that are consistent with the preferences of the responsible decision maker (Merkhofer 1999). Decision making is an iterative process as depicted in Figure 3.8. At each iteration, the decision model is revised until no further improvement is needed before a clear course of action can be taken.

Given the growing complexity and uncertainty in many real life situations, helping decision makers to use appropriate tools and methods to support their decision making process is quite important. For this reason, Decision Analysis (DA) was developed to provide a “formal methodology for systematic examination of complex and opaque decision situations, formulation of alternative courses of action, treatment of information and uncertainty, preferences, and evaluation of supposedly the “best” alternative or course of action” (Huang et al 1995). Decision analysis is, in fact, a merger of decision theory and system analysis, which occurred during the last 50 years. The term decision
analysis encompasses a variety of methods, techniques and activities ranging from those that focus on the decision making process itself, to those that can be used to provide and collate information required for decision making.

In addition, Table 3.2 provides a classification of various decision analysis methods and tools with a particular emphasis on energy and environmental modelling applications (Huang et al. 1995).

![Figure 3.8: Schematic of the Decision Making Process (Huang et al. 1995)](image)

<table>
<thead>
<tr>
<th>Decision Making Under Uncertainty (DMUU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision Tree (DT)</td>
</tr>
<tr>
<td>Influence Diagram (ID)</td>
</tr>
<tr>
<td>Multi-Attribute Utility Theory (MAUT)</td>
</tr>
<tr>
<td>Others</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Multi-Criteria Decision Making (MCDM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Objective Decision Making (MODM)</td>
</tr>
<tr>
<td>Multi-Attribute Decision Making (MADM)</td>
</tr>
<tr>
<td>- Analytic Hierarchy Process (AHP)</td>
</tr>
<tr>
<td>- Other MADM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decision Support Systems (DSS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary Decision Support Systems (ODSS)</td>
</tr>
<tr>
<td>Intelligent Decision Support Systems (ODSS)</td>
</tr>
</tbody>
</table>

Table 3.2: Classification of Decision Analysis Techniques (Huang et al. 1995)
3.5.2 Multi-Criteria Decision Making Methods

Multi-criteria decision making (MCDM) methods can be utilised to structure and model multidimensional decision problems where each criterion represents a particular dimension of the problem to be taken into account. Vincke (1992) presents MCDM as a method to provide the decision maker with some tools that enable him to advance in solving a decision problem where several, often contradictory, points of view must be taken into account simultaneously. Such methods are able to combine qualitative and quantitative data, such as sustainability dimensions, into a single assessment value. However, a distinction should be made between “discrete” and “continuous” MCDM problems. Discrete decision problems involve a finite set of alternative options while continuous decision problems are characterized by an infinite number of feasible alternatives. MCDM methods developed for the sorting or ranking of a finite set of alternatives refer as multi-attribute decision making (MADM), and those that assist in the synthesis of preferred solution when the potential solution set is described by continuous variables as multi-objective decision making (MODM) (Seppala et al. 2002). The emphasis in this thesis would be on discrete decision problems, because most common waste management problems involve the evaluation of a finite set of alternative options. Hence, this thesis is limited to consideration of multi-attribute decision making (MADM) methods such as the Analytic Hierarchy Process (AHP).

3.5.3 Decision Analysis in Waste Management Applications

In recent decades, several models have been developed to support decision making in waste management applications. In the 1970s, the goals of the waste management models were simple and narrow, such as optimizing waste collection routes or locating appropriate transfer stations (Helms and Clark 1971). In the 1980s, the focus was extended, mainly, to minimizing costs (Hasit and Warner 1981, Perlack and Willis 1985 and Gottinger 1988). In the 1990s, recycling and other waste management methods were being included and the criteria considered in waste management models were expanded to cover economic and environmental aspects (Smith and Baetz 1991, Morris 1991 and Chang and Wei 1999) but not social aspects (Morrissey and Browne 2004).
Currently, three types of models can be identified to support decision making in waste management applications: cost based models, environmental impact models and multi-criteria models (Morrisey and Browne 2004). Methods addressing only the environmental impacts are mostly based on the use of impact category indicators taken from Life Cycle Assessment (LCA) methods (Barton et al. 1996; Finnveden 1999, Powell 2000). At the other side, in cost based models the choice of the alternative options is based exclusively on minimizing cost or maximizing profits. Cost-Benefit Analysis (CBA) is often used to enable decision makers to assess the positive and negative effects of a set of scenarios by translating all impacts into monetary measurements (Chen et al. 1994, Reimer et al. 2000). Villanueva et al. (2006) point out that, currently, in Europe, CBA and LCA stand out as two of the most frequently used decision support tools for waste management with a wide range of applications. Finally, a last category of models, which has been less considered until now, is the multi-criteria approach. Such MCDM methods consider more than one criterion and the decisions are taken based on the whole number of criteria. The type of criteria chosen in these model types depends on the objectives of the model, and therefore could include risk and environmental assessment, financial evaluation etc (Hokkanen and Salminen 1997, Zopounidis and Doumpos 2002). The AHP method, in particular, has been applied in various waste management applications (MacDonald 1996, Haastrup et al. 1998 and Hung et al. 2007) to facilitating the choice of the best option among several alternatives.

3.6 Critical Summary

It is apparent that, over the past 20 years, the need to recycle post-consumer waste has become a pressing issue in the European Union. Approximately 80% in the UK and around 50% in the European Union of all solid waste is currently diverted to landfills. This led the European Commission to recommend actions to move waste flows away from landfill and into recycling and reuse. However, whereas the amount of materials recycled is increasing, the volume of waste sent to landfills remains steady, which is against the vision of “Zero Waste to Landfill”. For example, the amounts of paper, plastic, aluminium, and glass landfilled remain stable despite significant increases in the amounts recycled. In fact, only the composition of materials has changed as communities recycle more of their traditional materials but continue to discard less traditional materials. Thus, it is increasingly important that product recovery and recycling programs look beyond
traditionally recyclable materials to other recoverable materials in order to decrease the amount of materials send to landfills. A prime example of a less traditional recyclable material is post-consumer shoes.

Additionally, the increasing interest, as evident by a number of national and international legislations, on the concept of broadening manufacturer’s responsibility is expected to challenge the way industry is dealing with its end-of-life waste and eventually will necessitate changes within industry to extend its responsibility beyond the selling point to the end-of-life phase of its products.
Chapter 4

4 An Overview of the Footwear Sector

4.1 Introduction

This chapter provides an overview of various activities and practices in the footwear sector. The initial part of the chapter provides an analysis of materials and processes used to produce shoes while the latter sections investigate current reuse and recycling practices in the footwear sector and their environmental implications.

4.2 A Brief Overview of Footwear Industry

Footwear is a daily need of modern humans. The history of footwear goes back many thousands of years. Initially, footwear was developed to provide protection when moving over rough terrain in varying weather conditions. The moccasin is the oldest known form of footwear, dating back at least 14,000 years (Rossi 2000). Today the footwear industry manufactures a wide range of footwear ranging from leather, rubber and other synthetic materials, and styles ranging from casual, formal and athletic shoes.

According to the European Directive 94/11/EC (1994) on the labelling of main shoe components and footwear materials, footwear is defined as “all articles with applied soles designed to protect or cover the foot.” This definition has been adopted and recognised throughout the European Union.

4.2.1 Footwear Production and Consumption

The dynamics of contemporary footwear industry are driven by a combination of imports and exports with footwear products specified and designed in developed countries, made in developing countries (low-cost labour countries) before being transported back to the developed markets for consumption. The footwear industry is declining in Western
Europe and North America, due to relocation of industry to the Asian region. Currently, almost half of the shoes produced in North East Asia, with China now dominating the global production of footwear (World Footwear 2007). Figure 4.1 illustrates the breakdown of footwear production by region for the year 2005.

Worldwide footwear consumption is doubled every 20 years, from 2.5 billion pairs in 1950 to more than 19 billion pairs of shoes in 2005 (World Footwear 2007). From 1990 to 2004, in particular, worldwide footwear consumption has increased by a staggering 70% while by 2010 experts in the sector expect the global footwear output to reach 20 billion pairs. Figure 4.2 illustrates the growth in worldwide footwear consumption during the last 50 years against the increase of the world population. The figure also includes a forecast projection until year 2015, which indicates that worldwide footwear production and consumption is being doubled every 20 years. In the European Union, footwear consumption has increased by 22% from 2002 to 2005 to reach 2.3 billion pairs of shoes (Eurostat 2005).

![Regional Breakdown of Footwear Production](image)

**Figure 4.1:** Regional Breakdown of Footwear Production
Additionally, the worldwide per capita consumption of footwear has also been considerably increased, from 1 pair of shoes for every person in the world in 1950 to almost 2.6 pair of shoes in 2005. However, footwear consumption differs significantly per country. China, due to its large population, has the highest footwear consumption in the world. The United States is, however, the country with the highest per capita shoe consumption, since each inhabitant purchase an average of 6.9 pairs of shoes every year. In Europe and in the case of the 25 Member States of the European Union (including the new Member States), the yearly per capita shoe consumption in 2003 was 4.5 pairs of shoes, while in the United Kingdom the average is slightly higher at 5.3 pairs of shoes. At the other extreme, in the less developed poor countries, the per capita shoe consumption is 0.4 pairs for Vietnam and 0.7 pairs of shoes for India. Table 4.1 presents the per capita shoe consumption in a number of different countries. In European Union, not only the per capita consumption of footwear differs substantially per country but also the per capita expenditure, as can be seen in Figure 4.3. Italy represents the most mature footwear market in the EU-25, with a per capita expenditure amounted to around €266.12 per pair while Slovenians spend less than €50 per pair of shoes.
# Chapter 4

<table>
<thead>
<tr>
<th>Countries</th>
<th>Population (millions)</th>
<th>Footwear Consumption (million pairs)</th>
<th>Footwear Consumption /Capita/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU-25</td>
<td>456.5</td>
<td>2 054 571(^1)</td>
<td>4.5</td>
</tr>
<tr>
<td>Germany</td>
<td>82.5</td>
<td>320 800(^2)</td>
<td>3.9</td>
</tr>
<tr>
<td>France</td>
<td>59.6</td>
<td>335 502(^3)</td>
<td>5.6</td>
</tr>
<tr>
<td>UK</td>
<td>59.3</td>
<td>312 800(^2)</td>
<td>5.3</td>
</tr>
<tr>
<td>Italy</td>
<td>57.3</td>
<td>395 300(^2)</td>
<td>6.8</td>
</tr>
<tr>
<td>USA</td>
<td>289</td>
<td>2 007 899(^4)</td>
<td>6.9</td>
</tr>
<tr>
<td>China</td>
<td>1 287.1</td>
<td>2 900 000(^4)</td>
<td>2.2</td>
</tr>
<tr>
<td>Brazil</td>
<td>186.0</td>
<td>490 000(^4)</td>
<td>2.6</td>
</tr>
<tr>
<td>India</td>
<td>1 041.9</td>
<td>N/A</td>
<td>0.64(^4)</td>
</tr>
<tr>
<td>Vietnam</td>
<td>84.2</td>
<td>N/A</td>
<td>0.54(^4)</td>
</tr>
</tbody>
</table>

**Table 4.1: Per Capita Footwear Consumption in Different Countries**

![Figure 4.3: Per capita Expenditure on Footwear in Value and Pairs (CBI 2004)](image)

\(^1\) (Eurostat 2005)  
\(^2\) (CBI 2004)  
\(^3\) (AAFA 2005)  
\(^4\) (SATRA 2003)
4.3 Footwear Classifications and Market Trends

Currently, there are two basic internationally standardized systems of names and numbers for footwear products, the Harmonised Commodity Description and Coding System (HS) classification and the PRODCOM classification. In the HS classification system, which is used worldwide to give information regarding different trade flows between countries, footwear products are classified under Chapter 64, named “Footwear, gaiters and the like; parts of such articles” (WCO 2007). Besides the HS classification, the PRODCOM classification is used by EU countries to record annual production values (Eurostat 2007). Table 4.2 below shows the PRODCOM codes and the corresponding HS codes used for various footwear segments.

Generally, footwear products can be divided using a supply or demand point of view. From the supply point of view, shoes can be subdivided by upper materials, for example rubber/plastic, leather and textile, as depicted in Table 4.3. Another subdivision can also be made based on age and gender (i.e. men’s, women’s and children’s).

From the demand point of view, shoes can be divided by activity, for sports, casual, formal and outdoor shoes, as depicted in Table 4.4.

<table>
<thead>
<tr>
<th>Footwear Segments</th>
<th>HS Codes</th>
<th>PRODCOM Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber/Plastic Uppers</td>
<td>19.30.12, 19.30.21,</td>
<td>6402</td>
</tr>
<tr>
<td></td>
<td>19.30.23</td>
<td></td>
</tr>
<tr>
<td>Leather Uppers</td>
<td>19.3013, 19.30.21,</td>
<td>6403, 6405</td>
</tr>
<tr>
<td></td>
<td>19.30.23</td>
<td></td>
</tr>
<tr>
<td>Textile Upper</td>
<td>19.30.14, 19.30.22,</td>
<td>6404, 6405</td>
</tr>
<tr>
<td></td>
<td>19.30.32</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>19.30.11, 19.30.31,</td>
<td>6401, 6402, 6403,</td>
</tr>
<tr>
<td></td>
<td>19.30.32, 19.30.40</td>
<td>6405, 6406</td>
</tr>
</tbody>
</table>

Table 4.2: Footwear Segments with the Corresponding HS and PRODCOM codes
<table>
<thead>
<tr>
<th>Footwear Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber/Plastic</td>
<td>Footwear with rubber/plastic upper: sport (ski boots), indoor (slippers) and outdoor shoes.</td>
</tr>
<tr>
<td>Leather</td>
<td>Footwear with leather uppers: sport, indoors and outdoor (with or without leather soles) shoes.</td>
</tr>
<tr>
<td>Textile</td>
<td>Footwear with textile uppers: sport, indoor (with rubber/plastic or other soles) and outdoor shoes.</td>
</tr>
<tr>
<td>Other</td>
<td>Footwear with other uppers, safety footwear, waterproof outdoor footwear and parts of footwear.</td>
</tr>
</tbody>
</table>

**Table 4.3: Division of Footwear Based on Material Type**

<table>
<thead>
<tr>
<th>Footwear Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sports</td>
<td>Footwear used for sporting purposes.</td>
</tr>
<tr>
<td>Casual</td>
<td>Footwear used for spare time leisure activities.</td>
</tr>
<tr>
<td>Formal</td>
<td>Traditional classic footwear used for formal purposes.</td>
</tr>
<tr>
<td>Outdoor</td>
<td>Footwear used for outdoor activities. A general term for this type of shoes is “boot”.</td>
</tr>
</tbody>
</table>

**Table 4.4: Division of Footwear Based on Activity**

However, for the purpose of this thesis, footwear products have been categorised into six different types based on a combination of gender, age and purpose of use:

- Men’s formal shoes
- Men’s casual shoes
- Women’s court shoes
- Women’s fashion shoes
- Children’s shoes
- Adult sports trainer shoes
4.3.1 Footwear Market Trends

Traditionally, a consumer owned a few pairs of shoes, some for exercising and others for work or fashion. But today’s consumer demands a larger variety of shoes including options for specialised footwear such as sports, fashion and safety shoes. To meet the needs of customers and be competitive, footwear companies face a key challenges i.e. being responsive to market changes and establish efficient product development in order to identify or establish new consumer trends. Responsiveness to customer demands leads to a shorter product development cycle, and an even increasingly shorter life cycle of shoes. A shorter life cycle of shoes means that more shoes will be produced, hence leading to a higher level of end-of-life waste by the footwear industry.

Currently, footwear with leather uppers traditionally account for the larger share of the footwear market. In 2003, this type of shoes account for 69% of footwear sales in Germany, 61% in the UK, 45% in Spain, 41% in France, 40% in the Netherlands and 37% in Italy (CBI 2004). Looking at the difference between the countries, shoes with rubber/plastic uppers and textile uppers make up a substantial portion of the footwear market. Figure 4.4 presents shoe consumption statistics from different European countries based on the material type of the upper part of the shoe.

![Footwear Market by Material Type](image)

**Figure 4.4:** Shoe Consumption in Europe by Material Type (CBI 2004)
For example, shoes with rubber/plastic uppers represent 32% of the Spanish market while only 1% of the UK market share. In the same way, footwear with textile uppers make up 38% of the Italian market while only 18% of the Spanish footwear market.

Finally, women’s footwear capture around half of the footwear market in Europe while casual shoes represent more than half of the market share following by sports shoes. Table 4.5 presents shoe consumption statistics based on activity and gender in major European countries in year 2003.

### 4.4 Footwear Parts and Components

At their most simple, shoes can be only two components per pair, for example injection moulded PVC sandals, or can be complex constructions with 60 or more components per pair. However, most of them can be described as having a subset of parts and components that are generally common to all type of shoes.

<table>
<thead>
<tr>
<th>Shoe Consumption</th>
<th>Germany</th>
<th>France</th>
<th>UK</th>
<th>Italy</th>
<th>Spain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>By Activity (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casual</td>
<td>59.3</td>
<td>58.8</td>
<td>55.8</td>
<td>56</td>
<td>71.8</td>
</tr>
<tr>
<td>Formal</td>
<td>5.5</td>
<td>5.5</td>
<td>5.7</td>
<td>7.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Sport</td>
<td>31.8</td>
<td>32.5</td>
<td>34.4</td>
<td>32.8</td>
<td>24.6</td>
</tr>
<tr>
<td>Outdoor</td>
<td>3.5</td>
<td>3.3</td>
<td>4.2</td>
<td>3.8</td>
<td>2.4</td>
</tr>
<tr>
<td><strong>By Gender (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Women’s</td>
<td>49</td>
<td>51.2</td>
<td>47.7</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Men’s</td>
<td>31</td>
<td>32.1</td>
<td>36.6</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Children’s</td>
<td>20</td>
<td>16.7</td>
<td>15.7</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 4.5: Shoe Consumption in Europe by Activity and Gender (CBI 2004)
In this context, the basic parts of a shoe can be grouped broadly into three main categories (Clarks 1976):

- The Upper, which includes all parts of the shoe above the sole, such as vamp and quarters, that are stitched or joined together to become a unit and then attached to the insole and outsole of the shoe.
- The Lower, which refers to the whole bottom of a shoe but not the upper including the insole, the sole and the outsole of the shoe.
- The Grindery, which includes items that incorporated into the shoe and do not belong either to the Upper or the Lower part of the shoe such as toe puff, stiffener materials and eyelets.

Some of the major parts and components of a men’s formal shoe are depicted in Figure 4.5.

4.4.1 Footwear Construction

The production of footwear starts with the supply of materials. These materials include both raw materials (such as leather) and semi-finished products and components. These materials need to be inspected and modified in order to meet the quality requirements of the footwear industry.

![Figure 4.5: Major Parts and Components of a Men’s Formal Shoe (Rossi 2000)](image-url)
Often upper, lower and grindery components are manufactured separately by using different construction methods. Cutting, machining and pre-stitching operations are applied in order to fabricate these components. The next phase of manufacturing is the assembly of the components into finished products. The completed upper and lower parts are united using different assembling techniques. Usually the upper is stretched over the last (a fixture which represents the shape of the foot) and attached at the bottom part of the shoe in a process called lasting. Finally, finishing processes determined by the materials that have been used during the manufacturing process. Usually leather materials are stained, polished and waxed before tagged and delivered to the market.

There are typically three major assembling techniques used by the footwear industry (Harvey 1982):

- Cementing, where the upper and lower part assembled using adhesives
- Injection, where the sole material is injected directly to the upper part of the shoe
- Stitching, where the upper and lower part assembled together with threads.

The key steps in shoe cemented construction are depicted in Figure 4.6. Firstly, adhesive (usually thermoplastic polyurethane) is applied to the shoe upper and sole then the adhesive is activated by flash heating upper and sole unit at 50° to 80°C. The third step is spot bonding of sole to upper and finally press is applied for approximately 30 seconds at 0.2MPa to bond the shoe upper and sole (Randall and Lee 2003).

![Figure 4.6: Cementing Shoe Construction (adopted from Randall and Lee 2003)]
4.5 Footwear Materials

Leather, synthetic materials, rubber and textile materials are counted among the most commonly used materials in footwear. These materials differ not only in their appearance but also in their physical qualities, their service life, the different treatment needs as well as their recycling and recovery options at the end of their useful life. Figure 4.7 represents the average composition of a typical shoe which has been measured after grinding. According to Weib (1999) there are around 40 different materials used in the manufacturing of a shoe.

This research has developed a materials breakdown of different footwear types, as depicted in Table 4.6, which presents the basic shoe types and the most commonly used materials in their manufacture. Upper components, shoe soles and grindery items are presented according to their material of choice. Materials used in different shoe parts are discussed below in more details.

![Material Composition in Average Shoe (%wt) (adapted from Weib 1999)](image)

**Figure 4.7:** Material Composition in Average Shoe (%wt) (adapted from Weib 1999)
<table>
<thead>
<tr>
<th>Footwear Types</th>
<th>Men's Formal</th>
<th>Men's Casual</th>
<th>Women's Court</th>
<th>Women's Fashion</th>
<th>Children's</th>
<th>Adult Sports Trainer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Part</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Synthetic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leather</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leather/Polymer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vulcanise Rubber</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPR</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Polyurethane's</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>TPU</td>
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<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>EVA</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Lower Part</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leather</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leather/Polymer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vulcanise Rubber</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPR</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Polyurethane's</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>TPU</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>EVA</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Grindery Items</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shanks</td>
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<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nails</td>
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<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyelets</td>
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<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Laces</td>
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<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Threads</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Velcro &amp; Catches</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Textile Backers &amp; Linings</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Foams- (Padding)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Heal Backing supports.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Toe cap reinforcement.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Heals- (Ladies/Men's)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 4.6: Materials Breakdown of different Footwear Types
4.5.1 Upper Part Materials

Leather has been used as a main footwear material for centuries and it continues to be a popular form of shoe upper. Approximately 65% of worldwide leather production is utilised by the footwear industry (Price 2000). Leather has ideal characteristics for use in the upper part, is soft with very good absorption ability and able to adjust to the individual shape of the foot. On a global scale, it is estimated that shoes with leather uppers account for approximately 43% of the total worldwide footwear production (Price 2001). This amounted to around 11,100 million ft² of upper leather. However, leather is a natural material made from animal hides and therefore there is a limited and variable supply depending on stock levels in the meat industry of which hides are a by-product. For this reason, synthetic materials that designed to look or function like leather have been developed such as fabrics coated with Poly Vinyl Chloride (PVC) and Polyurethane (PU). PVC coated fabrics have traditionally dominated the market for synthetic materials because of cost and ease of use. This is declining significantly, however, due to environmental pressures on the use of PVC while the use of laminated PU films is growing in the footwear industry. In Europe and North America in particular, leather will continue to be looked on as natural, organic and luxurious material while in other parts of the world, especially Asia, synthetic leather is preferred because of its superior properties such as better washability and abrasion resistance (World Footwear 2007).

4.5.2 Lower Part Materials

In the lower part of the shoe, leather has also been largely superseded by synthetic materials. The first synthetic material to be used for soling was vulcanised rubber, introduced in the USA during the 1880’s (Randall and Lee 2003). In the 1950’s only four materials were used as soling materials namely leather, rubber, vulcanised rubber and resin rubber (World Footwear 2005). The next major change in soling materials was the development of flexible PVC, which was introduced in the 1960’s. Since then the choice of has been extended to include a number of different plastics and polymers such as TR, EVA etc. Polymeric and plastic materials currently dominate the production of shoe soles, outsoles and insoles, especially thermoplastic materials and rubbers. Table 4.7 presents the percentage of the major materials currently used in the construction of lower parts of shoes.
<table>
<thead>
<tr>
<th>Soling Materials</th>
<th>Percentage (%w.t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin Rubber</td>
<td>20</td>
</tr>
<tr>
<td>PVC and blends</td>
<td>19</td>
</tr>
<tr>
<td>Thermoplastic Rubber (TR)</td>
<td>15</td>
</tr>
<tr>
<td>Direct Vulcanised (DV) Rubber</td>
<td>8</td>
</tr>
<tr>
<td>Direct Injection Moulded (DIM) PVC and blends</td>
<td>8</td>
</tr>
<tr>
<td>Leather</td>
<td>7</td>
</tr>
<tr>
<td>Micro Ethylene Vinyl Acetate (EVA)/ Rubber</td>
<td>7</td>
</tr>
<tr>
<td>Polyurethane (PU)</td>
<td>7</td>
</tr>
<tr>
<td>Other (wood, cork, textile etc)</td>
<td>5</td>
</tr>
<tr>
<td>Vulcanised Rubber</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 4.7: Use of Soling Materials in Shoes (Wilson et al. 1997)

4.5.3 Grindery Components

Finally, grindery components include items that incorporated into the shoe and not belong to the upper or the lower part of the shoe. These items could be made by a variety of materials depending on their purpose of use. Toe puffs can be made of rubber or thermoplastic resins, stiffener components from leather, EVA and polyester while shank and eyelets can be made of metal (carbon steel). Finally, the heel of the shoe is usually made of Polystyrene (PS), Acrylonitrile Butadiene Styrene (ABS), or wood (Harvey 1982).

4.6 Environmental Concerns in the Footwear Industry

There are a number of environmental concerns linked with the footwear industry. These problems occur both in the production of raw materials and within footwear manufacturing itself and include the use of hazardous materials and chemicals in shoes, the air and water emissions and the solid waste generated during the production process. For instance, according to Chen and Chan (1999), footwear workers in China are being exposed to high levels of benzene, toluene, and other toxic solvents contained in the adhesives used during the shoe manufacturing process.

The generation of footwear manufacturing waste, in particular, has recently been documented within the EN 12940:2004 CEN standards entitled “Footwear Manufacturing
Waste – Waste Classification and Management” (British Standards 2004). This standard specifies the process steps which are involved in the generation of waste from footwear manufacture and the usual waste management practices. The standards intend to help shoe manufacturers to have a clear view of the waste generated inside their factories as well as to provide a waste ratio which can be compared to previous years, to other companies, to components suppliers etc. Such waste ratio per type of shoe is depicted in Figure 4.8. The figure shows the waste generated during the production process for various types of footwear. Safety shoes, due to their heavier weight, generate a larger quantity of waste during their production process compared to other types of footwear. Generally, 266 tonnes of waste is generated in order to produce a million pairs of an average type of shoe (UNIDO 2000).

In reality, however, the most serious risks to the environment and human health are to be found with suppliers of semi-finished products and components such as leather.

![Figure 4.8: Quantity of Waste during Footwear Manufacturing](image-url)
Especially, the use of chromium (III) as tanning agent in leather production has long been a major environmental concern for the footwear industry over the last few decades. Chromium (III) can be oxidised through fatliquors, moisture, heat and light to the much more toxic form of chromium (VI), which is highly toxic and a suspected carcinogen (Page 2005). The use of poly vinyl chloride (PVC) has also been reduced in the footwear manufacturing sector because it is claimed that when incinerated at low temperatures, it has the potential to form organo-chlorine substances, which are hazardous both for the environment and for human beings. Furthermore, solvents and other volatile organic compounds (VOCs), used in synthetic upper materials, leather finishing, adhesives and cleaners, are of major importance for the footwear industry since they contribute to the formation of ground-level ozone, an air pollutant harmful to human health as well as plant life (World Footwear 2004). Table 4.8 presents some of the major pollutants that linked with footwear materials and their manufacturing processes.

With the growing demand for more information about the environmental properties of consumer products it is logical that footwear products are also subject to a range of remarks about its ecological and toxicological properties. Therefore, a list of unwanted substances found at trace levels have been developed for finished leather products, including footwear.

<table>
<thead>
<tr>
<th>Footwear Materials</th>
<th>Environmental Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leather</td>
<td>Chromium (VI), Aldehydes, Solvents</td>
</tr>
<tr>
<td>Synthetic Materials</td>
<td>Solvents, VOCs</td>
</tr>
<tr>
<td>Textiles</td>
<td>Process Chemicals, Biocides</td>
</tr>
<tr>
<td>Rubbers</td>
<td>Rubber Fume</td>
</tr>
<tr>
<td>PVC</td>
<td>Vinyl Chloride Monomer</td>
</tr>
<tr>
<td></td>
<td>Cadmium, Plasticisers</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>Styrene Monomer</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Isocyanates, (CFCs)</td>
</tr>
<tr>
<td>Adhesives</td>
<td>Solvents, VOCs, Chlorine</td>
</tr>
</tbody>
</table>

Table 4.8: Major Pollutants in the Footwear Industry (Abbot and Wilford 1999)
The list of unwanted substances that should not be found in finished leather products includes the following (Page 2005):

- Formaldehyde
- Chromium (VI)
- Certain organic amines derived from azo dyes
- Organotin compounds
- Nickel, cadmium, lead and other heavy metals
- Pentachlorophenol and chlorinated phenols

In order to promote footwear products which have lower environmental impacts, the European Union (EU) recently has established the European Footwear Eco-Label scheme as a marketing and publicity tool for environmental-friendly shoes (Decision 2002/231/EC 2002). To be able to use the footwear eco-label some determined ecological criteria must be fulfilled. According to this European Decision, the criteria aim, in particular, “at limiting the levels of toxic residues, limiting the emissions of VOCs and promoting a more durable footwear product”. These criteria are set at levels that promote the labelling of footwear which has a lower environmental impact.

### 4.7 Footwear End-of-Life Waste

The major environmental challenge, however, that currently the footwear industry is facing is the enormous amount of waste generated at the end-of-life phase. As previously presented, some 19 billions pairs of shoes produced worldwide every year, with most of them being disposed in landfills. Landfill sites can result in serious environmental pollution and land contamination. On the other hand, landfill space is becoming extremely limited, especially in some Western European countries. Finally, forthcoming product-related environmental legislation is expected to change the approach of the footwear industry regarding its EoL waste.

In the UK, around 330 million pairs of shoes consumed every year (SATRA 2003). It is estimated that the waste amount arising from post-consumer shoes in the UK could reach 165,000 tonnes per year. A Department of Trade and Industry (DTI) study has estimated
that the total arising of textile waste is between 550,000 and 900,000 tonnes per year in the UK, while the amount of textile waste reused or recycled annually is estimated to be 250,000 tonnes (ERM 2002). Based on the same study, about 9% of all recovered post-consumer textiles are sold as second-hand shoes. This means that around 22,500 tonnes of post-consumer shoes are collected in the UK each year for direct reuse in less developed counties. Such reuse schemes are mainly supported by charitable organisations such as the Salvation Army Trading Company (SATCOL™), Oxfam™ and others in collaboration with local authorities and municipalities. However, approximately 10% of the collected second-hand shoes are not suitable for direct reuse due to their condition and, consequently end up in landfills (Barry 2006). Based on this estimations, approximately 12% (20,250 tonnes) of post-consumer shoes in the UK are collected and re-distributed as second hand shoes while the rest (88% or 145,200 tonnes) disposed in landfills.

4.7.1 Landfill Restrictions

The standard practice of dumping waste in landfills led to soil, surface and groundwater contamination. Landfill sites can result in serious environmental pollution of groundwater and rivers, due to landfill leachate. Furthermore, landfill space is becoming extremely limited, while the number of landfill sites in the European Union has considerable decreased over the last years. According to Hempen (2005), in the early 1990’s, in Germany, there were over 8000 landfill sites in use, while the number of currently operating landfill sites is below 300. The EU Landfill Directive clearly promotes the diversion of waste from landfills towards products and materials recycling using a variety of measures (Directive 99/31/EC 1999). The landfill restrictions introduced by the Article 5 of this Directive are very important, in particular the reduction in the amount of biodegradable waste going to landfill and the prohibition of landfilling for certain waste types. Since 1st June 2005, German landfills only accept biodegradable municipal waste that has been either incinerated or undergone mechanical and biological treatment while in Austria strict limits on the landfilling of organic wastes has also been introduced (Hempen 2005). Additionally, the UK Landfill Allowances and Trading Scheme Regulations (LATS) introduced in 2004, determines the percentage of certain waste type that regarded as biodegradable municipal waste. These biodegradable percentage range from paper, card and vegetable oils (potentially 100% biodegradable) through to footwear, furniture

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5 the liquid produced from the decomposition of waste within the landfill
and textiles (50% biodegradable) to batteries, glass and metal waste (0% biodegradable) (LATS 2004). This means that certain types of biodegradable materials such as leather, natural textiles, natural rubbers etc, which are extensively used by the footwear industry, will be soon required to be reused or recycled instead of directly disposed in landfill sites.

4.7.2 Producer Responsibility Issues

As previously mentioned, the concept of producer responsibility was first introduced in Germany with the 1991 Packaging Ordinance which required manufacturers and distributors to take back packaging from consumers and ensured that a specified percentage is recycled. Following this, producer responsibility legislation was introduced into the EU waste policy with the 1994 Packaging Directive and since then has spread to most industrialised countries (Directive 94/62/EC 1994). In 2000, the European Commission passed a Directive requiring its Member States to institute a producer responsibility program for end-of-life vehicles (ELV) (Directive 2000/54/EC 2000). Also, an additional Directive for Waste Electronics and Electrical Equipment (WEEE) is expected to be adopted soon by all EU Member States (Directive 2002/96/EC 2002). This concept of broadening manufacturer’s responsibility for products beyond their useful life into the post-consumer phase also concerns with closing the loop with respect to materials use and waste management at the end-of-life phase, while providing a source of financing to offset the cost disadvantage of recycling versus disposal and energy recovery. In this context, take-back and producer responsibility legislation is expected to affect the footwear sector similarly to what has happen in other consumer product sectors, e.g. with the implementation of the ELV and WEEE Directives.

4.8 Product Recovery Activities in the Footwear Sector

Product recovery activities in the footwear sector are, currently, limited. This research has identified two types of treatment options for post-consumer shoes, as described below.
4.8.1 Recycling

Footwear industry’s response to the increasing problem of post-consumer shoe waste has been negligible. In fact, only one major shoe manufacturer, Nike, has been taken measures to manage its end-of-life waste. Nike’s recycling programme “NikeGO Places” (formerly “Reuse-A-Shoe”) is the only product take-back and recycling scheme currently established by a shoe manufacturer. This programme has been operating for over a decade in the United States and also just recently started operating in the UK, Australia and Japan. Nike’s “Reuse-A-Shoe” programme involves a series of collection points in retail centres where people can deposit their worn-out and discarded athletic shoes. The shoes are then collected and taken to a central recycling facility where they are shredded, producing a material called “Nike Grid”, which can be used in surfacing of tennis and basketball courts, playground surfaces or running tracks. According to Nike (2007), since its inception in 1993, “Reuse-A-Shoe” programme has recycled in total more than 16 million pairs of worn-out and defective athletic shoes. A schematic overview of the activities under Nike’s “Reuse-A-Shoe” program are depicted in Figure 4.9.

![Figure 4.9: Nike’s “Reuse-A-Shoe” Scheme (Photos Courtesy of Nike Inc)](image-url)
However, the effectiveness of this recycling program in diverting end-of-life shoe waste from landfill is difficult to evaluate mainly due to the uncertainties regarding the proportion of defective and post-consumer shoes used as well as the lack of incentives for consumers to return shoes for recycling.

4.8.2 Reuse

Direct reuse of second-hand shoes is a well-established method of collecting and distributing worn or unwanted shoes from developed countries to developing countries. Such reuse schemes are mainly supported by charity organisations, local authorities and municipalities e.g. the Salvation Army Trading Company Ltd. (SATCOL), Oxfam and others. In the UK, SATCOL alone with its 2,300 banks, door-to-door collections and donations, has managed to collect around 971 tonnes of worn or unwanted shoes during the year 2000-2001 (Woolridge et al. 2006). However, there is a strong debate about such reuse activities in terms of their overall environmental impact and their economic consequences for the local communities. It has been argued that collection and distribution of worn or unwanted shoes in developing countries just diverts waste from the developed world to poor countries with no infrastructure to deal with the extra waste. According to Wicks and Bigsten (1996), re-distribution of second hand products into developing countries may also lead to net economic damage to the local economies due to ‘dumping’ of cheap used footwear. In the case of Uganda, the import of large volume of second hand shoes in recent years has significantly reduced the size of the local footwear industry. About 7 million pairs of second hand shoes are imported into Uganda annually while only 240,000 pairs of shoes are produced by the local footwear industry (Temsch and Marchich 2002). In Kenya, despite higher duties, second-hand shoes (mitumba) remained popular among Kenyans. According to Bata, a footwear company with long presence in Kenya, mitumba shoes are still being dumped into the local market while they clearly pointed out that “we want the Government to stop the importation of mitumba into Kenya because their continued presence is threatening the development of the local shoe manufacturing industries” (Mwai 2005). However, as the cost of producing new shoes is coming down and the markets are flooded with lower quality shoes, it is expected that the price difference between new shoes and second-hand shoes will shrink in less-developed countries. The demand for second-hand shoes might then drop in these countries, leading to more post-consumer shoes needing to be recycled and disposed in the developed world.
Another form of reuse activity is the repair and refurbishment of high quality hand-made shoes. Such shoes can be returned to the original equipment manufacturer to be repaired and refurbished and, hence, prolong their useful life. For example, repair and refurbishing is an important facet of the overall business of Church & Co, a British hand-made men’s shoe manufacturer. As many as 18,000 pairs of shoes returned every year which may be up to 40 years old. These worn shoes are stripped of their soles, heels, welts, stitching and cork infill before being returned to their original last to be rebuild. After refurbishment, shoes are boxed as new and returned to the customer (Leather International 2007).

4.9 Recycling of Materials Used in Footwear Industry

Once end-of-life waste is collected, separated and converted into a form that can be used by either the footwear industry or other industrial sectors, then it must compete with virgin materials both on price and performance. Although in the case of metal and glass established recycling markets already exist, in other materials such as leather, textiles and plastics the situation is more complex. This research has investigated the recyclability of the main materials used in footwear production.

4.9.1 Leather Recycling

Most of leather used in shoes is over-engineered, it has been dyed (tanned), fat liquored and finished (coated). This makes recycling of the finished product a complicated process. In general, three tanning methods are used to convert raw hides and skins into leather: chromium, aldehyde and vegetable tanning. Each of these methods produces leathers with distinctly different properties. Chromium tanning process has a well-established technology and is relatively cheap but has come under criticism lately due to its environmental impacts especially with regard to the use of chromium tanned leathers in children’s shoes and toys (Leather International 2006a). However, it should be mentioned that chromium-tanned leather still accounts for more than 90% of the global leather production (Hetland et al 2002). On the other hand, aldehyde and vegetable tanning methods are regarded as more environmental friendly, producing free-of-chromium leathers. These types of leathers are now widely used in the automotive industry but development for the footwear sector has not yet evolved mainly due to the fact that they cannot withstand a temperature of more that 100°C when saturated with water, the so-
called “boiling test” (World Footwear 2005). However, a new tanning method is under development by Loughborough University in collaboration with the British Leather Technology Centre (BLC), which will emulate chromium-tanned leather characteristics without actually using chromium. This is based on epoxy technology, which combines an epoxy resin with a vegetable tanning agent, to produce leathers with properties typical of chromium-tanned leather (Leather International 2006b).

In order to investigate suitable leather recycling methods, leather has been divided into chromium-tanned and chromium-free leather. Some recycling techniques that could be used for chromium-free leather are not applicable to finished footwear leather waste that has been chromium-tanned.

4.9.1.1 Chromium-Free Leather

One of the oldest established routes for recycling of chromium-free leather is the manufacture of leatherboard. Gish (2000) presents different methods of using fibers from tannery offal, grain shavings, split shavings, sole cuttings from the shoe industry and to a lesser extent some coloured upper scrap to produce leatherboard which can be used in the shoe and belt industry and other allied industries connected with the leather. Chromium-free leathers can also be used to produce gelatine and collagen additives but their use in human food production is restricted (ULTCS 2004). Another recycling method, recently developed by the University of Franca in Brasil, turns leather trimmings from the shoe manufacturing process into ready-to-use concrete which weight less and has good soundproofing properties and high resistant to weathering (World Footwear 2006a).

Chromium-free and un-tanned leather can also be recovered in order to generate heat and electricity. A number of well-established and emerging technologies such as incineration, gasification and pyrolysis have been applied to treat chrome-free leather. Gasification, in particular, provides a major route for treating solid wastes of many types including leather, food processing wastes, refuse derived bio-fuels, most forms of wood, energy crops and animal by-products (World Footwear 2006b). A 50kg/h leather waste gasification unit has been installed at Pittards plant in Leeds, UK with good results (ENDS 2003). At the moment, however, such gasification units accept only raw solid waste directly form the
tannery production and not finished leather products such as shoes. Finally, leather, as a biodegradable material, can be composted if it is free-of-chromium. TFL Leather Technology (2004) has been conducted a number of composting trails using chromium-free leather. It has been found that chromium-free leather is not slowing down the biological process of composting and, hence, can be used as fertiliser. But, it should always kept in mind that leather is often produced with unknown chemicals, which may slow down the composting and fertilising effect.

Table 4.9 presents potential recycling methods and technologies to treat chromium-free leather products.

<table>
<thead>
<tr>
<th>Recycling Method</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leatherboard Manufacturing</td>
<td>Use of tannery waste  &lt;br&gt; Leatherboard used inside the footwear industry</td>
</tr>
<tr>
<td>Gelatine Production</td>
<td>Commercially successful  &lt;br&gt; Gelatine used by a wide range of industries</td>
</tr>
<tr>
<td>Energy Recovery</td>
<td>Proven incineration and gasification technology  &lt;br&gt; High energy value  &lt;br&gt; Potentially production of toxic heavy metal residues (ash and slag)</td>
</tr>
<tr>
<td>Ready-to-Use Concrete</td>
<td>Proven technology  &lt;br&gt; Lighter than similar materials  &lt;br&gt; Weather resistant  &lt;br&gt; Good sound-proofing properties</td>
</tr>
<tr>
<td>Composting</td>
<td>Compost used as a high nutrient nitrogen fertiliser  &lt;br&gt; Too much leather in the compost may slow down the composting and fertilising effect</td>
</tr>
</tbody>
</table>

Table 4.9: Recycling Methods for EoL Chromium-Free Leather Products
4.9.1.2 Chromium-Tanned Leather

Due to its chromium content and environmental regulations, few solutions can be applied to chromium-tanned leather that are technically and commercially feasible as well as environmentally acceptable. Consequently, a considerable amount of research has been carried out to try and establish chromium recovery processes as well as isolation of protein fraction. Chromium can be recovered from leather by thermal, chemical or enzymatic means and then reused as a tanning agent (Petruzelli et al 1995, Cassano et al 1997). Chromium-tanned leather can also be used to produce valuable products. Cabeza et al (1997, 1998) demonstrated a two-step process to extract protein from chromium-tanned leather shavings, producing a technical gelatine and a collagen hydrolysate. The gelatine has potential use in cosmetics, adhesives, printing or even in finishing products for the leather industry while the collagen can be used as a fertiliser and in animal feeding additives. Chromium-tanned leather can also be used as a filler in the production of polymers and ceramics. The principle is to mix shredded leather particles with a thermoplastic (PVC or PU) binder in order to produce compounds with a “real” leather or plastic feeling. Ravichandran and Batchimauthu (2005) attempted to incorporate scrap rubber along with chromium-leather waste particles into a virgin natural rubber compound while Babanas et al (2001) incorporate waste leather granules into PVC polymer plasticized with di-octyl phthalate, with potential applications to the footwear industry. Other recycling options include applications as absorbing material, as a co-raw material in paper making and, finally, after a complete grinding process, leather fibres can be used for the production of non-woven materials (UNIDO 2000).

Chromium-tanned leather can also be incinerated under controlled conditions in order to produce energy. For this purpose, a special furnace (bubbling fluidised bed) has been used. Before being introduced into the furnace, leather waste need to be shredded down to 10-12 mm particle size and then feed into the furnace (van Den Bossche 1997). However, high NOx context has been found in the combustion gases as well as no information exits regarding the possible generation of dioxins due to the presence of chloride in the chromium-tanned leather scrap. Recently, Yilmaz et al (2007) investigated the application of pyrolysis on different types of leather waste to produce useful materials.
Three types of tannery waste, including chromium-tanned leather shavings, were pyrolysed in a fixed bed reactor at temperatures of 450° and 600°C. The study showed that activated carbon and solid fuel was successfully recovered from chromium-tanned leather. Table 4.10 presents potential methods and recycling technologies to treat chromium-tanned leather.

<table>
<thead>
<tr>
<th>Recycling Method</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium Recovery</td>
<td>Proven technology</td>
</tr>
<tr>
<td></td>
<td>Chromium used as a tanning agent</td>
</tr>
<tr>
<td>Protein Extraction</td>
<td>Complex process</td>
</tr>
<tr>
<td></td>
<td>High value by-product (gelatine, collagen)</td>
</tr>
<tr>
<td>Filler</td>
<td>Grinding process required</td>
</tr>
<tr>
<td></td>
<td>Simple process (mix ground leather with binder)</td>
</tr>
<tr>
<td></td>
<td>Application in construction industry</td>
</tr>
<tr>
<td>Absorbing Material</td>
<td>Grinding process required</td>
</tr>
<tr>
<td></td>
<td>High absorbency</td>
</tr>
<tr>
<td></td>
<td>No established markets</td>
</tr>
<tr>
<td>Paper Making</td>
<td>Grinding process required</td>
</tr>
<tr>
<td></td>
<td>Expensive process</td>
</tr>
<tr>
<td></td>
<td>Good quality paper</td>
</tr>
<tr>
<td>Non-Woven Material</td>
<td>Grinding process required</td>
</tr>
<tr>
<td></td>
<td>Expensive process</td>
</tr>
<tr>
<td></td>
<td>No established markets</td>
</tr>
<tr>
<td>Energy Recovery (incineration, pyrolysis)</td>
<td>Incineration in a special furnace</td>
</tr>
<tr>
<td></td>
<td>Sophisticated and expensive technology</td>
</tr>
<tr>
<td></td>
<td>Energy and activated carbon recovered</td>
</tr>
<tr>
<td></td>
<td>Potential harmful airborne emissions</td>
</tr>
</tbody>
</table>

Table 4.10: Recycling Methods for Chromium-Tanned Leather
According to Goodship (2001), recycling of plastic can be performed either mechanically or chemically. Mechanical recycling of plastics is a simple process which involves the melting, shredding or granulation of plastics. However, plastics must be sorted prior to recycling into type or colour, either manually or automatically. Following the sorting process, plastic is either melted down directly and moulded into a new shape, or melted down after being shredded into flakes and then processed into granules called re-granulate. On the other hand, chemical recycling involves processes to reduce the polymer back into its original feedstock, which is why sometimes referred as feedstock recycling. Chemical recycling includes a range of plastic recovery techniques to make new plastics. Such techniques usually break down the plastic into their basic monomers, which in turn can be used again in refineries, or petrochemical and chemical production. A range of chemical recycling technologies is currently available such as pyrolysis, hydrogenation, gasification and thermal cracking (Kalpakjian and Schmid 2006). However, chemical recycling is an expensive process and requires large quantities of used plastic in order to be economically viable. Finally, an economically viable solution, but not always environmentally friendly, is the energy recovery of plastics. Plastic materials can be incinerated to generate energy but there have been significant concerns over airborne emissions from plants incinerating plastics, particularly if PVC is involved.

As previously described, various types of plastics are utilised by the footwear industry. Thermoplastic materials i.e TPR, PVC, PP, TPU etc, are easy on recycling because they can be heated and formed without problems for many times. Thermoplastics can be blended with virgin materials, re-moulded and used in various applications. This type of recycling does not necessarily mean that the recycled material goes back into the application from which it originated because its properties may be changed or degraded. On the other hand, thermosets, are much more rigid and harder than thermoplastics and cannot be remoulded. However, some thermosetting polymers can be converted relatively easy back to their original monomer, such as polyurethane while for others, such as polyester and epoxy, it is not practical to depolymerise to their original constituents (Pickering 2006). Reaction Injection Moulded (RIM) Polyurethane scrap can be converted into a granular or powder form with the final particle size depends on the end use application or can be also used as filler during the injection itself (Hulme and
Goodhead 2003). However, such process requires expensive and sophisticated equipment for the grinding and injection processes. RIM PU scrap can also be chemically modified and reduced back to its original ingredients. Originally, this process was based on hydrolysis but recently the focus has been shifted on glycolysis with more than 200 patents produced (UNIDO 2000). Finally, natural and synthetic rubber can be recycled by various methods including thermo-mechanical reclamation, size reduction by cutting and grinding, chemical, gaseous, mechanical and physical surface activation, decomposition via pyrolysis, de-polymerisation, gasification and hydrogenation and, finally, incineration (Manuel 1997). In literature, many studies can be found examining the recycling process of rubber scrap (especially post-consumer scrap tyres) into valuable applications (Smith et al 1995, De 2001, Myhre and Mackillop 2002). Table 4.11 presents some of the possible recycling routes for plastic materials used in footwear industry.

<table>
<thead>
<tr>
<th>Recycling Method</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Recycling</td>
<td>Powdering/fillers</td>
</tr>
<tr>
<td></td>
<td>Particle/ granulate</td>
</tr>
<tr>
<td></td>
<td>Compression moulding</td>
</tr>
<tr>
<td></td>
<td>Injection moulding</td>
</tr>
<tr>
<td></td>
<td>Hydrolysis</td>
</tr>
<tr>
<td></td>
<td>Hydrogeneration</td>
</tr>
<tr>
<td></td>
<td>Pyrolysis</td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
</tr>
<tr>
<td></td>
<td>Glycolysis</td>
</tr>
<tr>
<td>Chemical Recycling</td>
<td>Co-combustion in municipal incineration plants</td>
</tr>
<tr>
<td></td>
<td>Fluidised bed</td>
</tr>
<tr>
<td></td>
<td>Rotary kilns</td>
</tr>
<tr>
<td></td>
<td>Specialist boilers</td>
</tr>
<tr>
<td></td>
<td>Cement kilns</td>
</tr>
</tbody>
</table>

**Table 4.11:** Recycling Methods for Plastic Materials
4.9.3 Textiles Recycling

Textiles, both natural and synthetic, can also be recycled. The main recycling technology applicable worldwide to textiles (cotton, wool, linen, polyester) is the production of fibres, the so-called “rag-pulling”. The process involves the breakdown of fabric to fibres through cutting, shredding, carding and other mechanical processes (Wang 2006). The fibre is then re-engineered into value-added products such as automotive car upholstery, carpet underlay, bed mattresses and water pipe insulation materials.

Recycled textiles can also be used as wiping and polishing cloths as well as wipers to the oil refining industry due to their excellent oleophilic properties. Of particular interest is the case of carpet recycling. During the 1990’s an EU-funded research project, called “Recycling of Carpet Materials” (RECAM), achieved remarkable technological progress through the development of a closed-loop recycling systems for carpet materials. The carpet recycling systems included a system for the collection of carpet waste, an automated sorting process, mechanical recycling of wool and polypropylene and mechanical and chemical recycling of polyamide 6 and 6.6. (RECAM 1999). However, as Laursen et al. (2004) point out the carpet recycling project has so far failed to fulfil its potential in the free market economy regardless its huge technological success and the potential environmental benefits.

4.10 Critical Summary

A wide range of issues related to footwear industry have been discussed in this chapter, highlighting the complexity of post-consumer shoe recycling. Currently, some 19 billions pairs of shoes consumed worldwide every year, with most of them being disposed in landfills. This review has shown that the footwear industry’s response to its end-of-life waste problem has been limited. In fact, only one application of end-of-life product recovery has been identified, namely the NIKE’s “Reuse-A-Shoe” program. On the other hand, the traditional approach of collecting and re-distributing second-hand shoes to less-developed countries is problematic and currently under scrutiny as there are evidences that cheap imports have a major impact both on the local footwear industry and the environment.
It has become evident, through this review, that the large amount of post-consumer shoe waste produced every year, the legislative pressures to divert waste from landfills as well as the hidden value of recyclable materials in post-consumer shoes are expected to challenge the way the footwear industry is dealing with its end-of-life waste.
Chapter 5

5 Research Methodology

5.1 Introduction

This chapter describes the research methodology used in undertaking the research reported in this thesis. The formulation of the research hypothesis, the development of research concepts and activities and the application of research through case studies are described in details as the methodological approach is outlined.

5.2 Research Methodology

The methodology adopted is based on a traditional approach to carry out a research program, which consist of four distinct phases: review, background and research hypothesis, data collection and model development, testing and validation, and finally the assessment and formulation of research conclusions. Figure 5.1 provides an overview of the research methodology adopted within this thesis.

The research hypothesis was initially formulated through the author’s involvement in a European Framework 6 research project named “Comfort, Environment and Custom – Made Shoe (CEC-Made Shoe)”. This hypothesis was refined and its validity was confirmed though an extensive literature review and survey of relevant research as well as an initial round of industrial visits to shoe manufacturing companies and footwear organisations as part of this EU research project. It became apparent at this stage that there was a lack of appropriate product recovery and recycling procedures for post-consumer shoes and that a holistic approach need to be adopted for the realisation of end-of-life product recovery in the footwear sector.

Establishment of the research hypothesis together with the aim, objectives and scope of the research moved the work into its second phase (i.e. model development and
experimentation). Potential waste treatment options and techniques that could be applied in the footwear industry were, initially, identified and classified into proactive and reactive approaches. A modelling technique (i.e. IDEF0) has been applied to identify end-of-life processes for post-consumer shoes, which then led to the initial drafting of a systematic methodology for considering end-of-life product recovery in the footwear industry. The End-of-Life Treatment of Shoes (ETS) methodology then developed to define alternative end-of-life scenarios for post-consumer shoes to a level of detail that will allow environmental, economic and socio-technical considerations to be analysed, calculated and compared.

At this stage of research, it became apparent that a number of possible treatment options with different environmental impacts, economic values and socio-technical requirements need to be considered in order to select a suitable treatment solution for post-consumer shoes. Hence, a multiple criteria decision making model for post-consumer shoes was proposed to provide an integrated approach to evaluate a number of related quantitative and qualitative waste management factors. In addition, a prototype end-of-life decision support tool for footwear products was specified to facilitate the implementation of the multiple criteria decision making model for selecting appropriate end-of-life treatment options for shoes.

At the third phase of work, the proposed research concepts were demonstrated through the application in two case study shoes. The case studies were selected in an attempt to represent two distinctly different cases of post-consumer shoes. The case studies were conducted in a step-by-step approach following the proposed ETS methodology and its associated decision support model and software tool.

Finally, at the final phase of the research methodology, conclusions were drawn from the case studies and research results were analysed in order to develop the research conclusions of this research.
Figure 5.1: Outline of Research Methodology
Chapter 6

6 Post-Consumer Shoe Waste in Footwear Sector

6.1 Introduction

This chapter presents an investigation into the definition and modelling of waste management in the footwear industry. Initial sections of the chapter outline and define the various waste management options for post-consumer shoes. The latter part of the chapter provides a modelling approach for identifying potential end-of-life treatment options for post-consumer shoes.

6.2 Waste Management in Footwear Industry

Waste management in footwear industry is a rather complex task influenced by many issues. The research, in general, has identified two types of waste problems in footwear sector. The first waste problem which comes from the manufacturing activities and facilities itself and the second waste problem which related with the management of used or discarded shoes at the end of their functional life. The scope of this research is focused on the end-of-life waste on the footwear sector, the so-called post-consumer shoe waste. Therefore, a systematic approach has been adopted to identify the various waste management options for post-consumer shoes.

Figure 6.1 provides a comprehensive overview of different waste reduction options and techniques that could be applied in footwear industry as well as suggests potential routes for the recycled materials to be used either inside (closed-loop) or outside (open-loop) the footwear product system.
As depicted in Figure 6.1, the research has categorised these options into two major methods that can be applied to manage post-consumer waste in footwear industry. These methods are referred to as proactive and reactive approaches.

6.2.1 *Proactive Approaches (Waste Minimisation)*

In general, it makes far more sense to reduce or even minimise waste at the source than to develop extensive treatment schemes and techniques to ensure that the waste poses no threat to the environment. Proactive approaches include all measures that are taken with the aim to minimise waste at the source. This practice, in literature, is also referred as waste minimisation. Although there is a wide range of waste minimisation activities, the research has identified two major improvement methods that could be applied in the case
of the footwear industry in order to minimise waste at the source, namely design improvements and material improvements.

6.2.1.1 Design Improvements

The design stage is the point of greatest leverage for improving a product's environmental performance. Eighty percent of a typical product's environmental impact is determined by its design (ENDS 2001). Waste minimisation strategies should, therefore, start at the beginning of a product's life cycle, in the product design phase, using Design for Environment (DfE) improvements.

Design improvements in the footwear sector could have significant impact on environmental quality and could reduce the amount of materials needed, thus reducing the amount of waste that need to be handled at the end of the lifecycle. In addition, a footwear product, which is designed for ease of disassembly will make reuse and recycling of its components and parts easier, the so-called "Design for Recycling" approach, thus reducing the amount of materials disposed into landfill. For example, the replacement of a steel shank in a footwear product with a fibreglass shank could significantly affect the recyclability of the post-consumer shoe. Such design alterations could provide a wider range of end-of-life treatment options for post-consumer shoes.

6.2.1.2 Material Improvements

The environmental properties of shoes can also be improved by simply choosing different materials. Material improvements, under certain circumstances, can achieve significant reduction of waste. For example, eco-friendly fabrics can be used in uppers and natural rubber in shoe soles, which can be recycled at the end of the functional life of shoes. Moreover, recycled materials can be used to produce shoes such as Worn Again trainers made from 99% recycled materials such as old tyres, car seat leather and used coffee bags (Worn Again 2006).

Biodegradable materials such as natural rubber or leathers tanned with biodegradable polymers instead of chromium can also be used to substitute conventional materials in
shoes. In terms of their overall environmental implications, it is claimed that biodegradable materials improve the environmental properties of shoes because of their potential biodegradability or compostability at the EoL phase and the use of renewable resources in their manufacture. This thesis has investigated the applicability of biodegradable materials in shoes and their environmental implications as shown below.

**Biodegradable Materials in Shoes**

According to the British Standards (2000), a material is deemed biodegradable if it undergoes degradation by biological activity under specific environmental conditions to a defined extent and within a given time. Currently there are several types of biodegradable materials that being used by the footwear industry. Natural biodegradable materials such as leather and natural rubber and biodegradable polymers made from starchy crops such as maize and potatoes, developed as a “green” alternative to conventional petrochemical-based polymers.

Natural rubber used for shoe soles, and leather used in upper shoe materials are naturally occurring biodegradable biopolymers. However, to provide stability and good properties in service, these materials have been chemical modified to produce cross-linked stable structures. The reversibility of such cross-linking has been studied, for instance several patents have been published in the last decade for the devulcanisation of rubber, although there is little evidence of these patents being turned into effective industrial processes. Therefore there is a need to produce materials which are stable in service but then will readily breakdown when no longer wanted.

Also, in recent years, a wide range of biodegradable polymeric materials from rubbers to thermoplastic materials have been developed to be used as construction materials and adhesives in the footwear industry. According to Abbot and Wilford (1999), biodegradable materials that based on polypeptides offer the most potential for use as adhesives while bio-polymers based on polysaccharides and polyhydroxyalkanoates offer wider potential for use in coatings, films and fibres. Few materials, however, have become commercially available in the footwear industry. For example, Biopol®™, which is a biodegradable thermoplastic material, is currently used by the footwear industry in similar applications as polypropylene or polyethylene. However, there are considerable
technical and economic challenges to be overcome before these type of materials are widely used in the production of shoes.

**Waste Treatment of Biodegradable Materials**

There are two established methods for the waste treatment of biodegradable materials: biological treatment and conventional methods. Biological treatment includes both aerobic (composting) and anaerobic digestion. Aerobic digestion generates carbon dioxide, water and methane as well as some form of compost, which can be used as a fertilizer. However, carbon dioxide and methane are well-known greenhouse gases which contribute to additional atmospheric loading. It has also been recently recognised that for achieving composting, biodegradable materials have to be held at 50°C to 60°C. So if biodegradable products are to be composted, they must meet stringent quality criteria. Dedicated standards and certification schemes have been established for verifying the compostability of biodegradable products.

Anaerobic digestion, on the other hand, is a process where biodegradable material is broken down in the absence of oxygen in an enclosed vessel. The process produces carbon dioxide, a biogas and solids/liquors known as digestate, which can also be used as fertiliser. However, anaerobic digestion can be problematic as some of the biodegradable materials are known to be non-biodegradable under anaerobic conditions, another possible problem with PLA (Klauss and Bidlingmaier 2004). It should be noted that the EU Landfill Directive recognises biological treatment activities as a form of recycling.

Biodegradable waste materials can also be treated using conventional methods, such as incineration and landfills. Mass burn incineration of biodegradable materials, however, generates carbon dioxide, water, and ash, with the release of thermal energy. In the case where renewable resources used, thermal recovery is carbon dioxide neutral. Biodegradable materials also could be send to landfill, where broke down to produce a powerful greenhouse gas, methane. As previously mentioned, the EU Landfill Directive requires a considerable reduction to the volume of biodegradable materials being sent to landfill and even such materials are being excluded from landfilling by law.
6.2.2 Reactive Approaches (End-of-Life Management)

Total elimination of post-consumer waste through proactive approaches is infeasible mainly due to economic and technical factors involved. Hence, there will always be some waste that cannot be prevented at the source. Where waste material is produced, an optimal treatment option must be selected with the lowest possible risks to human health and the environment. Reactive approaches include all the appropriate waste management options which act in response to the post-consumer waste problem when the useful life of the product has ended, and hence referred as End-of-Life Management.

In the case of the footwear industry, four end-of-life strategies have been identified based on the waste hierarchy concept (see Section 3.4.3), namely: Reuse, Recycling, Energy Recovery and Disposal.

6.2.2.1 Reuse

Direct reuse can be practised with the use of products that designed to be used a number of times. Direct reuse of post-consumer shoes with minimal processing is a possible option but there are a few variables that need to be considered such as the condition of the shoe at the end of its life, the collection and distribution system as well as the purpose of its reuse. Such reuse activities mainly include the collection and distribution of second-hand shoes to developing countries. As discussed in Section 4.8.2, such reuse activities raise a number of important questions regarding their overall impact on local communities in terms of environmental and economic consequences and, therefore, need to be further investigated.

6.2.2.2 Recycling

In the case of the footwear industry, recycling mainly involves the reprocessing of end-of-life footwear products, parts or materials, either into the same product system (closed loop) or into different ones (open-loop). The post-consumer waste is re-introduced back into the market through a series of recycling processes that can be divided into two major methods: destructive and non-destructive. Destructive methods, mainly through shredding process, could be used to transform shoes into other useful materials. Shredded materials
can be directly used in secondary applications such as surfacing of roads, playgrounds and sound insulation. On the contrary, non-destructive recycling methods involve the dismantling of shoes to isolate materials for further recycling in order to obtain higher grade and quality of recycled materials which can be used in a wider range of applications. Non-destructive methods generally include sorting, inspection, disassembly, and then shredding of separated materials. However, disassembly of shoes is not an easy task due typically to the large amount of adhesive used to join shoe parts together along with stitching techniques.

6.2.2.3 Energy Recovery

Post-consumer shoe waste can be recovered in order to generate heat and electricity. Energy recovery from waste includes a number of established and emerging technologies such as incineration, gasification and pyrolysis. In the case of leather waste, gasification technology has been applied for heat generation and chromium recovery. For example, a 50kg/h leather waste gasification unit has been installed in a leather tannery plant in Leeds, UK with some reported success in early experimentation (ENDS 2003). At the moment, however, such gasification units accept only raw solid waste directly from the tannery production and not finished leather products such as shoes.

6.2.2.4 Disposal

Disposal of post-consumer waste in landfills is regarded, according to the waste hierarchy, as the last resort waste management option with the highest environment impact. However, not all post-consumer shoe waste can be prevented or recycled and there will always be some waste to finally be disposed off in landfills. However, this approach may present difficulties in the future due to the recently introduced legislations that ban landfilling of certain waste streams. Clearly, due to the vision of “Zero Waste to Landfill” in the footwear sector introduced by this research, this option is avoided wherever possible.
6.3 Modelling End-of-Life Management Options for Shoes

A system modelling tool have been utilised in order to map precisely the different waste management options for post consumer shoes. The modelling tool used is the Integrated Computer Aided Manufacturing Definition (IDEF) developed by US Air Force’s ICAM project (IDEF0 1981). The functional modelling approach of IDEF is defined as IDEF0. There are five fundamental elements in the IDEF0 functional model, namely activities, inputs, outputs, controls and mechanisms. The activities are represented by boxes. The inputs, outputs, controls and mechanisms are represented by arrows, as depicted in Figure 6.2. The arrows going into the boxes represent the inputs into the process. The arrows going into the top of the activity boxes represent controls or constrains on the process while the arrows going into the bottom of the boxes represent mechanisms that will be able to perform the activity. The outputs are arrows that come out of the right-hand side of the activity boxes such as a product or waste. A characteristic of the IDEF0 modelling technique is that activities and arrows can be decomposed into hierarchical levels of analysis, which makes IDEF0 models easily mapped into other tools and techniques. In our case the decomposition characteristics of IDEF0 models are quite helpful for connection with the AHP method.

Figure 6.2: IDEF0 Diagram
6.3.1 A IDEF0 Model for Post-Consumer Shoe Waste

The first step in trying to model the end-of-life process for post-consumer shoe waste is to identify the different recovery and recycling scenarios involved. In total five different end-of-life scenarios for post-consumer shoes have been considered by this research. These are:

i) Reuse
ii) Recycling (destructive)
iii) Recycling (non-destructive)
iv) Incineration with energy recovery
v) Landfilling

Each of these scenarios will be investigated to try and identify the major inputs and outputs of each end-of-life strategy. At top level diagram, the overall end-of-life process is represented, as shown in Figure 6.3. At the initial stage of the process the end-of-life shoe is introduced to the processes. The decision is constrained by legislation and uses technology as a mechanism. The output of this process is a product. This product may be in the form of recycled material, energy or, when there is not any technically feasible or economically viable option, waste will be send to landfill.

The IDEF0 model assumes also that the end of life shoe waste goes into the highest stage of the process before moving on to the next stage. Figure 6.4 illustrates the process flow of the four basic types of scenarios for post consumer shoes. There are two major outputs from each scenario. Firstly there is product (i.e. recycled material) and secondly there may be some waste. The recycling processes for post consumer shoes can be broken down into two distinct processes, namely destructive and non-destructive recycling.
Figure 6.3: IDEF0 Diagram of End-of-Life Process

Figure 6.4: IDEF0 Diagram of EoL Scenarios for Shoes
Figure 6.5 shows the inputs and outputs to each of these processes. Non-destructive recycling (shoe disassembly) processes aims to obtain high grade of quality materials which can be used in a wider range of applications, and hence produce high-value recycled materials such as pure leather trimmings that can be used for gelatine extraction and in various applications in the construction industry (e.g., absorbing materials, thermo-acoustic insulation etc.).

On the contrary, shredded materials can be used in low-value secondary applications such as surfacing of roads and playgrounds. The incineration processes can also be broken down into incineration with and without energy recovery. The output of these processes is the waste or ash of the incineration and energy. Incineration with energy recovery may have a higher waste as their needs to be more substances filtered in order to keep the temperature high. Figure 6.6 below shows the incineration scenarios for post-consumer shoes exploded into the two types. It should be mentioned, however, that this thesis has investigated only the incineration with energy recovery option since is the most widely used energy recovery option in Europe.

![Figure 6.5: IDEF0 Diagram of Recycling Scenarios](image-url)
6.4 Waste Management Model for Post-Consumer Shoes

This Chapter has outlined a waste management model for post-consumer shoes developed by the research. The overall aim of this model is to provide a systematic approach to the treatment of post-consumer shoe waste. The selection of the most appropriate end-of-life treatment option, as defined in this waste management model, is a complex task that requires the consideration of a number of factors that influences the environmental, economic and socio-technical aspects of product recovery and recycling. This research has, therefore, developed a methodology to consider these factors in a systematic way and to select the most appropriate end-of-life treatment option. This end-of-life product recovery methodology will be described in Chapter 7.
Chapter 7

7 A Methodology for End-of-Life Product Recovery in Footwear Industry

7.1 Introduction

This chapter describes a formal methodology developed in this research for considering end-of-life product recovery in the footwear industry. The first part of the chapter highlights the rationale and the requirements for the development of such methodology for the footwear sector. The main part of the chapter describes the major phases of the End-of-Life Treatment of Shoes (ETS) methodology. The chapter concludes by outlining the potential applications of ETS methodology in the footwear sector.

7.2 Rationale for the Development of the ETS Methodology

A methodology could be described as an organised set of procedures (methods) and guidelines to describe how something will be done. According to the Oxford Dictionary (2000) a methodology “is a system of methods used in a particular field”. Methodologies explain how a system functions and are a mechanism to achieve a better decision making process. The End-of-Life Treatment of Shoes (ETS) Methodology aims to determine the most appropriate set of treatment actions for particular types of post-consumer shoes. The ETS methodology addresses three major shortcomings of the current approach:

- The lack of an appropriate systematic consideration of end-of-life product recovery processes in the footwear industry.
- The lack of decision making support to consider both quantitative (environmental, economic) and qualitative (socio-technical) aspects of the end-of-life phase.
• The need for a bespoke tool for the footwear industry to be used both during the shoe design phase and for determining the most appropriate end-of-life scenario for post-consumer footwear products.

These highlight the need for a flexible methodological approach able to handle multiple criteria in order to help shoe designers, shoe manufacturers, decision makers and recovery operators to evaluate alternative end-of-life scenarios for post-consumer shoes. Although the focus of the ETS methodology is on the end-of-life phase of shoes, the theoretical aspects can be extended to the whole life cycle of the shoe, in particular during the design phase.

7.3 End-of-Life Treatment of Shoes (ETS) Methodology

The ETS methodology enable the definition of alternative end-of-life scenarios to a level of detail that will allow environmental, economic and socio-technical factors to be calculated, analysed and compared. The most appropriate end-of-life option based on the ETS methodology, is the option that minimise the overall environmental impacts in a technically feasible way and at a reasonable cost. An integrated approach is therefore developed in order to incorporate all the potential decision criteria and considered both quantitative and qualitative factors. The ETS methodology consists of four phases, as depicted in Figure 7.1:

i) Product characterisation
ii) End-of-life scenario definition
iii) End-of-life scenario assessment
iv) Recovery value chain identification

The methodology starts with consideration of a set of input data regarding the type of the post-consumer shoe. In the first phase, the condition, value and type of shoe are assessed together with the construction methods and the materials used for each part of the shoe. Identification of potential product recovery scenarios and their related decision factors forms the next step in the decision making process.
ETS METHODOLOGY

<table>
<thead>
<tr>
<th>Phase 1: Product Characterisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Level Screening (Preliminary)</td>
</tr>
<tr>
<td>2nd Level Screening (Construction)</td>
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<tr>
<td>3rd Level Screening (Component)</td>
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<tr>
<td>4th Level Screening (Material)</td>
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<table>
<thead>
<tr>
<th>Phase 2: End-of-Life Scenario Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse</td>
</tr>
<tr>
<td>Recycling</td>
</tr>
<tr>
<td>Energy Recovery</td>
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<tr>
<td>Disposal</td>
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<table>
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<tr>
<th>Phase 3: EoL Scenario Assessment</th>
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<tbody>
<tr>
<td>Step 1: Identification of Decision Factors</td>
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<td>Step 2: Calculation of Decision Factors</td>
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<tr>
<th>Phase 4: Recovery Value Chain Identification</th>
</tr>
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<tbody>
<tr>
<td>Value Added Activities</td>
</tr>
<tr>
<td>Non-Value Added Activities</td>
</tr>
</tbody>
</table>

**Figure 7.1: ETS Methodology**

Finally, quantitative (economic and environmental) and qualitative (socio-technical) factors are calculated, using a bespoke decision making model, and an optimal product recovery scenario for a selected range of post-consumer shoes is proposed. The ETS methodology provides a systematic way of considering all the appropriate factors in an attempt to identify optimal waste management options for post-consumer shoes. Figure 7.1 provides a visual representation of various activities in each phase included in the End-of-Life Treatment of Shoes (ETS) methodology, each of which is described in more details below.
7.3.1 Phase 1: Product Characterisation

The first phase of the methodology identifies the main characteristics of the post-consumer shoe under consideration. This step is needed in order to classify the product into its basic attributes and identify the crucial factors that determine the choice of a end-of-life treatment option. Product characterisation is performed in four levels, as depicted in Figure 7.2, which also referred to as screening levels. The major output of the first phase is a general categorisation and classification of post-consumer shoes based on their specific attributes as well as the identification of important factors that influence the choice of an appropriate end-of-life management option.

7.3.1.1 1st Level Screening

The first screening level determines the basic characteristics (preliminary) of worn shoes such as the condition (e.g. suitable or unsuitable for reuse), the value (based on material content and shoe style), the type of the shoe (men’s casual, sports trainers etc) and its weight.

![Phase 1: Product Characterisation Diagram](image)

**Figure 7.2:** Phase 1 of ETS Methodology
This screening level is very important for the selection of a suitable product recovery option at a later stage of the ETS methodology. For example, post-consumer shoes in a relatively good condition can be easily refurbished and then reused while in the case of damaged or destroyed shoes, the reuse option is simply not considered.

7.3.1.2 2nd Level Screening

The second screening level provides necessary background information regarding the structure of the shoe and the construction methods that have been used to produce the shoe. In particular, the adhesives or stitching operations that have been applied to create a shoe can significantly influence the choice of appropriate destructive (shredding or granulating) or non-destructive (disassembly of upper and sole) recycling option.

7.3.1.3 3rd Level Screening

The third screening level simply determines the major components and parts of the shoe. Although, most of the footwear components can be grouped broadly into three main categories, a different subset of parts and components are generally used to construct a shoe. For example, sandals can only consist of only two components per pair while a men’s boot can be of much complex construction with a variety of components and parts used.

7.3.1.4 4th Screening Level

Finally, at the fourth screening level, materials used are classified according to their properties and then grouped into four major groups: leather, textiles, plastics and others. This classification is necessary because these materials significantly differ not only in their appearance and physical qualities but also in their ability to be treated by different recycling and product recovery operations at the end of their useful life.
Once the essential product characteristics (condition, value, type and weight of shoe together with the construction methods and the materials used for each part of the shoe) have been identified, the next step is to generate a list of appropriate waste management scenarios for a particular shoe under consideration. Hence, in the second phase of the ETS methodology, a shoe end-of-life scenario model is constructed based on the output from the first phase. The waste management model for post-consumer shoes (as described in Chapter 6) will be used to determine the various end-of-life scenario options, giving priority to reuse and recycling to minimise cost and environmental impacts.

Figure 7.3 provides an overall view of potential end of life scenarios. Such end-of-life scenario model would identify potential treatments for post-consumer shoes depending on the shoe type. The overall output of Phase 2 is a list of potential end-of-life scenarios for post-consumer shoes, which are subsequently evaluated at Phase 3 of the ETS methodology.
7.3.3 Phase 3: End-of-Life Scenario Assessment

The objective of the third Phase of the ETS methodology is to identify and calculate the factors that influence the final selection of an appropriate end-of-life treatment option. The key element of this phase is the development of a bespoke decision making model for end-of-life shoes. This decision making model is able to allow both quantitative (environmental and economic) and qualitative (socio-technical) factors to be selected, analysed and calculated using different evaluation methods in an integrated approach. Phase 3 of the ETS methodology is carried out in two steps, as depicted in Figure 7.4. The final output of Phase 3 would be an evaluation matrix of potential end-of-life treatment options. This matrix would assign an assessment value on each end-of-life scenario based on socio-technical, economic and environmental considerations as well as would prioritise the different treatment options according to their assessment value.

7.3.3.1 Step 1: Identification of decision factors

Decision factors that influence the potential end-of-life scenarios for post-consumer shoes need to be first identified. In conformity with the multiple criteria nature of the ETS methodology, these decision factors should take into consideration both quantitative (environmental and economic) and qualitative (socio-technical) criteria. Environmental criteria include a number of well-established and measurable environmental impact category indicators such as global warming potential, human eco-toxicity, etc.

Figure 7.4: Phase 3 of the ETS Methodology
Economic criteria are simply represent the costs of processing and the revenues from products (i.e. reuse option) and materials (i.e. recycling option) for each end-of-life scenario together with the cost of landfilling. Finally, the list of potential socio-technical criteria that could be considered is almost endless and includes criteria such as process technical feasibility, market pressures and compliance with legislation. This list could be easily changed in different applications depending on the requirements of the analysis and the type of shoe under consideration.

7.3.3.2 Step 2: Calculation of decision factors

Once the decision factors have been selected, these are then need to be analysed for each end-of-life scenario in order to measure the impacts associated with all of the processes within each scenario. Information and data are collected and analysed in order to provide guidance on which is the optimal waste management solution for the selected type of shoe. For this purpose, a multi-criteria decision making model has been developed utilising various decision aiding techniques to analyse and calculate the decision criteria. The Analytic Hierarchy Process (AHP), which was described in Chapter 3, has been used as the basic framework for simultaneous consideration of all these criteria. Economic criteria are calculated using Cost-Benefit Analysis (CBA) to identify cost and benefits for each scenario while environmental criteria are analysed using the Life Cycle Assessment (LCA) technique. Finally, socio-technical criteria are calculated by applying the AHP method in a micro level. The decision making model, and its basic functions, is described in more details in Chapter 8.

7.3.4 Phase 4: Recovery Value Chain

Once post-consumer shoes collected, sorted and converted into a form that can be used by either the footwear industry or other industrial sectors, then it must compete with virgin materials both on price and performance. A sustainable shoe recycling application heavily depends on establishing a successful value shoe recovery chain. Hence, the final phase of the ETS methodology aims to identify a recovery value chain for the end-of-life scenarios, as previously defined in the previous phases of the ETS methodology.
In this respect, a product recovery value chain can be described as the service of recovery and reuse of resources across a number of different sectors. Also the market conditions should be investigated to make sure that a market exists for such recovered products or materials. Therefore, suitable applications would be identified for each end-of-life scenario in this phase of the methodology. This can be achieved by establishing procedures that identify, within a broader context, value-added activities and benefits and seeking out the best recycling practices along different industrial sectors.

Figure 7.5 presents a product recovery value chain for alternative end-of-life scenarios for shoes. A value-added activity, as defined in this research, is a product recovery activity in which the post-consumer shoe has generated some value through a change in its character or composition through a recycling process. Activities for simply collecting, sorting, and baling of post-consumer shoes for ease of transport does not constitute adding value and will not be considered. However, not all post-consumer shoes can be considered to be suitable for recycling or reuse and, therefore, landfiling (or even incineration without energy recovery) of such materials could be considered as a practical option. Such activities does not generate value and, hence, referred in this thesis as non-value added activities.

![Figure 7.5: Phase 4 of the ETS Methodology](image-url)
Other issues that also need to be considered in establishing a recovery value chain for post-consumer shoes is the size and the value of the end market, the current and predicted buying trends as well as the range and price of competing materials and products. Hence, the main output of this phase is a list of potential applications for shoe recycled materials.

### 7.4 Utilisation of ETS Methodology

The author has identified three major applications for the ETS methodology within the footwear industry, which belong to different stages of the footwear life cycle, as depicted in Figure 7.6:

1. The ETS methodology could be utilised during the design phase. The scope is to aid the shoe designer in choosing the best design in terms of environmental, economic and socio-technical considerations.

2. It has become apparent that materials chosen have an influence on the manufacturing process as well as on the process of recycling and disposing the product at the end of its functional life. Hence, the ETS methodology could be used to provide information and knowledge about the materials chosen in the supply phase.

![Figure 7.6: Application of ETS Methodology in Footwear Sector](image-url)
iii) Finally, as already discussed, deciding which is the preferable way to treat a post-consumer shoe at the end of its functional life is a crucial issue that affects a wide range of stakeholders e.g. manufacturer, recycler, local authorities etc. The prime application of the ETS methodology is, hence, to evaluate different end-of-life treatment options for post-consumer shoes. This evaluation is capable of simultaneous consideration of a number of criteria related to environmental impacts, economic considerations and socio-technical issues that influence the selection of an appropriate end-of-life treatment option for post-consumer shoes.
Chapter 8

8 Decision Making Model for End-of-Life Shoes

8.1 Introduction

This chapter presents the development of a multi-criteria decision making (MCDM) model for end-of-life management of post-consumer shoes. The chapter will, in the first place, define the variables of this decision problem and then describe a MCDM approach that has been developed in this research to generate a decision making model for simultaneous consideration of a number of competing and, at times, conflicting factors.

8.2 Multi-Criteria Decision Making

The selection of an appropriate treatment option for post-consumer products concerns a wide range of users from local authorities and recyclers to original equipment manufacturers and designers, with each of them having their own objectives and priorities. However, the environmental, economic and socio-technical impacts of a product during its use phase also influence the way the product must be treated at the end of its functional life. To select the most suitable end-of-life treatment solution for post-consumer shoes, the various alternatives need to be compared on the basis of their performances with respect to the abovementioned criteria. Usually, the selected criteria are conflicting, for example incineration of post-consumer shoes might seems as the most economically viable option to treat end-of-life waste but the environmental consequences of such approach need to be fully investigated, especially if the footwear product is made of PVC or other plastic materials, which might produce dioxins when incinerated. Therefore, this research has identified a need to investigate a multi-criteria decision making approach as described in the remaining section of this chapter.
8.3 Formulation of a Multi-Criteria Decision Making Model for Post-Consumer Shoes

This research has developed, and described in previous chapters, a methodology for the consideration of various criteria in order to select the most appropriate end-of-life treatment option for post-consumer shoes. More specifically, a set of alternative options are considered in order to find the best solution with respect to a number of criteria. According to Vince (1992), a MCDM problem is a situation in which, having defined a set $A$ of alternatives and a consistent family $F$ of criteria on $A$, one wishes to determine a subset of alternatives considered to be the best with respect to $F$. Based on this definition, the decision making problem to select the best end-of-life option for post-consumer shoes is classified as a typical MCDM problem, and hence should be treated as such.

This research has identified a three-step process in order to explore this MCDM problem:

I. Define decision variables
II. Identify evaluation methods
III. Construct decision making model

The three-step process proposed by this research will be described in the remain section of this chapter.

8.4 Define Decision Variables

The decision variables in a MCDM problem include the set of alternative options to be considered in order to find the best solution as well as the set of criteria that need to be evaluated. In general, criteria measured using one or more indicators. Indicators are defined as instruments which synthesize, in qualitative or quantitative terms, certain information to formulate a judgement on an alternative with respect to some of its characteristics, attributes or effects (consequences) which might arise from its implementation (Roy 2000). Hence, three types of decision variables need to be clearly defined in this research, namely alternative options, decision criteria and indicators.
8.4.1 Alternative Options

This research has identified five alternative options to consider in the process of selecting the best treatment option for end-of-life shoes. It should be mentioned, however, that these options are not necessarily always feasible. For example, if the potential end-of-life scenario (e.g. incineration) associated with a particular type of shoe is not acceptable by legislation or there is no market or technological infrastructure for its application, then this scenario should be removed from the list of potential alternatives. As previously described in Chapter 6, the potential alternative options are:

i) Reuse
ii) Recycling (Destructive)
iii) Recycling (Non-Destructive)
iv) Incineration with Energy Recovery
v) Landfilling

8.4.1.1 Decision Criteria and Indicators

The ETS methodology considers three types of decision criteria, namely environmental, economic and socio-technical. For each of these criteria, this research has identified a list of predefined indicators, as depicted in Table 8.1. These decision indicators are used to measure the performance of each criterion in this particular decision making problem. The environmental indicators were selected from the EDIP 97 environmental impact assessment method, which is commonly used in Life Cycle Assessment studies. The economic indicators were selected to facilitate the calculation process under a Cost Benefit Analysis approach while a number of socio-technical indicators can be selected depending on the nature of the decision making problem. Socio-technical indicators mainly include compliance issues (legislation), socio-economic issues (not technical issues such as market pressures) and technical issues (feasibility). In fact, the list of socio-technical criteria is endless and could be easily modified by the user depending on the requirements of the analysis and the type of shoe under consideration. However, this research has identified technical feasibility, public opinion, market pressures and compliance with legislation as the most relevant indicators for the footwear industry.
Table 8.1: List of Decision Indicators

8.5 Identify Evaluation Methods

Once the feasible alternatives \( A_i \) (in our case \( i=5 \)) and the relevant criteria \( F_j \) (in our case \( j=3 \)) are defined, each alternative should be evaluated with respect to each criterion, using the predefined indicators. These evaluations are usually denoted by \( E_{ij} \), and presented in a form of a matrix, as shown in Table 8.2.

<table>
<thead>
<tr>
<th>( A_i )</th>
<th>( F_1 )</th>
<th>( F_2 )</th>
<th>( F_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_1 )</td>
<td>( E_{11} )</td>
<td>( E_{12} )</td>
<td>( E_{13} )</td>
</tr>
<tr>
<td>( A_2 )</td>
<td>( E_{21} )</td>
<td>( E_{22} )</td>
<td>( E_{23} )</td>
</tr>
<tr>
<td>( A_3 )</td>
<td>( E_{31} )</td>
<td>( E_{32} )</td>
<td>( E_{33} )</td>
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<tr>
<td>( A_4 )</td>
<td>( E_{41} )</td>
<td>( E_{42} )</td>
<td>( E_{43} )</td>
</tr>
<tr>
<td>( A_5 )</td>
<td>( E_{51} )</td>
<td>( E_{52} )</td>
<td>( E_{53} )</td>
</tr>
</tbody>
</table>

Table 8.2: Matrix of Evaluations
To perform the evaluation of possible alternatives with respect to the defined criteria, this research has identified three evaluation methods to be utilised in order to calculate each criteria score. Life Cycle Assessment (LCA) for environmental criteria, Cost Benefit Analysis (CBA) for economic criteria and Analytic Hierarchy Process (AHP) for socio-technical criteria. In addition, AHP has been also employed as the main multi-criteria decision making method in order to analyse and synthesise each criteria score.

For this purpose, an evaluation framework has been constructed, as presented in Figure 8.1, to specify the methods being utilised to calculate the various decision criteria scores as well as to show the interconnections between the three evaluation methods. The selected evaluation methods to be applied in this research are briefly discussed in the following sections.

---

**Figure 8.1: Evaluation Framework for MCDM**
8.5.1 Life Cycle Assessment

The generally recognised term for environmental assessment of products and services is Life Cycle Assessment (LCA). In fact, LCA is an environmental assessment methodology that considers all product environmental burdens over the entire life cycle, from the material production to part manufacture, product assembly, operation, servicing, maintenance, and end-of-life disposition. For this reason, LCA is sometimes referred to as "cradle-to-grave" assessment because it provides the required wider perspective of a product system. In 1997, the International Organization for Standardization (ISO) initiated the ISO 14040 standards regarding the use of LCA (ISO 1997). These standards attempt to provide consistency among LCA efforts and ensure that all LCA practitioners are using similar tools and techniques. In accordance with the current terminology of the ISO 14040 standards, LCA is structured within a framework, which divides the entire LCA procedure into four distinct phases, as depicted in Figure 8.2. The goal and scope definition is the phase in which the initial choices which determine the working plan of the entire LCA study are made. In this first phase the purpose of the LCA study is also described. In the Inventory Analysis phase the product system of the LCA study is defined.

![Life Cycle Assessment Framework](image-url)

**Figure 8.2:** LCA Framework (ISO 1997)
Defining the product system includes designing the flow diagrams with unit operations, collecting the data for each of these operations, and completing the final calculations. Mass flows and environmental inputs and outputs associated with the functional unit are calculated, interpreted and presented. In the third step of the LCA methodology, the Impact Assessment phase, the environmental impacts are evaluated. The set of results from the Inventory Analysis phase are further processed and interpreted in terms of potential environmental impacts using standard impact assessment methods. Finally, in the interpretation phase the results from the inventory analysis and the impact assessment are evaluated and analysed from a perspective consistent with the defined goal and scope of the LCA study. The purpose of this phase is to reach relevant conclusions and recommendations for the LCA study.

8.5.1.1 The EDIP 97 Impact Assessment Method

The EDIP 97 (EDIP is the abbreviation of "Environmental Design of Industrial Products") impact assessment method is the result of a four year effort in the mid 1990’s in Denmark. The method was first published in Wenzel et al. (1997), followed by a second publication one year later in Hauschild and Wenzel (1998). According to Wenzel et al. (1997), the EDIP 97 method translates the cumulated inventory data of an examined system “into potential contributions to various impacts within the main groups environment, resources and working environment”. In order to have a maximum of transparency and reproducibility, the whole method distinguishes between three different steps:

1) Environmental impact potentials: the contribution of each individual emission to the various impact categories is calculated by using the respective equivalency factors. In EDIP 97 method there are sixteen (16) environmental impact categories.

2) Normalization with a common reference: In order to see which of the various impact potentials are relevant, they compared with a common reference (e.g. total European values).

3) Weighting of the normalized impact potentials: According to Wenzel et al. (1997), “before the normalized impact potentials are directly comparable, account must be taken of the seriousness of each individual impact in relation to the others". 
Therefore, weighting factors have been calculated based on scientific, political and normative considerations provided by the EDIP 97 method.

8.5.2 Cost Benefit Analysis

Cost Benefit Analysis (CBA) is an economic tool to aid the decision making process. CBA can be applied in a wide range of applications from social and environmental policies to large scale private and public projects (Pearce 1998). According to Boardman (2001) CBA “is a method of comparing the cost of a program with its expected benefits in monetary values”. Generally, CBA produces an overview of the revenues and costs of one or more alternative options, usually in the form of a balance sheet. Where possible, these revenues and costs are evaluated in terms of money based on market prices. However, contrary to the ISO 14040 series of standards for LCA studies, there are no international standards for conducting CBA and as a result, many different assumptions and guidelines have been applied in CBA studies.

In this research, revenues and costs of alternative options will be calculated and analysed using the Benefit-to-Cost Ratio (BCR) approach. According to Rideout and Hesseln (2001), BCR is defined as “the present value of all benefits (revenues) to the present value of all cost, where the point of reference for both benefit and costs is the base time period”. Usually, future benefits and costs are discounted relative to present benefits and costs in order to obtain their present values (PV). A cost or benefit that occurs in years \( t \) is converted to its present value by dividing it by \( (1 + s)^t \), where \( s \) is the discount rate. Hence, the present value of benefits PV(B) and the present value of costs PV(C) are calculated as shown in Equations 8.1, 8.2:

\[
P V(B) = \sum_{i=0}^{n} \frac{B_i}{(1 + s)^i}
\]

Equation 8.1

\[
P V(C) = \sum_{i=0}^{n} \frac{C_i}{(1 + s)^i}
\]

Equation 8.2

where

- PV(B) = present value of benefits
- PV(C) = present value of costs
- \( n \) = number of periods
s = discount rate
\( t = \text{years} \)

Hence, Benefit-to-Cost Ratio (BCR) is calculated as shown in Equation 8.3:

\[
BCR = \frac{\sum_{t=0}^{n} B_t / (1 + s)^t}{\sum_{t=0}^{n} C_t / (1 + s)^t}
\]

**Equation 8.3:** Equation for Calculating the Benefit/Cost Ratio (BCR)

8.5.3 *Analytic Hierarchy Process*

The Analytic Hierarchy Process (AHP), developed by Saaty (1980), is a fundamental approach to multi-criteria decision making. It allows the consideration of both quantitative and qualitative (objective and subjective) factors in selecting the best alternative option with respect to several criteria.

The first step in the AHP method is to structure the decision problem in a hierarchy consisting of three levels; namely the goal of the decision at the top levels, followed by a second level consisting of the criteria by which the alternatives, located in the third level, will be evaluated. Such hierarchical decomposition of a decision problem is depicted in Figure 8.3.

![Figure 8.3: Hierarchical Representation of a Decision Problem](image-url)
Once the hierarchical structure of the decision problem has been defined, the next step is to determine the relative importance of the alternatives with respect to the criteria. In the AHP method, pairwise comparison is employed to identify, the so-called, priority weight of alternatives.

Pairwise comparisons can be performed by experts or during brainstorming sessions involving various stakeholders. Firstly, a value is chosen from a scale to express the relative significance of one alternative over another based on a fundamental Saaty (1980) scale of 1 to 9, as shown in Table 8.3. From the set of pairwise comparison of the alternatives, a judgment matrix \( A \) is generated with \( i \) rows and \( i \) columns, where \( i \) is the number of alternatives being considered. Then a series of calculation are performed in order to determine the priority weight of each alternative within the hierarchy.

The priority weights for each alternative are calculated in two steps as follows:

i) A normalised matrix is obtained from the judgement matrix by dividing each entry in each column by the total of that column.

ii) The average of each row is obtained by adding the values in each row of the normalised matrix and dividing the sum by the number of entries in each row. The result is the priority weight of the alternative.

<table>
<thead>
<tr>
<th>Numerical Rating</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Both criteria equally important</td>
</tr>
<tr>
<td>3</td>
<td>Very slight importance of one criterion over the other</td>
</tr>
<tr>
<td>5</td>
<td>Moderate importance of one criterion over the other</td>
</tr>
<tr>
<td>7</td>
<td>Demonstrated importance of one criterion over the other</td>
</tr>
<tr>
<td>9</td>
<td>Extreme or absolute importance of one criterion over the other</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values between two adjacent judgements</td>
</tr>
</tbody>
</table>

Table 8.3: Pairwise Comparison Saaty Scale
However, it is possible that through the pairwise comparison exercise experts may be inconsistent in their judgements. For example, they can weigh A higher than B, and B higher than C. But also it is possible that they can weigh C higher than A. This choice produces inconsistency in the judgement matrix because AHP is expected to weigh A higher than C, based on the previous comparisons. For this reason, Saaty (1996) also developed the consistency index (CI) as a metric for measuring inconsistency in the AHP method, as depicted in Equation 8.4. First, he calculated the maximum eigenvalue\(^6\) (\(\lambda_{\text{max}}\)) by summing each column of the judgement matrix and multiplying those sums by the corresponding priority weight. He showed that the judgement matrix has an eigenvalue equal to \(n\) (where \(n\) is the number of variables or criteria) if the comparisons are perfectly consistent. However, the maximum eigenvalue (\(\lambda_{\text{max}}\)) is greater than \(n\) if the comparisons are not perfectly consistent. The difference between \(\lambda_{\text{max}}\) and \(n\) is expressed as the consistency index (CI), which is computed as follows:

\[
CI = \frac{(\lambda_{\text{max}} - n)}{(n-1)}
\]

where

- CI = consistency index
- \(\lambda_{\text{max}}\) = maximum eigenvalue
- \(n\) = number of variables or criteria

To establish a consistency threshold, CI is then compared to the average CI’s of 500 randomly generated matrices of the same dimension (called RI), as shown in Table 8.4. Once the consistency ratio (CI/RI) of the pairwise comparison matrix is less that or equal to 0.10 (i.e. 90% consistency or 10% inconsistency) then the ratings can be accepted. Otherwise, it is recommended that the pairwise compassion be revised to improve the consistency of these comparisons.

\(^6\) An eigenvector of a given linear transformation is a vector whose direction is not changed by that transformation. The corresponding eigenvalue is the proportion by which an eigenvector’s magnitude is changed.
Chapter 8

<table>
<thead>
<tr>
<th>Size of Matrix ($n$)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>0.00</td>
<td>0.00</td>
<td>0.58</td>
<td>0.90</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
<td>1.45</td>
<td>1.49</td>
</tr>
</tbody>
</table>

Table 8.4: Random Consistency Indices (adopted from Saaty 1996)

8.6 Construct Decision Making Model

In this section, the decision making model for post-consumer shoes is outlined and explained. This model is an integral part of the ETS methodology. The overall aim of the model is to identify the most appropriate end-of-life scenario for a selected range of post-consumer shoes with respect to economic, environmental and socio-technical criteria. The major attributes of the decision making model are:

- all decisions are taken at the end-of-life phase
- the model is able to handle both quantitative and qualitative data
- the basic framework of the model is being constructed using the AHP method
- a number of evaluation methods have been utilised to calculate the decision variables

The proposed decision making model follows a reasoning process, the so-called decision making process, to produce a final selection. The decision making process of the model, as depicted in Figure 8.4, is conducted into five steps, including a consistency check to make sure that pairwise comparisons of alternatives and criteria are consistent with the recommended values of the Saaty scale. These steps are:

1) Structuring the problem into a hierarchy
2) Making pairwise comparisons of criteria
3) Calculate decision variables
4) Consistency check
5) Synthesize the priorities
8.6.1 Structuring the Decision Problem

The first step in the decision making process is called decomposition, or the structuring of the problem into a hierarchy. Decomposition requires that the decision problem be decomposed into a hierarchy that captures the essential elements of the problem. This research has structured the hierarchy into three level, as depicted in Figure 8.5:
On the first (or top) level is the overall goal of the decision problem. In our model, the goal is to identify optimal EoL options for post-consumer shoes. The main goal can also be further divided into sub-goals based on a selected range of shoe types e.g. sports trainers, men’s shoes, women’s shoes and children’s shoes.

On the second level, the main objectives or criteria that contribute to the overall goal are defined, namely environmental, economic and socio-technical. These criteria are further divided into a number of sub-objectives or indicators that used to measure performance, impact and progress towards the goal of the decision making problem.

On the third (or bottom) level are the six alternative EoL options, as defined by the ETS methodology, that are to be evaluated in terms of the criteria and indicators within the second level.
8.6.2 Making Pairwise Comparisons

To estimate the significance of each end-of-life scenario (hierarchy level 3) in achieving the overall goal (hierarchy level 1), pairwise comparisons of the decision variables within a lower level of the hierarchical structure with respect to the variables in the next higher level are performed. The pairwise comparison exercise is carried out using the fundamental Saaty scale, as described previously in Section 8.5.3.

Although the Analytical Hierarchy Process is an efficient and effective means at measuring people preferences on alternative options, it should be noted that the pairwise comparison process may be influenced by peoples skills set. AHP assumes that the pairwise comparisons are obtained by direct questioning of people (stakeholders) who may or may not be experts, but who are familiar with the problem. In general, two types of stakeholders can be identified, namely outside stakeholders and local stakeholders (Strager and Rosenberger 2006). Outside stakeholders consist of professionals in related fields such as policy makers, economists, and other scientists. These type of stakeholders bring universally relevant knowledge to decisions but often lack specific knowledge. Conversely, local stakeholders such as footwear designers and manufacturers can provide their specific expertise in judging various criteria.

Hence, the decision variables weights could be determined by using questionnaires to obtain outside and local stakeholders viewpoints. Table 8.5 shows how such viewpoint can be obtained for a single matrix by using a simple questionnaire. This table indicates Saaty scale values (one to nine) ranging from one extreme down towards equality and then again rising to the other extreme.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Absolute</th>
<th>Very Strong</th>
<th>Strong</th>
<th>Weak</th>
<th>Equal</th>
<th>Weak</th>
<th>Strong</th>
<th>Very Strong</th>
<th>Absolute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Economic</td>
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<td>Economic</td>
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<td>Economic</td>
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<td>Economic</td>
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</tr>
</tbody>
</table>

Table 8.5: AHP Questionnaire to Obtain Judgements
In Table 8.5, the left column lists the criteria to be compared for dominance with the other criteria in the right column. In all, each column contains \( \frac{n(n-1)}{2} \) criteria, where \( n \) is the number of criteria to be compared (in our case three). Then, people asked to check the judgement which indicates the dominance of the criterion in the left column over the corresponding one in its row in the right column. If there is such dominance some position in the set of values to the left of equality is checked. Otherwise equality or position in the right set of values is checked.

Based on the questionnaire responses, a judgment matrix (A) is generated with three rows and three columns, because three criteria are compared at this level. Table 8.6 illustrates the judgement matrix, which populated with randomly selected values for demonstration purposes.

In Table 8.6, for example, in comparing the economic criteria row with the environmental criteria column, a value of 1/2 is assigned. However, when comparing it with socio-technical factors it is preferred, and a value of 3 is entered in the first row. At the same time, the reciprocal value 1/3 is automatically entered in the third row under socio-technical factors. Table 8.6 also shows the priority weight, which gives the relative priority of the criteria measured on a ratio scale. In our case, environmental criteria have the highest priority with 0.5571 (max scale is 1) while socio-technical criteria receive the lowest weight with 0.1226. The consistency ratio of this pairwise comparison exercise is 0.015, which is quite acceptable for AHP calculations.

<table>
<thead>
<tr>
<th>Selected Criteria</th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
<th>Priority Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>1</td>
<td>1/2</td>
<td>3</td>
<td>0.3202</td>
</tr>
<tr>
<td>Environmental</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>0.5571</td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>1/3</td>
<td>1/4</td>
<td>1</td>
<td>0.1226</td>
</tr>
</tbody>
</table>

**Table 8.6**: Judgement Matrix (A) for Criteria
The priority weights are calculated using a matrix algebra approach, developed as part of the AHP method. This method starts by calculating a new normalised matrix \((A_{\text{norm}})\). The priority weight of each criterion is then estimated based on average values of each row in the normalised matrix. An illustrated example is provided below.

1) For each of the columns of the judgement matrix \((A)\), we divide each entry in the column by the sum of the entries in the column. This yields a new normalised matrix \((A_{\text{norm}})\) in which the sum of the entries in each column is 1:

\[
A = \begin{bmatrix} 1.0000 & 0.5000 & 3.0000 \\ 2.0000 & 1.0000 & 4.0000 \\ 0.3333 & 0.2500 & 1.0000 \end{bmatrix}
\]

\[
A_{\text{norm}} = \begin{bmatrix} 0.3000 & 0.2857 & 0.3750 \\ 0.6000 & 0.5714 & 0.5000 \\ 0.1000 & 0.1429 & 0.1250 \end{bmatrix}
\]

2) Priority weight for each criterion is then calculated as the average of the entries in each row of the normalised matrix \((A_{\text{norm}})\):

\[
w_1 = \frac{0.3000 + 0.2857 + 0.3750}{3} = 0.3202
\]

\[
w_2 = \frac{0.6000 + 0.5714 + 0.5000}{3} = 0.5571
\]

\[
w_3 = \frac{0.1000 + 0.1429 + 0.1250}{3} = 0.1226
\]

Hence, the priority weights matrix \((A_w)\) is:

\[
A_w = \begin{bmatrix} 0.3202 \\ 0.5571 \\ 0.1226 \end{bmatrix}
\]

3) Finally, consistency of the pairwise comparison matrix needs to be checked. This procedure starts by calculating the consistency matrix \((A_{\text{cl}})\):

\[
A_{\text{cl}} = A \times A_w = \begin{bmatrix} 1.0000 & 0.5000 & 3.0000 \\ 2.0000 & 1.0000 & 4.0000 \\ 0.3333 & 0.2500 & 1.0000 \end{bmatrix} \times \begin{bmatrix} 0.3202 \\ 0.5571 \\ 0.1226 \end{bmatrix} = \begin{bmatrix} 0.9667 \\ 1.6881 \\ 0.3687 \end{bmatrix}
\]
Then, the ratio of each element of the consistency matrix ($A_{ei}$) to the corresponding weight in the priority weights matrix ($A_w$) is computed and averaged. This process yields the maximum eigenvalue ($\lambda_{\text{max}}$) of the comparison matrix:

$$\lambda_{\text{max}} = \frac{0.9667 + 1.6881 + 0.3687}{3} = 3.0183$$

The consistency index (CI) is calculated by using Equation 8.4:

$$CI = \frac{(\lambda_{\text{max}} - n)}{(n-1)} = \frac{3.0183 - 3}{3 - 1} = 0.00915$$

Finally, the Consistency Index (CI) needs to be compared with the with Random Consistency Index (RI), as depicted in Table 8.4, in order to produce the Consistency Ratio (CR) of the comparison matrix:

$$CR = \frac{CI}{RI} = \frac{0.00915}{0.58} = 0.015$$

This means that this particular comparison matrix has 98.5 % consistency or, in other words, 1.5 % inconsistency.

Following a similar approach, pairwise comparisons of each end-of-life scenarios is performed with respect to each of the criteria. For example, the defined end-of-life scenarios are compared to one another, first relative to economic criteria, then relative to environmental criteria and, finally, relative to socio-technical criteria.

### 8.6.3 Calculating Decision Variables

The next step in the decision making process is the calculation of the criteria indicators, which used to measure performance, impact and progress towards the goal of the decision problem. As previously described, three evaluation methods (LCA, CBA and AHP) have been utilised to calculate three types of distinctly different indicators. Based on the evaluation framework presented previously in Figure 8.1, a calculation process has been developed as illustrated in Figure 8.6.
Figure 8.6: Calculation Process of Decision Variables

Figure 8.6 outlines the main evaluation methods, and the steps followed in each of them in order to calculate the criteria indicators. This calculation process constitutes an integral part of the decision making model for end-of-life shoes.

8.6.3.1 Calculation of Environmental Indicators

Environmental indicators for the various end-of-life scenarios are calculated using the Life Cycle Assessment (LCA) methodology. The calculation process is conducted in four steps, as shown in Figure 8.6, according to the ISO 14040 series of LCA standards.

**Step 1: Formulate Life Cycle Model**

In this step, the goal, scope and functional unit of the assessment are firstly defined. The life cycle model of the alternative end-of-life scenarios is then constructed including definition of the system boundaries for each study.

**Step 2: Calculate Life Cycle Inventory**

Life Cycle Inventory (LCI) results for each scenario are calculated using the SimaPro 7 LCA software package (PRE 2007). Generalised manufacturing data found in commercial
databases, such as the Eco-Invent database, have been utilised in order to conduct the streamlined LCA study for each scenario.

**Step 3: Estimate Potential Environmental Impacts**

In this step, the LCI results for each scenario are further interpreted in term of potential environmental impacts, the so-called life cycle impact assessment (LCIA) phase of LCA. The EDIP 97 impact assessment method is used to estimate the potential environmental impact. As previously defined, sixteen (16) impact category indicators \((IC_{i})\) have been selected to measure the environmental impact of each end-of-life scenario. If the emission of the substance \((s)\) has a magnitude \(Q_{s}\), and if the substance’s equivalency factors for the environmental impact category \((i)\) is called \(EF(i)\), then the indicator’s potential contribution \(IC_{i}(i)_{s}\) to the environmental impact \((i)\) is calculated as shown in Equations 8.5 and 8.6:

\[
IC_{i}(i)_{s} = Q_{s} \times EF(i)_{s} \quad \text{Equation 8.5}
\]

and

\[
IC_{i} = \sum IC_{i}(i)_{s} = \sum (Q_{s} \times EF(i)_{s}) \quad \text{Equation 8.6}
\]

where

- \(IC_{i}\) = impact category indicators
- \(Q_{s}\) = magnitude of substance \((s)\)
- \(EF(i)\) = substance’s equivalency factors for the environmental impact category \((i)\)
- \(IC_{i}(i)_{s}\) = indicator’s potential contribution \(IC_{i}(i)_{s}\) to the environmental impact \((i)\)

Hence, the environmental impact \((EI)\) score of each end-of-life scenario, expressed in eco-indicator points \((mPt)\), is calculated by using Equation 8.7:

\[
EI_{(i)} = \sum_{n} IC_{i} \quad \text{Equation 8.7}
\]

where

- \(IC_{i}\) = Impact Category Indicator \((i)\)
- \(n\) = number of impact category indicators
- \(j\) = number of end-of-life scenarios
Chapter 8

Step 4: Normalise Results

Finally, the environmental impact score \((EI_{(j)})\) of each end-of-life scenario need to be normalised, for consistency purposes, and expressed in unit-free numbers. The normalised environmental impact score \((NEI_{(j)})\) for each scenario is calculated as follows:

i) calculate the reciprocal of each environmental impact score \((REI_{(j)})\):

\[
REI_{(j)} = \frac{1}{EI_{(j)}}
\]

Equation 8.8

ii) divide the reciprocal of each environmental impact score \((REI(j))\) by the sum of all reciprocal scores.

\[
NEI_{(j)} = \frac{REI_{(j)}}{\sum REI_{(j)}}
\]

Equation 8.9

where \(EI_{(j)} = \) environmental impact score of each scenario \((j)\)

8.6.3.2 Calculation of Economic Indicators

Economic indicators for each end-of-life scenario are calculated using the Benefit-to Cost (BCR) ratio approach, a subset of the Cost Benefit Analysis (CBA) method. The Benefit-to-Cost Ratio (BCR) approach has been utilised in this research because it provides a useful method of ranking different alternative options based on their relative ratio. The process of calculating costs and benefits, as previously presented in Figure 8.6, is conducted in four steps:

Step 1: Develop Cost-Benefit Models for EoL Scenarios

Potential revenues and costs for each end-of-life scenario need to be identified. Algebraically each scenario is calculated as follows:
I. Reuse Scenario

The revenue of the reuse scenario \((B_{RE})\) derived from the resale value of the second hand shoe \((B_{resale})\). The costs \((C_{RE})\) arise from collection costs \((C_{col})\), transportation costs \((C_{trans})\), operating costs \((C_{op})\) i.e. sorting, refurbishing and the cost of disposing the residue of the sorting process \((C_{disp})\) due to damaged or unsuitable condition of the second hand shoe. The cost of disposal of residue is based on the type of treatment or disposal facility (e.g., incineration or landfill) used.

\[
B_{RE} = B_{resale}
\]

\[
C_{RE} = C_{col} + C_{trans} + C_{op} + C_{disp}
\]

II. Recycling Scenario (Destructive)

The revenues of the destructive recycling scenario \((B_{RD})\) is a function of the weight of the recovered material \((B_{weight})\) and the market value of the material \((B_{value})\). The costs \((C_{RD})\) arise from collection costs \((C_{col})\), transportation costs \((C_{trans})\) and operating costs \((C_{op})\) i.e. shredding, magnetic separation, recycling process.

\[
B_{RD} = (B_{weight}) \times (B_{value})
\]

\[
C_{RD} = C_{col} + C_{trans} + C_{op}
\]

III. Recycling Scenario (Non-Destructive)

The revenues of the non-destructive recycling scenario \((B_{RND})\) is a function of the weight of the recovered material \((B_{weight})\) and the market value of the material \((B_{value})\). The costs \((C_{RND})\) arise from collection costs \((C_{col})\), transportation costs \((C_{trans})\), disassembly costs \((C_{dis})\) and operating costs \((C_{op})\) i.e. shredding, granulating, magnetic separation, recycling process.

\[
B_{RND} = (B_{weight}) \times (B_{value})
\]

\[
C_{RND} = C_{col} + C_{trans} + C_{dis} + C_{op}
\]

IV. Incineration Scenario

The revenues of the incineration with energy recovery scenario \((B_{ER})\) is a function of the net energy produced \((B_{energy})\) and the unit price of the produced energy \((B_{price})\). The costs
(C<sub>ER</sub>) arise from collection costs (C<sub>col</sub>), transportation costs (C<sub>trans</sub>), operating costs (C<sub>op</sub>) and residue disposal costs (C<sub>disp</sub>) i.e. landfilling of incineration ash.

\[
B_{ER} = (B_{energy}) \times (B_{price})
\]

\[
C_{ER} = C_{col} + C_{trans} + C_{op} + C_{disp}
\]

V. Landfilling Scenario

There are no projected revenues for the landfilling scenario (B<sub>LS</sub>). The costs (C<sub>LS</sub>) arise from collection costs, (C<sub>col</sub>), transportation costs (C<sub>trans</sub>) and disposal costs (C<sub>disp</sub>). Disposal cost (C<sub>disp</sub>) is a function of the weight of the end-of-life shoe (W<sub>shoe</sub>) and the actual cost of landfilling per tonne of material (C<sub>al</sub>) i.e. landfill tax, tipping fee.

\[
B_{LS} = \text{nil}
\]

\[
C_{LS} = C_{col} + C_{trans} + C_{disp} = C_{col} + C_{trans} + [W_{shoe} \times (C_{al})]
\]

Table 8.6 presents a list with all the abbreviations used in the aforementioned cost-benefit models.

**Step 2: Attach Monetary Values to Models**

The second step in the calculation process of economic indicators is to attach monetary values to potential revenues and costs, as previously defined, of each end-of-life scenario for post-consumer shoes. These values can be derived from either literature sources or actual estimations based on “real” data.

**Step 3: Calculate Results**

To calculate the benefit-to-cost ratio (BCR) for each scenario, the equation 8.3 of Section 8.5.2 and the abovementioned cost-benefit models are utilised. However, because BCR is a construct of present values, it also shares many of the same disadvantages of using present values. First of all, the BCR approach requires the selection of a discount rate and, secondly, BCR needs to be further normalised for proper comparison between different alternatives. However, in this particular research, there is no need for future economic flows to be discounted. Therefore, this thesis assumes that the discount rate is zero (s = 0). Also, it is assumed that the time period of the analysis is over one year (t = 1).
<table>
<thead>
<tr>
<th>Reuse Scenario</th>
<th>Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{RE} = B_{resale}$</td>
<td>$B_{resale}$: revenue of reuse scenario</td>
</tr>
<tr>
<td>$C_{RE} = C_{col} + C_{trans} + C_{op} + C_{disp}$</td>
<td>$C_{RE}$: costs of reuse scenario</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recycling (destructive) Scenario</th>
<th>Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{RD} = (B_{weight}) \times (B_{value})$</td>
<td>$B_{RD}$: revenue of destructive recycling scenario</td>
</tr>
<tr>
<td>$C_{RD} = C_{col} + C_{trans} + C_{op}$</td>
<td>$B_{weight}$: weight of recovered material</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recycling (non-destructive) Scenario</th>
<th>Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{RND} = (B_{weight}) \times (B_{value})$</td>
<td>$B_{RND}$: revenue of non-destructive recycling scenario</td>
</tr>
<tr>
<td>$C_{RND} = C_{col} + C_{trans} + C_{op}$</td>
<td>$B_{weight}$: weight of recovered material</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Incineration Scenario</th>
<th>Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{ER} = (B_{energy}) \times (B_{price})$</td>
<td>$B_{ER}$: revenue of incineration scenario</td>
</tr>
<tr>
<td>$C_{ER} = C_{col} + C_{trans} + C_{op} + C_{disp}$</td>
<td>$B_{energy}$: net energy produced</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Landfilling Scenario</th>
<th>Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{LS} = nil$</td>
<td>$B_{LS}$: revenue of landfilling scenario</td>
</tr>
<tr>
<td>$C_{LS} = C_{col} + C_{trans} + C_{disp} = C_{col} + C_{trans} + (W_{shoe}) \times (C_{at})$</td>
<td>$C_{LS}$: costs of landfilling scenario</td>
</tr>
</tbody>
</table>

Table 8.6: List of Abbreviations for Cost-Benefit Models
Hence, equation 8.3 for calculating the Benefit/Cost Ratio (BCR) is transformed as follows:

\[
BCR_j = \frac{\sum B_i / (1 + s)^t}{\sum C_i / (1 + s)^t} = \frac{\sum B}{\sum C}
\]

\text{Equation 8.10}

Where:
- \( B \) = benefits
- \( C \) = costs
- \( j \) = end-of-life scenarios
- \( s \) = discount rate (\( s = 0 \))
- \( t \) = time period (\( t = 1 \))

Based on the Equation 8.10, Benefit/Cost Ratio for each end-of-life scenario is calculated using the following formulas:

I. Reuse Benefit/Cost Ratio (BCR\textsubscript{RE})

\[
BCR_{RE} = \frac{\sum B_{RE}}{\sum C_{RE}} = \frac{B_{\text{reuse}}}{C_{\text{col}} + C_{\text{trans}} + C_{\text{op}} + C_{\text{disp}}}
\]

\text{Equation 8.11}

II. Recycling (Destructive) Benefit/Cost Ratio (BCR\textsubscript{RD})

\[
BCR_{RD} = \frac{\sum B_{RD}}{\sum C_{RD}} = \frac{(B_{\text{weight}}) \times (B_{\text{value}})}{C_{\text{col}} + C_{\text{trans}} + C_{\text{op}}}
\]

\text{Equation 8.12}

III. Recycling (Non-Destructive) Benefit/Cost Ratio (BCR\textsubscript{RND})

\[
BCR_{RND} = \frac{\sum B_{RND}}{\sum C_{RND}} = \frac{(B_{\text{weight}}) \times (B_{\text{value}})}{C_{\text{col}} + C_{\text{trans}} + C_{\text{dis}} + C_{\text{op}}}
\]

\text{Equation 8.13}

IV. Incineration Benefit/Cost Ratio (BCR\textsubscript{ER})
**Chapter 8**

### V. Landfilling Benefit/Cost Ratio (BCRLS)

\[
BCRLS = \sum \frac{B_{ER}}{C_{ER}} = \frac{(B_{energy}) \times (B_{price})}{C_{col} + C_{trans} + C_{rep} + C_{disp}}
\]

*Equation 8.14*

**Step 4: Normalise Results**

The benefit-to-cost ratio (BCR\(_j\)) for each shoe end-of-life scenario \((j)\) is then need to be normalised for consistency purposes. The Normalised Benefit/Cost Ratio \((NBCR\(_j\))\) is calculated by dividing each Benefit/Cost Ratio by the sum of all Benefit/Cost ratios:

\[
NBCR\(_j\) = \frac{BCR\(_j\)}{\sum_{j} BCR\(_j\)}
\]

*Equation 8.16*

where

- **NBCR\(_j\) = Normalised Benefit/Cost Ratio for each scenario**
- **BCR\(_j\) = Benefit/Cost Ratio for each scenario**
- **\(j\) = number of end-of-life scenarios**

#### 8.6.3.3 Calculation of Socio-Technical Indicators

The socio-technical indicators are calculated by applying the AHP method in a local scale. In fact, a micro-AHP analysis is performed to calculate the indicators weights, as part of a macro-AHP analysis for the overall decision problem. In this respect, a series of pairwise comparisons are initially performed in order to identify the weight of each indicator and then compared to each other with respect to each end-of-life scenario. The final result is a score (composite weight) for each end-of-life scenario with respect to the socio-technical indicators. The pairwise comparison exercise is carried out in a similar way as previously described in Section 8.6.2. Table 8.7 illustrates a questionnaire to obtain stakeholders judgements for the predefined socio-technical indicators. Based on the questionnaire responses, a judgment matrix is generated with four rows and four columns. Table 8.8 illustrates the generated judgement matrix including the priority weight of each indicator. The priority weight is again calculated using a the AHP method, as previously illustrated in Section 8.5.2.
It should be mentioned that Table 8.8 has populated with randomly selected values for demonstration purposes. At this level of AHP analysis, the indicators also need to be compared with respect to how much better one is than the other in satisfying each end-of-life scenario. For this reason, four 6x6 pairwise comparison matrices are constructed since there are four indicators and six end-of-life scenarios to be pairwise compared.

Table 8.9 presents the pairwise comparison matrix of end-of-life scenarios and their priorities with respect to market pressures. Once again, the table is populated with randomly selected values for demonstration purposes. Similar tables are constructed for the other three social-technical indicators i.e. Public Opinion, Technical Feasibility and Compliance with Legislation.

Table 8.7: AHP Questionnaire for Social-Technical Indicators

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Absolute</th>
<th>Very Strong</th>
<th>Strong</th>
<th>Weak</th>
<th>Equal</th>
<th>Weak</th>
<th>Strong</th>
<th>Very Strong</th>
<th>Absolute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market Pressures</td>
<td>Public Opinion</td>
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<td></td>
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<tr>
<td>Market Pressures</td>
<td>Technical Feasibility</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Market Pressures</td>
<td>Compliance with Legislation</td>
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<tr>
<td>Public Opinion</td>
<td>Technical Feasibility</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public Opinion</td>
<td>Compliance with Legislation</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical Feasibility</td>
<td>Compliance with Legislation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.8: Pairwise Comparison Matrix for Socio-Technical Indicators (Level 1)
Finally, the priority weights of each scenario with respect to socio-technical indicators need to be synthesised in order to calculate the composite weights of the local AHP analysis. The six end-of-life scenarios are presented in a matrix with respect to each social-technical indicator as shown in Table 8.10. The composite weight is calculated by multiply each column of scenario by the priority of the corresponding criterion and add across each row. This will give us the composite weight of the end-of-life options.

<table>
<thead>
<tr>
<th>Market Pressures</th>
<th>Reuse</th>
<th>Recycling (Destructive)</th>
<th>Recycling (Non-destructive)</th>
<th>Incineration</th>
<th>Landfilling</th>
<th>Priority Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse</td>
<td>1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>5.00</td>
<td>8.00</td>
<td>0.2461</td>
</tr>
<tr>
<td>Recycling (Destructive)</td>
<td>2.00</td>
<td>1.00</td>
<td>0.50</td>
<td>4.00</td>
<td>7.00</td>
<td>0.2669</td>
</tr>
<tr>
<td>Recycling (Non-Destructive)</td>
<td>2.00</td>
<td>2.00</td>
<td>1.00</td>
<td>4.00</td>
<td>8.00</td>
<td>0.3214</td>
</tr>
<tr>
<td>Incineration</td>
<td>0.20</td>
<td>0.25</td>
<td>0.25</td>
<td>1.00</td>
<td>5.00</td>
<td>0.0909</td>
</tr>
<tr>
<td>Landfilling</td>
<td>0.13</td>
<td>0.14</td>
<td>0.13</td>
<td>0.20</td>
<td>1.00</td>
<td>0.0223</td>
</tr>
</tbody>
</table>

Table 8.9: Pairwise Comparison Matrix for Social-Technical Indicators (Level 2)

<table>
<thead>
<tr>
<th>End-of-Life Scenarios</th>
<th>Technical Feasibility</th>
<th>Public Opinion</th>
<th>Market Pressures</th>
<th>Compliance with Legislation</th>
<th>Composite Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.16</td>
<td>0.18</td>
<td>0.26</td>
<td>0.26</td>
<td>0.2415</td>
</tr>
<tr>
<td>Recycling Scenario (destructive)</td>
<td>0.44</td>
<td>0.33</td>
<td>0.33</td>
<td>0.32</td>
<td>0.3353</td>
</tr>
<tr>
<td>Recycling Scenario (non-destructive)</td>
<td>0.23</td>
<td>0.37</td>
<td>0.26</td>
<td>0.29</td>
<td>0.2415</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.08</td>
<td>0.09</td>
<td>0.11</td>
<td>0.09</td>
<td>0.0969</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.0381</td>
</tr>
</tbody>
</table>

Table 8.10: Composite Weights of Socio-Technical Indicators
8.6.4 Consistency Check

A consistency check is necessary to be performed before synthesising the overall priority weights of the alternative options. This task ensures that the various pairwise comparisons of the alternatives, criteria and indicators are consistent with the recommended values of the Saaty scale (Saaty 1996). This is performed by calculating the consistency index (CI) of each pairwise comparison matrix and compare it to the randomly generated index (RI), as previously illustrated in Section 8.6.2.

8.6.5 Synthesise Priorities

The final step in the decision making process is to synthesise the overall results in order to estimate the preference of each end-of-life option with respect to the defined criteria (economic, environmental and socio-technical). This is performed by calculating the global priority vector ($W_j$) of each end-of-life scenario ($j$). The global priority vector is calculated by multiply each column of priority weight of decision criteria ($P_i$) by the priority weight of the corresponding scenarios ($K_{ij}$) and then add across each row, as shown in equation 8.17:

$$W_j = \sum (P_i \times K_{ij})$$  \hspace{1cm} \text{Equation 8.17}

where

$W_j$ = global priority vector of end-of-life scenario  
$P_i$ = priority weight of decision criterion with respect to the overall decision making goal  
$K_{ij}$ = priority weight of end-of-life scenario with respect to decision criterion  
i = decision criteria  
j = end-of-life scenarios

For demonstration purposes, the global priority weight of each end-of-life scenario ($W_j$) is presented in Table 8.11. This table synthesises the results of both the priority weights of decision criteria with respect to the overall goal ($P_i$), and the priority weights of scenarios with respect to decision criteria ($K_{ij}$). The global priority weight ($W_j$) indicates the overall significance of each end-of-life treatment option after considering the importance of the
decision variables. The graphical representation of the aggregated results for each end-of-life scenario is shown in Figure 8.7. This figure indicates that the destructive recycling scenario (shedding the shoe as a whole) is the most preferable option for this specific type of shoe, whereas disposal scenario (landfilling) is the least.

<table>
<thead>
<tr>
<th>Decision Criteria</th>
<th>Environmental</th>
<th>Economic</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority Weight of Decision Criteria (Pj)</td>
<td>0.5571</td>
<td>0.3202</td>
<td>0.1226</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>End-of-life Scenarios</th>
<th>Priority Weight of End-of-Life Scenarios with respect to Criteria (Kj)</th>
<th>Global Priority Weight (Wj)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.2656 0.3200 0.2415</td>
<td>0.2801</td>
</tr>
<tr>
<td>Recycling Scenario (Destructive)</td>
<td>0.3367 0.2667 0.3353</td>
<td>0.3141</td>
</tr>
<tr>
<td>Recycling Scenario (Non-Destructive)</td>
<td>0.3351 0.2800 0.2415</td>
<td>0.3060</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.0351 0.1333 0.0969</td>
<td>0.0741</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.0273 0.0000 0.0381</td>
<td>0.0199</td>
</tr>
</tbody>
</table>

Table 8.11: Global Priority Weight of End-of-Life Scenarios for Shoes

Figure 8.7: Graphical Representation of Aggregated Results
However, the priority weight given to each decision criterion clearly influence the final results. If, for example, an end-of-life management option received the least weight with respect to most of the criteria, then it will most likely be the least preferable option, as in the case of disposal. Based on the aggregated results, the priority weight given to environmental criteria (0.5571) as the most important factor in evaluating the end-of-life management options corresponds to the high composite weight given to reuse and recycling scenarios.
9 End-of-Life Decision Support Tool for the Footwear Sector

9.1 Introduction

This chapter highlights the requirements and discusses the design and specification of an end-of-life decision support tool to facilitate the activities within the proposed multi-criteria decision making model for post-consumer shoes. The chapter begins by outlining the system architecture of the proposed decision support tool while the main sections of the chapter describe the development of the multi-criteria decision making engine and its associated computational models.

9.2 End-of-Life Footwear Decision Support Tool

The determination of the most suitable (in environmental, economic and socio-technical terms) manner in which to treat post-consumer shoe waste, as described in Chapter 7 and 8, is a complex process involving the consideration of a wide range of materials, construction methods and recycling processes. Therefore, this research has designed and specified a prototype end-of-life footwear decision support tool (EF-DST) to support the implementation of the proposed ETS methodology as well as to facilitate the decision making model for identifying optimal treatment options for selected ranges of post-consumer shoes. The prototype software tool has three main modules, namely:

- a presentation module
- a database module
- a assessment module
The software tool was developed using the commonly adopted three-tier architecture (Rahimifard 2004). The presentation module acts as a user interface environment to receive and control user's input as well as to present the output. The database module provides a data repository in which information is stored and retrieved while the assessment module comprise the assessment/logic element of the system that support the decision making process. These modules work interactively to support the key decisions selecting the most appropriate treatment option for post-consumer shoes, as depicted in Figure 9.1.

Figure 9.1: System Architecture of EF-DST
9.2.1 Presentation Module

The user interface environment has been developed in Visual Basic for Applications (VBA) and integrated with a MS-Access environment. The presentation module consists of a series of forms that guide the user in pursuing the decision process. A welcome page is the first screen that appears in the EF-DST, as presented in Figure 9.2. Then a password protected login process is required to access the main user interface of the tool, as depicted in Figure 9.3. Figure 9.4 illustrates the main interface of the software tool, which controls and integrates the major components of the proposed system and contains seven options to indicate the user selection. This main menu includes most of the major functions of the tool, which lead to further functions following the steps in the first phase of the ETS methodology, as depicted in Figures 9.5, 9.6 and 9.7.

Figure 9.2: EF-DST - Welcome Page

Figure 9.3: EF-DSTS -Login Screen
Figure 9.4: EF-DST- Main Interface Screen

Figure 9.5: EF-DST- Product Characterisation (Level 1)

Figure 9.6: EF-DST- Product Characterisation (Level 2 and 3)
9.2.2 Database Module

The database module provides a backend database, comprising both data sets and the database tables that manages and provides access to the data. These tables provide the knowledge that required for solving specific aspects of the problem domain, and have referred to as the knowledge-based element of the proposed software tool.

![Database Model Structure](image)

**Figure 9.7:** EF-DST- Product Characterisation (Level 4)

**Figure 9.8:** Database Model Structure
The input data is managed by the user, via the user interface, and the output is prepared by the assessment module of the software tool. The core database has been developed on commercial software (MS-Access) and consists of 16 tables in total. A pictorial representation of the database model outlining these tables, is illustrated in Figure 9.8.

### 9.2.3 Assessment Module

The third module of the EF-DST software comprises the assessment element, referred to as the logic of the software tool that supports the decision making process. As previously described in Chapter 8, each end-of-life scenario is assessed in terms of its environmental, economical, and socio-technical criteria. Three evaluation methods have been utilised to calculate the value of the pre-defined criteria, namely Life Cycle Assessment (LCA) for environmental criteria, Cost Benefit Analysis (CBA) for economic criteria and Analytic Hierarchy Process (AHP) for socio-technical criteria. In addition, AHP has also been employed as the main multi-criteria decision making method in order to construct the basic framework for analysing, calculating and synthesising the criteria into a final score. The assessment process in the EF-DST software tool has been described previously in Chapter 8 and graphically illustrated in Figure 8.1.

However, one of the novel contributions of this research is the design and implementation of a computational method to automatically take into account the various considerations, related to the three abovementioned criteria, in order to identify the best end-of-life option for post-consumer shoes. This is achieved through the development of a multi-criteria decision making engine, an integral part of the proposed EF-DST software tool. The remain section of this chapter describes the development of the MCDM engine.

### 9.2.4 MCDM Engine

The MCDM engine is the proposed solution used to calculate and synthesise the scores of the environmental, economic and socio-technical criteria. The MCDM engine comprises four main computational models, as depicted in Figure 9.9, namely LCA model, Cost/Benefit model, micro-AHP model and macro-AHP model.
Environmental Assessment (LCA Model)

Economic Assessment (Cost/Benefit Model)

Technical Assessment (micro-AHP Model)

Global Assessment (macro-AHP Model)

Figure 9.9: Structure of the MCDM Engine
Chapter 9

It should be noted that the AHP technique has been adopted in two levels, namely micro and macro level. The micro-AHP model has been constructed to assess socio-technical criteria only while the macro-AHP model used to integrate (global assessment) the environmental, economic and socio-technical scores into a final solution. The MCDM engine has been developed by combining two commercially available software packages, SimaPro for the development of LCA model and MS-Excel for cost/benefit and AHP models. These models are described in more details below.

9.2.4.1 LCA Model

Initially, an LCA study is performed to calculate the environmental indicators of various end-of-life scenarios for post-consumer shoes using SimaPro 7 LCA software package (PRE 2007). An example of a streamlined LCA study for a particular type of post-consumer shoe is presented in Appendix IV. Then, the LCA model is developed in MS-Excel following the steps previously described in Section 8.6.3.1. The process is conducted in three steps. Firstly, the environmental impact score (EI) for each end-of-life scenario are presented in Figure 9.10.

| Environmental Assessment of End-of-Life Scenarios for Post-Consumer Shoes |
|-------------------------------|---------------|
| **Step 1: Calculate Environmental Impact Score (EI)** |
| **Reuse Scenario**            |               |
| $E_{EI} = 25,900$             |               |
| **Recycling Scenario 1**      |               |
| $E_{EI1} = 23,200$            |               |
| **Recycling Scenario 2**      |               |
| $E_{EI2} = 23,300$            |               |
| **Incineration Scenario**     |               |
| $E_{EI3} = 222,000$           |               |
| **Landfilling Scenario**      |               |
| $E_{EI5} = 283,000$           |               |

**Figure 9.10:** Calculate Environmental Impact score (EI)
Then, the reciprocal environmental impact score (REI) and the normalised environmental impact score (NEI) are calculated as shown in Figures 9.11 and 9.12.

**Environmental Assessment of End-of-Life Scenarios for Post-Consumer Shoes**

**Step 2: Calculate the Reciprocal Environmental Impact Score (REI)**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>REI Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.0386</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.0431</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.0429</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.0045</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.0035</td>
</tr>
</tbody>
</table>

**Figure 9.11: Calculate Reciprocal Environmental Impact score (REI)**

**Step 3: Calculate Normalised Environmental Impact Score (NEI)**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NEI Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.2910</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.3249</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.3235</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.0340</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.0266</td>
</tr>
</tbody>
</table>

**Figure 9.12: Calculate Normalised Environmental Impact score (NEI)**
9.2.4.2 Cost/Benefit Model

The cost/benefit model of the various end-of-life scenarios is also developed in MS-Excel following the steps previously described in Section 8.6.3.2. The calculation process is conducted in three steps. Firstly, the cost/benefit models are constructed for each end-of-life scenario, as shown in Figure 9.13. Then, the cost/benefit ratio, as presented in Figure 9.14, is calculated. Finally, the normalised cost/benefit ratio is computed, which gives the economic score (preference) of each end-of-life scenario, as depicted in Figure 9.15.

![Economic Assessment of End-of-Life Scenarios for Post-Consumer Shoes](Figure 9.13: Construct Cost/Benefit Models)
Economic Assessment of End-of-Life Scenarios for Post-Consumer Shoes

**Step 2: Calculate Cost/Benefit Ratio**

<table>
<thead>
<tr>
<th>Scenario</th>
<th><strong>BCR</strong></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td></td>
<td>2.0000</td>
</tr>
<tr>
<td>Recycling Scenario (destructive)</td>
<td></td>
<td>1.6600</td>
</tr>
<tr>
<td>Recycling Scenario (non-destructive)</td>
<td></td>
<td>1.7500</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td></td>
<td>0.8300</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td></td>
<td>0.0000</td>
</tr>
</tbody>
</table>

**Figure 9.14: Calculate Cost/Benefit Ratio**

**Step 3: Normalise Results**

<table>
<thead>
<tr>
<th>Scenario</th>
<th><strong>NBCR</strong></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td></td>
<td>0.4454</td>
</tr>
<tr>
<td>Recycling Scenario (destructive)</td>
<td></td>
<td>0.3697</td>
</tr>
<tr>
<td>Recycling Scenario (non-destructive)</td>
<td></td>
<td>0.3898</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td></td>
<td>0.1849</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td></td>
<td>0.0000</td>
</tr>
</tbody>
</table>

**Figure 9.15: Normalise Cost/Benefit Results**
9.2.4.3 micro-AHP Model

The micro-AHP model calculates the socio-technical score (composite weight) of each end-of-life scenario with respect to the pre-defined socio-technical indicators. The micro-AHP model is developed in MS-Excel following the process described in Section 8.6.3.3. The calculation process requires a three-level analysis. At the first level, pairwise comparison is performed among the socio-technical criteria and the priority weight is calculated, as depicted in Figure 9.16. A consistency check is also performed at this level to make sure that the various pairwise comparisons of the indicators are consistent with the recommended values of the Saaty scale.

<table>
<thead>
<tr>
<th>micro-AHP: Calculate Socio-Technical Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level 1: Pairwise Comparison among Socio-Technical Indicators</strong></td>
</tr>
<tr>
<td><strong>STEP 1</strong> Construction of Judgment Matrix</td>
</tr>
<tr>
<td>Market Pressures</td>
</tr>
<tr>
<td>Market Pressures</td>
</tr>
<tr>
<td>Public Opinion</td>
</tr>
<tr>
<td>Technical Feasibility</td>
</tr>
<tr>
<td>Compliance with Legislation</td>
</tr>
</tbody>
</table>

| **STEP 2** Construction of Normalised Matrix |
| Market Pressures | Public Opinion | Technical Feasibility | Compliance with Legislation |
| Market Pressures | 0.0714 | 0.0769 | 0.0909 | 0.0476 |
| Public Opinion | 0.1429 | 0.1536 | 0.2273 | 0.0962 |
| Technical Feasibility | 0.3671 | 0.3077 | 0.4546 | 0.5714 |
| Compliance with Legislation | 0.4266 | 0.4615 | 0.2273 | 0.2957 |

| **STEP 3** Calculate Priority Weights |
| Market Pressures | 0.0717 |
| Public Opinion | 0.1546 |
| Technical Feasibility | 0.4227 |
| Compliance with Legislation | 0.3636 |

| **STEP 4** Consistency Check: Calculate the Product |
| Market Pressures | 0.2921 |
| Public Opinion | 0.6265 |
| Technical Feasibility | 1.7525 |
| Compliance with Legislation | 1.4269 |

| Consistency Check: Calculate the Ratio |
| Market Pressures | 4.0731 |
| Public Opinion | 4.0472 |
| Technical Feasibility | 4.2405 |
| Compliance with Legislation | 4.1533 |

| Consistency Check: Calculate Consistency Index |
| CI | 0.042637309 |
| RI | 0.5 |
| CRI | 0.085274677 |

**Figure 9.16:** micro-AHP (level 1)
It should be mentioned that a fully automated version of the micro-AHP model has also been developed as part of this research. This program has been developed in MS-Excel and written in Visual Basic for Application (VBA). The program performs the calculations through the various stages of the micro-AHP model. The automated version of the micro-AHP tool is presented in Appendix I.

At the next level of the micro-AHP model, the indicators need to be compared with respect to how much better one is than the other in satisfying each end-of-life scenario. Hence, a series of pairwise comparisons are performed among the end-of-life scenarios with respect to the various indicators. Based on these comparison matrices, the priority weight of each scenario is calculated, as shown in Figure 9.17. Finally, the priority weights of scenarios with respect to the indicators are synthesised in order to calculate the composite weights of each scenario, as illustrated in Figure 9.18.

<table>
<thead>
<tr>
<th><strong>Micro-AHP: Calculate Socio-Technical Criteria</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level 2: Calculate Decision Variables</strong></td>
</tr>
<tr>
<td><strong>Market Pressures</strong></td>
</tr>
<tr>
<td><strong>Reuse Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.3151</td>
</tr>
<tr>
<td><strong>Recycling Scenario</strong></td>
</tr>
<tr>
<td>(Destructive)</td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.3137</td>
</tr>
<tr>
<td><strong>Recycling Scenario</strong></td>
</tr>
<tr>
<td>(Non-Destructive)</td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.3124</td>
</tr>
<tr>
<td><strong>Incineration Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.0329</td>
</tr>
<tr>
<td><strong>Landfilling Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.0256</td>
</tr>
<tr>
<td><strong>Technical Feasibility</strong></td>
</tr>
<tr>
<td><strong>Reuse Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.3151</td>
</tr>
<tr>
<td><strong>Recycling Scenario</strong></td>
</tr>
<tr>
<td>(Destructive)</td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.3137</td>
</tr>
<tr>
<td><strong>Recycling Scenario</strong></td>
</tr>
<tr>
<td>(Non-Destructive)</td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.3124</td>
</tr>
<tr>
<td><strong>Incineration Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.0329</td>
</tr>
<tr>
<td><strong>Landfilling Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.0000</td>
</tr>
<tr>
<td><strong>Public Opinion</strong></td>
</tr>
<tr>
<td><strong>Reuse Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.315</td>
</tr>
<tr>
<td><strong>Recycling Scenario</strong></td>
</tr>
<tr>
<td>(Destructive)</td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.314</td>
</tr>
<tr>
<td><strong>Recycling Scenario</strong></td>
</tr>
<tr>
<td>(Non-Destructive)</td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.000</td>
</tr>
<tr>
<td><strong>Incineration Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.033</td>
</tr>
<tr>
<td><strong>Landfilling Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.026</td>
</tr>
<tr>
<td><strong>Compliance with Legislation</strong></td>
</tr>
<tr>
<td><strong>Reuse Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.3151</td>
</tr>
<tr>
<td><strong>Recycling Scenario</strong></td>
</tr>
<tr>
<td>(Destructive)</td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.3137</td>
</tr>
<tr>
<td><strong>Recycling Scenario</strong></td>
</tr>
<tr>
<td>(Non-Destructive)</td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.3124</td>
</tr>
<tr>
<td><strong>Incineration Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.0329</td>
</tr>
<tr>
<td><strong>Landfilling Scenario</strong></td>
</tr>
<tr>
<td>Priority Weight</td>
</tr>
<tr>
<td>0.0000</td>
</tr>
</tbody>
</table>

**Figure 9.17:** micro-AHP (level 2)
Chapter 9

micro-AHP: Calculate Socio-Technical Criteria

Level 3: Determining Composite Weigh of Socio-Technical Criteria

<table>
<thead>
<tr>
<th>STEP 1: Synthesise the Overall Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market Pressures</td>
</tr>
<tr>
<td>0.0717</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse</td>
<td>0.3151</td>
</tr>
<tr>
<td>Recycling (Destructive)</td>
<td>0.3137</td>
</tr>
<tr>
<td>Recycling (Non-Destructive)</td>
<td>0.3124</td>
</tr>
<tr>
<td>Incineration</td>
<td>0.0000</td>
</tr>
<tr>
<td>Landfilling</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STEP 2: Calculate the Global Priority Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse</td>
</tr>
<tr>
<td>0.3151</td>
</tr>
<tr>
<td>Recycling (Destructive)</td>
</tr>
<tr>
<td>0.3137</td>
</tr>
<tr>
<td>Recycling (Non-Destructive)</td>
</tr>
<tr>
<td>0.3124</td>
</tr>
<tr>
<td>Incineration</td>
</tr>
<tr>
<td>0.0000</td>
</tr>
<tr>
<td>Landfilling</td>
</tr>
<tr>
<td>0.0000</td>
</tr>
</tbody>
</table>

Figure 9.18: micro-AHP (level 3)

9.2.4.4 macro-AHP Model

The macro-AHP model follows a similar approach to the micro-AHP model. First, a pairwise comparison process is performed with respect to the decision criteria, namely environmental, economic and socio-technical. Then, the priority weights of each scenario are calculated, including the calculation of the consistency index. At the next stage, the results from the various evaluation methods (LCA, CBA and AHP) are combined and synthesised in order to identify the best end-of-life option for the selected post-consumer shoe. The three levels of the macro-AHP model are presented in Figures 9.19, 9.20 and 9.21. Once again, a fully automated version of the macro-AHP model has also been developed as part of this research. However, this program automates only the first level of the proposed macro-AHP model. The automated version of the macro-AHP model (Level 1) is described in Appendix II.
macro-AHP: Selection of End-of-Life Options for Post-Consumer Shoes

**Level 1: Pairwise Comparison among Criteria**

**STEP 1** Construction of Judgment Matrix

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>1.0000</td>
<td>0.5000</td>
<td>3.0000</td>
</tr>
<tr>
<td>Environmental</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>0.3333</td>
<td>0.2500</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

**Step 2** Construction of Normalised Matrix

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>0.3000</td>
<td>0.2667</td>
<td>0.3333</td>
</tr>
<tr>
<td>Environmental</td>
<td>0.6000</td>
<td>0.5714</td>
<td>0.6667</td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>0.1000</td>
<td>0.1429</td>
<td>0.1333</td>
</tr>
</tbody>
</table>

**STEP 3** Calculate Priority Weights

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>0.3202</td>
</tr>
<tr>
<td>Environmental</td>
<td>0.5271</td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>0.1225</td>
</tr>
</tbody>
</table>

**STEP 4** Consistency Check: Calculate the Product

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>0.9867</td>
</tr>
<tr>
<td>Environmental</td>
<td>1.6881</td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>0.3607</td>
</tr>
</tbody>
</table>

Consistency Check: Calculate the Ratio

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>3.0118</td>
</tr>
<tr>
<td>Environmental</td>
<td>3.0299</td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>3.0966</td>
</tr>
</tbody>
</table>

Consistency Check: Calculate Consistency Index

- CI = 0.000162397
- RI = 0.9
- CR = 0.015797238 < 0.10

**Figure 9.19:** macro-AHP (level 1)

**Level 2: Calculate Decision Variables**

**Economic Criteria**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Priority Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse</td>
<td>0.3200</td>
</tr>
<tr>
<td>Recycling (Destructive)</td>
<td>0.2667</td>
</tr>
<tr>
<td>Recycling (Constructive)</td>
<td>0.2800</td>
</tr>
<tr>
<td>Incineration</td>
<td>0.1333</td>
</tr>
<tr>
<td>Landfilling</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

**Environmental Criteria**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Priority Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse</td>
<td>0.2656</td>
</tr>
<tr>
<td>Recycling (Destructive)</td>
<td>0.3367</td>
</tr>
<tr>
<td>Recycling (Constructive)</td>
<td>0.3367</td>
</tr>
<tr>
<td>Incineration</td>
<td>0.0351</td>
</tr>
<tr>
<td>Landfilling</td>
<td>0.0273</td>
</tr>
</tbody>
</table>

**Socio-Technical Criteria**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Priority Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse</td>
<td>0.2415</td>
</tr>
<tr>
<td>Recycling (Destructive)</td>
<td>0.3353</td>
</tr>
<tr>
<td>Recycling (Constructive)</td>
<td>0.2415</td>
</tr>
<tr>
<td>Incineration</td>
<td>0.0969</td>
</tr>
<tr>
<td>Landfilling</td>
<td>0.0381</td>
</tr>
</tbody>
</table>

**Figure 9.20:** macro-AHP (level 2)
Chapter 9

macro-AHP: Selection of End-of-Life Options for Post-Consumer Shoes

Level 3: Determining Best End-of-Life Option

<table>
<thead>
<tr>
<th></th>
<th>Economic Criteria</th>
<th>Environmental Criteria</th>
<th>Socio-Technical Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.300</td>
<td>0.2666</td>
<td>0.2415</td>
</tr>
<tr>
<td>Recycling Scenario (Destructive)</td>
<td>0.2687</td>
<td>0.3307</td>
<td>0.3393</td>
</tr>
<tr>
<td>Recycling Scenario (Non-Destructive)</td>
<td>0.2000</td>
<td>0.3351</td>
<td>0.2415</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.1333</td>
<td>0.3361</td>
<td>0.0969</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.0000</td>
<td>0.0073</td>
<td>0.0911</td>
</tr>
</tbody>
</table>

Figure 9.21: macro-AHP (level 3)
10 Case Studies

10.1 Introduction

This chapter utilises two case studies to demonstrate the various stages of the ETS methodology and its associated decision support tool described within this thesis. The chapter begins by providing an overview of how the ETS methodology will be evaluated by these case studies. Then, two case studies are presented, each demonstrating the recovery and recycling of two distinctly different types of shoes.

10.2 An Overview of the Case Studies

Two types of post-consumer shoes have been utilised in the research as case studies. The first case study shoe is a typical casual footwear for men, mainly used for leisure activities. A simple construction process has been utilised to produce this type of footwear with leather and rubber as the main materials. In contrast, the second case study shoe is a women’s fashion boot with a more complex construction and a more extensive components and materials list.

In keeping with the structure of the ETS methodology, as outlined in Chapter 7, the following phases are applied in both case studies:

i) Product characterisation
ii) End-of-life scenario definition
iii) End-of-life scenario assessment
iv) Recovery value chain identification
10.3 Case Study 1: Men’s Casual Shoe

The shoe under consideration in the first case study is a men’s casual shoe (MCS) which has been selected because it is mainly made of leather and rubber, two of the most common materials used in footwear industry. The MCS case study shoe is depicted in Figure 10.1.

10.3.1 Product Characterisation of MCS Case Study Shoe

The first phase in applying the ETS methodology is to identify the main characteristics of the post-consumer shoe. The product characterisation phase is performed in four levels, also referred to as screening levels.

10.3.1.1 1st Level Screening: Basic Characteristics

This screening level determines the basic characteristics of the selected shoe. These are the condition (e.g. suitable or unsuitable for reuse), the value (based on style and brand), the weight and the type of the post-consumer shoe. These characteristics are depicted in Table 10.1. It should be mentioned that the screening process to identify the basic characteristics is performed visually. For example, the case study shoe is considered to be in a relatively good condition, no major damage identified, which means that it can be easily refurbished and then reused.

Figure 10.1: Picture of Men’s Casual Shoe
Chapter 10

<table>
<thead>
<tr>
<th>Shoe Basic Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Men’s Casual Shoes</td>
</tr>
<tr>
<td>Condition</td>
<td>Good</td>
</tr>
<tr>
<td>Value</td>
<td>High</td>
</tr>
<tr>
<td>Weight</td>
<td>350g</td>
</tr>
</tbody>
</table>

Table 10.1: Basic Characteristics of the Men’s Casual Shoe

The value of the shoe is considered to be high because it is produced by a well-known footwear brand (French Connection UK), which represents the higher end-price range of the footwear market. Finally, the shoe has been weighted (350g / single pair of shoe) and its type has been identified (men’s casual shoe).

10.3.1.2 2nd Level Screening: Construction Method

At this screening level, the shoe construction method, and the possible use of adhesives, is identified. This case study shoe is build using the stitchdown construction method. In this method the upper part of the shoe is stretched over the last, folded and glued to the insole. Then the various parts are stitched together, using a special stitching machine. It should be mentioned that this screening process has also been performed visually, which means that a good practical understanding of various footwear construction techniques is required by the assessor.

10.3.1.3 3rd Level Screening: Parts and Components

This level of screening identifies the major components and parts of the shoe. A physical disassembly investigation has been performed to determine the exact parts and components used in the MCS shoe, as depicted in Figures 10.2. A particular emphasis has been given on the identification of components and parts that might have an effect on the choice of a potential recycling process. For example, a physical assessment of the case study shoe identified that it does not contain a steel shank and
eyelets which means that destructive recycling of the shoe as a whole (shredding) is a feasible end-of-life management option.

Figure 10.2: Disassembly of the Men’s Casual Shoe
A list of the major parts and components of the MCS shoes is presented in Table 10.2. It should be mentioned that this screening process was also conducted as means of understanding the ease of disassembly for this particular type of shoe.

10.3.1.4 4th Level Screening: Materials

Finally, at the fourth screening level, materials used in various parts and components of the MCS case study shoe are identified and listed as illustrated in Table 10.3. This classification is necessary because these materials significantly differ not only in their appearance and physical qualities but also in their ability to be treated by different recycling and product recovery operations at the end of their useful life.

10.3.2 End-of-Life Scenario Definition

Once the basic characteristics of the shoe under consideration have been identified, the next step is to formulate a list of potential end-of-life management scenarios. Five end-of-life scenarios have been identified for this particular type of shoe, as depicted in Figure 10.2.

Table 10.2: Parts and Components List of the Men’s Casual Shoe

<table>
<thead>
<tr>
<th>Upper</th>
<th>Lower</th>
<th>Grindery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vamp</td>
<td>Insole</td>
<td>Stiffener</td>
</tr>
<tr>
<td>Quarters</td>
<td>Midsole</td>
<td>Laces</td>
</tr>
<tr>
<td>Lining</td>
<td>Outsole</td>
<td>No Shank</td>
</tr>
<tr>
<td>N/A</td>
<td>N/A</td>
<td>No Eyelets</td>
</tr>
</tbody>
</table>

Table 10.3: Materials List for the Men’s Casual Shoe

<table>
<thead>
<tr>
<th>Upper</th>
<th>Lower</th>
<th>Grindery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vamp: Leather</td>
<td>Insole: PU foam and Fabric</td>
<td>Laces: Synthetic Fibres</td>
</tr>
<tr>
<td>Quarters: Leather</td>
<td>Midsole: PU foam</td>
<td>Stiffener: Leather and Rubber</td>
</tr>
<tr>
<td>Lining: Leather and Fabric</td>
<td>Outsole: Rubber</td>
<td>N/A</td>
</tr>
</tbody>
</table>
A short description of these alternative treatment options for the MCS shoe is provided below:

i) Reuse Scenario: Reuse of MCS shoe to less-developed countries with minimal refurbishing.

ii) Recycling Scenario 1: Shredding or granulating of MCS shoe as a whole.

iii) Recycling Scenario 2: Disassembly of MCS shoe to separate the upper and the lower part. The separated parts are then shredded/granulated while the ferrous metals are removed using a magnetic drum. Finally, air separation or density separation process is performed in order to isolate valuable materials such as leather particles.

iv) Incineration Scenario: Incineration of MCS shoe in municipal solid waste incinerators to generate heat and electricity.

v) Disposal Scenario: Landfilling of MCS shoe.
10.3.3 End-of-Life Scenario Assessment

Following the ETS methodology, the third phase is to identify and calculate the decision variables that influence the final adoption of an appropriate end-of-life treatment option for post-consumer shoes. This phase is carried out in two steps: identification of decision factors and calculation of decision factors.

10.3.3.1 Identification of decision factors

In accordance with the multi-criteria considerations in the ETS methodology, three decision criteria are being considered for this case study, namely Environmental, Economic and Socio-Technical. For each of these criteria, a number of pre-defined indicators have been selected as previously defined in Section 8.4.1.1. The list of predefined decision indicators for the MCS shoe is depicted in Table 10.4.

<table>
<thead>
<tr>
<th>Economic Indicators</th>
<th>Socio-technical Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Benefit/Cost Ratio</td>
<td>Technical Feasibility</td>
</tr>
<tr>
<td>Recycling Benefit/Cost Ratio</td>
<td>Public Opinion</td>
</tr>
<tr>
<td>Incineration Benefit/Cost Ratio</td>
<td>Market Pressures</td>
</tr>
<tr>
<td>Disposal Benefit/Cost Ratio</td>
<td>Compliance with Legislation</td>
</tr>
</tbody>
</table>

| Environmental Indicators             |                                          |
|--------------------------------------|                                          |
| Global Warming Potential             | Human Toxicity Air                       |
| Ozone Depletion                      | Human Toxicity Water                     |
| Acidification                        | Human Toxicity Soil                      |
| Eutrophication                       | Bulk Waste                                |
| Photochemical Smog                   | Hazardous Waste                          |
| Ecotoxicity Water Chronic            | Radioactive Waste                        |
| Ecotoxicity Water Acute              | Slags/Ashes                               |
| Ecotoxicity Soil Chronic             | Resources                                 |

Table 10.4: List of Pre-Defined Indicators
10.3.3.2 Calculation of decision factors

The calculation process of decision criteria is conducted in five steps, as described in Section 8.6:

I. Structuring the problem into a hierarchy
II. Making pairwise comparisons criteria
III. Calculate decision variables
IV. Consistency check
V. Synthesize the priorities

**Structuring the problem into a hierarchy**

Figure 10.3 presents the decision hierarchy of the MCS waste management problem. At the top level is the overall goal of the decision making problem. In our case, the goal is to identify an optimal end-of-life management option for MCS. At the second level, the goal is broken down into Quantitative and Qualitative factors while at the third level, the factors are divided into criteria and indicators. Finally, at the bottom level, the five MCS end-of-life management options that are to be evaluated in terms of the decision criteria are presented.

**Making Pairwise Comparisons**

To estimate the significance of each end-of-life scenario (Level 4) in achieving the overall goal (Level 1), pairwise comparisons of the decision variables within a lower level of the hierarchical structure with respect to the variables in the next higher level are performed. The decision variables' weights have been determined by using questionnaires to obtain stakeholders' judgements. Three experts from the footwear sector were asked to fill in the questionnaires, which are included in Appendix III. Their aggregated judgements are depicted in Table 10.5.
Figure 10.3: Decision Hierarchy of MCS Case Study

Table 10.5: Aggregated Questionnaire Judgements for MCS criteria

Based on the results from the questionnaires, the priority weight of each criterion computed in the macro-AHP model, as shown in Figure 10.4, using the end-of-life footwear decision support tool (EF-DST) developed as part of this research (see Chapter 9). In this specific case study, environmental criteria have the highest priority (0.6806) while socio-technical criteria have the lowest priority weight (0.1179) with a calculated consistency index of 0.021.
Chapter 10

**macro-AHP: Selection of End-of-Life Options for Post-Consumer Shoes**

**Level 1: Pairwise Comparison among Criteria**

**STEP 1** Construction of Judgment Matrix

<table>
<thead>
<tr>
<th></th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>1.0000</td>
<td>0.2000</td>
<td>1.0000</td>
</tr>
<tr>
<td>Environmental</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>1.0000</td>
<td>0.2000</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

**STEP 2** Construction of Normalised Matrix

<table>
<thead>
<tr>
<th></th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>0.1429</td>
<td>0.1429</td>
<td>0.1429</td>
</tr>
<tr>
<td>Environmental</td>
<td>0.7143</td>
<td>0.7143</td>
<td>0.7143</td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>0.1429</td>
<td>0.1429</td>
<td>0.1429</td>
</tr>
</tbody>
</table>

**STEP 3** Calculate Priority Weights

<table>
<thead>
<tr>
<th></th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>0.1429</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td>0.7143</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>0.1429</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**STEP 4** Consistency Check: Calculate the Product

<table>
<thead>
<tr>
<th></th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>0.4286</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td>2.1429</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>0.4286</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Consistency Check: Calculate the Ratio

<table>
<thead>
<tr>
<th></th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>3.0000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td>3.0000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>3.0000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Consistency Check: Calculate Consistency Index

<table>
<thead>
<tr>
<th></th>
<th>CI</th>
<th>RI</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.58</td>
<td>&lt;0.10</td>
</tr>
</tbody>
</table>

**Figure 10.4:** Priority Weights of Criteria for MCS Case Study

**Calculating Environmental Indicators**

A streamlined LCA study of the men’s casual shoe based on generalised manufacturing data has been conducted using SimaPro LCA software. The total environmental impact ($EI_t$) of each MCS end-of-life scenario and the score of each impact category indicator ($IC_l$), are presented in Figure 10.5.

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**Figure 10.5:** Total Environmental Impact (EI) for MCS Case Study

The Disposal scenario has the highest environmental impact with a total score of 283 mPt while Recycling Scenario 1 (shredding of the shoe as a whole) has the lowest environmental impact total score of 23.2 mPt. The calculations were conducted in SimaPro 7 using the EDIP (Environmental Design of Industrial Products) impact assessment method. The total environmental impact (EI) score for each scenario is then normalised, and expressed in unit-free numbers. The calculation process has been performed by using the LCA model (see Section 8.6.3.1) following the steps shown in Figures 10.6 and 10.7.

**Table:**

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>A. Reuse Scenario</th>
<th>B. Recycling Scenario 1</th>
<th>C. Recycling Scenario 2</th>
<th>D. Incineration Scenario</th>
<th>E. Landfill Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming (GWP 100)</td>
<td>Pt</td>
<td>0.00622</td>
<td>0.006012</td>
<td>0.0000613</td>
<td>0.000809</td>
<td>0.001696</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>Pt</td>
<td>3.16E-5</td>
<td>2.97E-5</td>
<td>2.93E-5</td>
<td>2.93E-5</td>
<td>2.94E-5</td>
</tr>
<tr>
<td>Acidification</td>
<td>Pt</td>
<td>0.00168</td>
<td>0.00124</td>
<td>0.00124</td>
<td>0.00124</td>
<td>0.00124</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>Pt</td>
<td>5.48E-5</td>
<td>4.07E-5</td>
<td>4.03E-5</td>
<td>4.03E-5</td>
<td>4.00E-5</td>
</tr>
<tr>
<td>Photochemical smog</td>
<td>Pt</td>
<td>0.000214</td>
<td>0.000209</td>
<td>0.000209</td>
<td>0.000211</td>
<td>0.000216</td>
</tr>
<tr>
<td>Ecotoxicity water chronic</td>
<td>Pt</td>
<td>0.000767</td>
<td>0.000667</td>
<td>0.000699</td>
<td>0.102</td>
<td>0.121</td>
</tr>
<tr>
<td>Ecotoxicity water acute</td>
<td>Pt</td>
<td>0.0074</td>
<td>0.00639</td>
<td>0.0064</td>
<td>0.0064</td>
<td>0.0064</td>
</tr>
<tr>
<td>Human toxicity air</td>
<td>Pt</td>
<td>0.00117</td>
<td>0.00115</td>
<td>0.00115</td>
<td>0.00115</td>
<td>0.00115</td>
</tr>
<tr>
<td>Human toxicity water</td>
<td>Pt</td>
<td>0.00152</td>
<td>0.00149</td>
<td>0.0015</td>
<td>0.0015</td>
<td>0.0015</td>
</tr>
<tr>
<td>Human toxicity soil</td>
<td>Pt</td>
<td>0.00257</td>
<td>0.0022</td>
<td>0.0022</td>
<td>0.0022</td>
<td>0.0022</td>
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<tr>
<td>Bulb waste</td>
<td>Pt</td>
<td>0.00102</td>
<td>0.00102</td>
<td>0.00102</td>
<td>0.00105</td>
<td>0.00105</td>
</tr>
<tr>
<td>Hazardous waste</td>
<td>Pt</td>
<td>0.000946</td>
<td>0.000946</td>
<td>0.000946</td>
<td>0.000946</td>
<td>0.000946</td>
</tr>
<tr>
<td>Radioactive waste</td>
<td>Pt</td>
<td>0.000788</td>
<td>0.000641</td>
<td>0.000641</td>
<td>0.000663</td>
<td>0.000676</td>
</tr>
<tr>
<td>Slags/lashes</td>
<td>Pt</td>
<td>5.23E-7</td>
<td>5.11E-7</td>
<td>5.11E-7</td>
<td>5.11E-7</td>
<td>5.11E-7</td>
</tr>
<tr>
<td>Resources (all)</td>
<td>Pt</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Figure 10.6:** Reciprocal Environmental Impact Score (REI) for MCS Case Study
Environmental Assessment of End-of-Life Scenarios for Post-Consumer Shoes

**Step 3: Calculate Normalised Environmental Impact Score (NEI)**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NEI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.2910</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.3249</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.3235</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.0340</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.0266</td>
</tr>
</tbody>
</table>

\[ \sum_{(NEI)} = 0.1327 \]

![Normalized Environmental Impact Score (NEI) for MCS Case Study](image)

**Figure 10.7:** Normalised Environmental Impact Score (NEI) for MCS Case Study

**Calculating Economic Indicators**

An experimental data set based on average values derived from literature sources (Turner and Hewett 2007, Sunthonpagasit and Duffey 2004, Lave et al. 1998) for costs and benefits has been utilised to calculate the benefit/cost ratio for each MCS end-of-life treatment scenario. Each scenario is calculated using the CBA model (see Section 8.6.3.2), as depicted in Figure 10.8.

![Benefit/Cost Ratio for MCS Case Study](image)

**Figure 10.8:** Benefit/Cost Ratio for MCS Case Study
Figure 10.9: Normalised Benefit/Cost Ratio Score for MCS Case Study

Benefit to cost ratios are then need to be normalised in order to be used by the macro-AHP model. Figure 10.9 presents the benefit to cost ratio and the normalised results for each end-of-life scenario.

**Calculating Socio-Technical Indicators**

The socio-technical indicators are calculated by using the micro-AHP model, as previously described in Chapter 9. Once again, a series of pairwise comparisons are performed in order to identify the weight of each criterion. The MCS end-of-life scenarios are then compared to each other with respect to each criterion, again by making a series of pairwise comparisons. The final result is a score (composite weight) for each alternative MCS end-of-life waste management scenarios with respect to socio-technical criteria. The results of the pairwise comparison of alternative scenarios with respect to each socio-technical criterion as well as the final composite weight of each scenario are presented in Figure 10.10.
### micro-AHP: Calculate Socio-Technical Criteria

#### Level 3: Determining Composite Weigh of Technical Criteria

**STEP 1: Synthesise the Overall Results**

<table>
<thead>
<tr>
<th></th>
<th>Market Pressures</th>
<th>Public Opinion</th>
<th>Technical Feasibility</th>
<th>Compliance with Legislation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.2718</td>
<td>0.1459</td>
<td>0.5233</td>
<td>0.0590</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.3606</td>
<td>0.327</td>
<td>0.3645</td>
<td>0.3000</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.2530</td>
<td>0.249</td>
<td>0.2731</td>
<td>0.3284</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.1161</td>
<td>0.111</td>
<td>0.1050</td>
<td>0.1210</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.0548</td>
<td>0.047</td>
<td>0.0463</td>
<td>0.0538</td>
</tr>
</tbody>
</table>

**STEP 2: Calculate the Global Priority Vector**

<table>
<thead>
<tr>
<th></th>
<th>Global Priority Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.2190</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.3616</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.2699</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.1104</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.0481</td>
</tr>
</tbody>
</table>

**Figure 10.10:** Socio-Technical Indicators Score for MCS Case Study

**Synthesise the priorities**

Finally, the global priority vector of each MCS end-of-life management option is calculated using the macro-AHP model as described in Chapter 9. To do this, the results from previous calculations are integrated in order to identify the option with the highest score (i.e. global priority vector). Figure 10.11 shows the results of both the relative weights of decision criteria with respect to the overall goal, and the relative weights of alternative options with respect to each decision criterion. The global priority vector indicates the overall significance of each end-of-life management option after considering the importance of the decision variables. In fact, global priority vector represents the cumulative weights of each alternative option throughout the entire AHP hierarchy. For example, the composite weight of reuse scenario after considering the entire hierarchy is 0.2694. This is the cumulative weight after considering the relative weight of reuse scenario with respect to each decision variable and the relative weight of the decision variables to overall goal.
Chapter 10

macro-AHP: Selection of End-of-Life Options for Post-Consumer Shoes

Level 3: Determining Best End-of-Life Option

<table>
<thead>
<tr>
<th>STEP 1: Synthesise the Overall Results</th>
<th>Environmental Criteria</th>
<th>Economic Criteria</th>
<th>Socio-Technical Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.7143</td>
<td>0.1429</td>
<td>0.1429</td>
</tr>
<tr>
<td>Reuse Scenario</td>
<td>0.2910</td>
<td>0.2791</td>
<td>0.2100</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.3249</td>
<td>0.2181</td>
<td>0.3516</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.3236</td>
<td>0.2967</td>
<td>0.3699</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.0340</td>
<td>0.2662</td>
<td>0.1104</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.0266</td>
<td>0.0000</td>
<td>0.0491</td>
</tr>
</tbody>
</table>

| STEP 2: Calculate the Global Priority Vector |
|----------------------------------------------|------------------------|
| Global Priority Vector                       |                         |
| Reuse Scenario                               | 0.2790                 |
| Recycling Scenario 1                         | 0.3135                 |
| Recycling Scenario 2                         | 0.3034                 |
| Incineration Scenario                        | 0.0781                 |
| Landfilling Scenario                         | 0.0260                 |

Figure 10.11: Determining Most Appropriate EoL Option for MCS Case Study

Figure 10.11 also shows the graphical representation of the aggregated results for each MCS end-of-life management scenario. Final results indicate that Recycling Scenario 1 (shedding/granulating the shoe as a whole) is the most preferable option for a men casual shoe, whereas Disposal Scenario (landfilling) is the least. However, the priority weight given to each decision variable clearly influences the final results. If an end-of-life management option received the least weight with respect to most of the criteria, then it will most likely be the least preferable option, as in the case of disposal. Based on the results, the priority weight given to environmental criteria (0.6806) as the most important factor in evaluating the end-of-life management options of MCS corresponds to the high composite weight given to MCS reuse and recycling scenarios.
10.3.4 Recovery Value Chain

The final phase of the ETS methodology aims to identify a recovery value chain for the most appropriate end-of-life scenario. This case study has shown that Recycling Scenario 1 (shredding/granulating the shoe as a whole) is the preferable option for the end-of-life treatment of the MCS shoe. Based on this recommendation, a physical size reduction experiment has been conducted using the Zerma ZWS single shaft shredding machine, as depicted in Figure 10.12, with a 20 mm screen size. This process was able to produce recycled materials with particle sizes of 16-17 mm, as shown in Figure 10.13.

Furthermore, a list of potential applications for the recycled material has been considered. Obviously, the most viable option for the application of this material is to be used in surfacing of various surfacing construction applications. For example, Nike is producing a similar material called “Nike Grid”, which comes from the shredding of post-consumer athletic shoes, and has been successfully used in surfacing of tennis and basketball courts, playground surfaces and running tracks as depicted in Figure 10.14.

![Zerma ZWS Shredding Machine](image-url)

**Figure 10.12:** Zerma ZWS Shredding Machine
Figure 10.13: Shredded Material from MCS Case Study

Figure 10.14: List of Potential Applications for Recycled Material from MCS Case Study (photos courtesy of Nike Inc.)
10.4 Case Study 2: Women’s Fashion Boot

The second case study shoe is a women’s fashion boot (WFB) typically used as fashion statement both at work or during spare time activities. This type of shoe has been selected because it provides a sharp contrast to the basic features of the first case study shoe. The WFB case study shoe is depicted in Figure 10.15.

It should be noted that the process of conducting the second case study is identical to the first case study which follows the various steps in ETS methodology, and hence it will not be explained in detail herein.

10.4.1 Product Characterisation of WFB Case Study Shoe

The main characteristics of the shoe under investigation are identified. This phase is performed in four screening levels.

10.4.1.1 1st Level Screening: Basic Characteristics

The basic characteristics of the WFB are depicted in Table 10.6. The screening process is performed visually.

Figure 10.15: Picture of Women’s Fashion Boot (WFB)
This case study shoe is considered to be in an average condition, including a damaged heel and scratches in the upper leather part of the boot. Its condition, however, is recoverable through minor repair and refurbishing. The value of the WFB is considered to be low because it is produced by an unidentified footwear manufacturer. Finally, this shoe weighs 275g per single pair.

<table>
<thead>
<tr>
<th>Shoe Basic Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Women’s Fashion Boot</td>
</tr>
<tr>
<td>Condition</td>
<td>Average</td>
</tr>
<tr>
<td>Value</td>
<td>Low</td>
</tr>
<tr>
<td>Weight</td>
<td>275g</td>
</tr>
</tbody>
</table>

**Table 10.6:** Basic Characteristics of Women’s Fashion Boot

10.4.1.2 2nd Level Screening: Construction Method
This case study shoe is made using the cementing process. As previously explained in Chapter 4, cementing is the method of construction in which the bonding of sole to the upper, after securing to the insole, is done by means of an adhesive material (cement).

10.4.1.3 3rd Level Screening: Parts and Components
This screening level identifies a list of the major parts and components of the WFS shoe, as depicted in Table 10.7. A physical disassembly exercise has also been performed to determine the exact parts and components used in the Women’s Fashion Boot, as depicted in Figure 10.16.

<table>
<thead>
<tr>
<th>Upper</th>
<th>Lower</th>
<th>Grindery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vamp</td>
<td>Insole</td>
<td>Fastener</td>
</tr>
<tr>
<td>Lining</td>
<td>Bottom Filling</td>
<td>Shank</td>
</tr>
<tr>
<td>N/A</td>
<td>Midsole</td>
<td>Heel</td>
</tr>
<tr>
<td>N/A</td>
<td>Outsole</td>
<td>Stiffener</td>
</tr>
</tbody>
</table>

**Table 10.7:** Parts and Components List for Women’s Fashion Boot
A particular emphasis has been given on the identification of components and parts that might have an effect on the choice of a potential recycling process. For example, the case study shoe contains a steel shank and heel which means that recycling of the shoe as a whole (shredding) could be problematic.
10.4.1.4 4th Level Screening: Materials

Materials used in various parts and components of the Women’s Fashion Boot are identified and listed in Table 10.8.

<table>
<thead>
<tr>
<th>Upper</th>
<th>Lower</th>
<th>Grindery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vamp: Leather</td>
<td>Insole: Plastic</td>
<td>Fastener: Plastic Zip</td>
</tr>
<tr>
<td>Lining: Leather</td>
<td>Midsole: Leather</td>
<td>Shank: Steel</td>
</tr>
<tr>
<td>N/A</td>
<td>Bottom Filling: Fibreboard</td>
<td>Heel: Wood + Plastic</td>
</tr>
<tr>
<td>N/A</td>
<td>Outsole: EVA</td>
<td>Stiffener: EVA</td>
</tr>
</tbody>
</table>

**Table 10.8**: Materials List for Women’s Fashion Boot

10.4.2 End-of-Life Scenario Definition

A list of potential end-of-life management scenarios for the WFB case study shoe is formulated. Five end-of-life treatment options have been identified for this particular shoe, namely Reuse Scenario, Recycling Scenario 1, Recycling Scenario 2, Incineration Scenario and Disposal Scenario. These end-of-life treatment options are described previously in Section 10.4.2.

10.4.3 End-of-Life Scenario Assessment

This step identifies and calculates the decision variables that influence the final adoption of an appropriate end-of-life treatment option for the WFB case study shoe.

10.4.3.1 Identification of decision factors

In accordance with the ETS methodology, three decision criteria are being considered for this case study, namely Environmental, Economic and Socio-technical. The list of pre-defined indicators is identical with the previous case study.
10.4.3.2 Calculation of decision factors

**Structuring the problem into a hierarchy**

The decision hierarchy for the WFB case study is identical to the previous case study. Hence, at the top level is the overall goal. At the second level, the goal is broken down into decision factors while at the third level, the factors are divided into criteria and indicators. Finally, at the bottom level, the five alternative end-of-life options for the WFB are evaluated with regard to the decision criteria.

**Making Pairwise Comparisons**

To estimate the significance of each end-of-life scenario with regards to the overall goal, pairwise comparisons of the decision variables have been performed. Once again, the decision variables weights have been determined by using questionnaires to obtain stakeholders judgements. Three experts from the footwear sector were asked to fill in the questionnaires, which are included in Appendix III. Their aggregated judgements are depicted in Table 10.9. Based on the aggregated questionnaire judgments, the priority weight of each criterion computed using the macro-AHP model, as shown in Figure 10.17. In this case study, environmental criteria have the highest priority (0.5889) while socio-technical criteria have the lowest priority weight (0.1593) with a calculated consistency index of 0.046.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Absolute</th>
<th>Very Strong</th>
<th>Strong</th>
<th>Weak</th>
<th>Equal</th>
<th>Weak</th>
<th>Strong</th>
<th>Very Strong</th>
<th>Absolute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Economic</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 10.9: Aggregated Questionnaire Judgements for WFB Case Study*
Chapter 10

**macro-AHP: Selection of End-of-Life Options for Post-Consumer Shoes**

**Level 1 : Pairwise Comparison among Criteria**

**STEP 1** Construction of Judgment Matrix

<table>
<thead>
<tr>
<th></th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>1.0000</td>
<td>0.2500</td>
<td>3.0000</td>
</tr>
<tr>
<td>Environmental</td>
<td>4</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>0.3333</td>
<td>0.3333</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

**STEP 2** Construction of Normalised Matrix

<table>
<thead>
<tr>
<th></th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>0.1575</td>
<td>0.1479</td>
<td>0.4266</td>
</tr>
<tr>
<td>Environmental</td>
<td>0.7500</td>
<td>0.6316</td>
<td>0.4266</td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>0.0625</td>
<td>0.2105</td>
<td>0.1429</td>
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</tbody>
</table>

**STEP 3** Calculate Priority Weights

<table>
<thead>
<tr>
<th></th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>0.2500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td>0.6034</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>0.1466</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**STEP 4** Consistency Check: Calculate the Product

<table>
<thead>
<tr>
<th></th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td>2.0512</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>0.4286</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Consistency Check: Calculate the Ratio

<table>
<thead>
<tr>
<th></th>
<th>Economic</th>
<th>Environmental</th>
<th>Socio-Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>3.1967</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td>3.9996</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Socio-Technical</td>
<td>3.0712</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Consistency Check: Calculate Consistency Index

<table>
<thead>
<tr>
<th></th>
<th>CI</th>
<th>RI</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI</td>
<td>0.111240077</td>
<td>0.58</td>
<td>&gt;0.10</td>
</tr>
<tr>
<td>RI</td>
<td>0.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>0.191753336</td>
<td>&gt;0.10</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 10.17:** Priority Weights of Criteria for WFB Case Study

**Calculating Environmental Indicators**

A streamlined LCA study for the WFB case study shoe has been conducted with the aid of SimaPro LCA software. Following a similar process with the previous case study, the total environmental impact \( (EI) \) of each WFB end-of-life scenario and the score of each impact category indicator \( (ICI) \) are calculated and normalised. The normalised environmental impact scores (NEI) for each alternative option for the WFB case study are presented in Figure 10.18.
Environmental Assessment of End-of-Life Scenarios for Post-Consumer Shoes

Step 3: Calculate Normalise Environmental Impact Score (NEI)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Normalised Score (NEI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td></td>
</tr>
<tr>
<td>$\text{NEI}_\text{RE} =$</td>
<td>0.2942</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td></td>
</tr>
<tr>
<td>$\text{NEI}_\text{R1} =$</td>
<td>0.3186</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td></td>
</tr>
<tr>
<td>$\text{NEI}_\text{R2} =$</td>
<td>0.3176</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td></td>
</tr>
<tr>
<td>$\text{NEI}_\text{IR} =$</td>
<td>0.0367</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td></td>
</tr>
<tr>
<td>$\text{NEI}_\text{L} =$</td>
<td>0.0329</td>
</tr>
</tbody>
</table>

Total Normalised Score ($\sum(\text{REI})$): 0.0663

**Figure 10.18:** Normalised Environmental Impact Score (NEI) for WFB Case Study

**Calculating Economic Indicators**

To calculate the benefit/cost ration for each WFB end-of-life management scenario, the CBA model has been utilised as previously. Benefit to cost ratio is then need to be normalised, as depicted in Figure 10.19.

**Calculating Socio-Technical Indicators**

The socio-technical indicators are calculated by using the micro-AHP model. The results of the pairwise comparison of alternative scenarios with respect to each socio-technical criterion as well as the final composite weight of each scenario are presented in Figure 10.20.
Economic Assessment of End-of-Life Scenarios for Post-Consumer Shoes

Step 3: Normalise Results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Sum of Benefit/Cost ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.1079</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.2698</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.2929</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.3294</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Figure 10.19: Normalised Benefit/Cost Ratio Score for WFB Case Study

micro-AHP: Calculate Socio-Technical Criteria

Level 3: Determining Composite Weight of Technical Criteria

STEP 1: Synthesise the Overall Results

<table>
<thead>
<tr>
<th>Market Pressures</th>
<th>Public Opinion</th>
<th>Technical Feasibility</th>
<th>Compliance with Legislation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6792</td>
<td>0.1162</td>
<td>0.1677</td>
<td>0.6169</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Market Pressures</th>
<th>Public Opinion</th>
<th>Technical Feasibility</th>
<th>Compliance with Legislation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.2134</td>
<td>0.266</td>
<td>0.2111</td>
<td>0.1978</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.3606</td>
<td>0.327</td>
<td>0.3645</td>
<td>0.3000</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.2630</td>
<td>0.249</td>
<td>0.2731</td>
<td>0.3284</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.1181</td>
<td>0.111</td>
<td>0.1050</td>
<td>0.1210</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.0548</td>
<td>0.047</td>
<td>0.0463</td>
<td>0.0528</td>
</tr>
</tbody>
</table>

STEP 2: Calculate the Global Priority Vector

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Global Priority Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.0095</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.3193</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.0035</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.1166</td>
</tr>
<tr>
<td>Landfilling Scenario</td>
<td>0.0511</td>
</tr>
</tbody>
</table>

Figure 10.20: Calculate Socio-technical Indicators for WFB Case Study
Synthesise the priorities

Finally, the global priority vector of each WFB end-of-life option has been calculated using the macro-AHP model. To do this, the results from previous calculations have been integrated in order to identify the option with the highest score (i.e. global priority vector). Figure 10.21 shows the results of both the relative weights of decision criteria with respect to the overall goal, and the relative weights of alternative options with respect to each decision criterion. Most appropriate end-of-life option for WFB is the Recycling Scenario 2 (disassembly of shoe parts and then shredding/granulating of separated materials).

![Diagram showing macro-AHP process]

**Figure 10.21:** Determine Most Appropriate EoL Option for WFB Case Study
10.4.4 Recovery Value Chain

The WFB cases study has identified Recycling Scenario 2 as the most appropriate end-of-life treatment option. According to the definition of the Recycling Scenario 2, the shoe under investigation is disassembled into upper and lower part. The separated parts are then shredded/granulated while the ferrous metals are removed using a magnetic drum. Finally, air separation or density separation process is performed in order to isolate valuable materials such as leather particles.

Based on this recommendation for end-of-life treatment, a physical size reduction experiment has been conducted to process the upper leather part of the shoe. The Zerma GSL granulator, as depicted in Figure 10.22, has been used to conduct the experiment. A 6 mm screen size has been used in the granulator to produce recycled materials with a particles size of 4-5 mm, as depicted in Figure 10.23. A density separation process was then used to remove unwanted materials such as fluff and textiles in order to increase the purity of generated leather trimmings. The end leather-based material is depicted in Figure 10.24.

Figure 10.22: Zerma GSL granulator
Figure 10.23: Granulated Material from Upper Part of WFB Case Study

Figure 10.24: Density Separated Leather Trimmings from WFB Case Study
This process clearly results in better quality of recycled materials which can be used in high-value applications. Potential applications for leather-based trimmings have been discussed in Section 4.9.1. These include extraction of protein (gelatine, collagen), applications in the construction industry (absorbing material, filler, thermo-acoustic insulation, etc.), recovery of chromium, production of non-woven material, paper making, ready-to-use concrete as well as utilisation of these recycled materials within the footwear manufacturing process to produce upper and lower parts and materials.

10.5 Analysis of Case Study Results

The case studies described in this chapter have effectively demonstrated the applicability of the End-of-life Treatment of Shoes (ETS) methodology and its associated decision support tool, developed as part of this research. In the first case study i.e. men’s casual shoe, the lack of end-of-life problematic components (e.g. metal shank, heel, or toe puff) resulted in the recommendation for a destructive recycling process in order to use the resultant material for surfacing in construction applications. In the second case study shoe i.e. women’s fashion boot, due to the presence of the problematic components (i.e. steel shank, fastener and heel) and the high value of the material content, it was recommended to carried out a non-destructive disassembly (separation of upper from sole and removal of steel shank, fastener and heel) in the first place, before down-sizing the upper part into much smaller particles to generate higher quality leather-based recycled material to be used in valuable applications within a number of industrial sectors.
Chapter 11

11 Concluding Discussion

11.1 Introduction

This chapter compiles and discusses the main research issues highlighted within this thesis in order to formulate research conclusions. The first part of the chapter highlights the main research contributions proposed in this thesis, while the latter part presents a discussion based on the broad headings identified as the research scope in Chapter 2, to highlight the key findings and knowledge gained from the research.

11.2 Research Contributions

The research in this thesis has investigated product recovery and recycling procedures in the footwear industry and the generation of an end-of-life product recovery methodology for post-consumer shoes together with the development of a multi-criteria decision making model and software tool. The major research contributions of these activities can, therefore, be summarised as follows:

- Generation of a formal methodology for end-of-life product recovery in footwear industry, which assesses and analyses shoe materials composition, construction methods, and shoe condition at its end-of-life in order to identify the most appropriate end-of-life option based on parallel consideration of environmental, economic and socio-technical criteria.

- Definition of a novel approach for parallel consideration of environmental, economic and socio-technical criteria influencing the recovery and recycling of post-consumer shoes.

- Integration of three evaluation techniques, namely LCA for environmental impacts, CBA for economic implications and AHP for socio-technical...
requirements into a multi-criteria decision making model to support the abovementioned methodology.

- Design and implementation of a decision support tool to aid the selection of the most appropriate end-of-life treatment option for post-consumer shoes.

**11.3 Concluding Discussions**

The following sections discuss the results of the main research activities outlined as part of the thesis scope.

*11.3.1 Review of Relevant Literature and Footwear Sector Analysis*

The comprehensive literature review carried out as part of this research has highlighted the growing body of evidence that the industry will be forced to extend its responsibility beyond the selling point to the end-of-life phase of its products, as evident by the ELV and WEEE Directives in automotive and electrical/electronic sectors. In addition, there is an increasing expectation by both public and government in adopting sustainable approaches to deal with the end-of-life waste and eventually divert waste from landfill (through a “zero waste to landfill” approach). The response of the footwear industry to these challenges has been limited. In fact, throughout this research there was only one application of end-of-life product recovery and recycling identified, namely the NIKE's “Reuse-A-Shoe” program. In addition, the traditional collection and re-distribution of second-hand shoes in less developed countries, through charitable organisations, is on the close scrutiny as there are evidences that cheap imports both impact the local footwear industry and the environment while the varying style and types of shoes that typically have a short life and hence in a reusable condition does not lend itself to the user lifestyle expected in these countries. All of these evident clearly point to the requirement of a holistic approach to end-of-life product recovery in the footwear sector which has been the main scope of the research reported in this thesis.

*11.3.2 Generation of an End-of-Life Product Recovery Methodology for Footwear Products*

Typically, when considering potential end-of-life treatment options of any product a wide range of issues regarding its material content, production process, condition at its end-of-
life, etc., need to be considered. In addition, there is a need to investigate the environmental consequences, the economic implications and the socio-technical feasibility of these end-of-life treatment options. The results from each of these considerations impact the final decision on the most suitable end-of-life option. Hence this research has developed the End-of-Life Treatment of Shoes (ETS) methodology to provide a systematic approach in considering all these relevant issues to aid the selection process for the most appropriate end-of-life treatment option for post-consumer shoes. The ETS methodology enables a holistic consideration of all relevant information and knowledge required for decision making and could be applied for a wide range of shoe types and styles as highlighted by the cases studies. In addition, the author is of the opinion that though the ETS methodology has been developed for the footwear sector, it offers great potential for re-application in other industrial sectors.

11.3.3 Development of a Multi-Criteria Decision Making Model for Post-Consumer Shoes

During this research, it became apparent that a number of competing criteria had to be considered to identify the best solution for treatment of end-of-life shoes. The determination of the most suitable (in environmental, economic and socio-technical terms) manner in which to treat post-consumer shoe waste, as described in Chapter 7 and 8, is a complex process involving the consideration of a wide range of materials, construction methods and recycling processes. Therefore, this thesis has provided a novel integrated approach for adopting modified LCA, CBA and AHP techniques to perform a parallel consideration of the main criteria influencing the selection of the most appropriate option. The ever increasing number of legislative pressures, as those identified within automotive and electrical/electronic sectors, will introduce additional considerations and criteria (e.g., recovery and recycling targets, hazardous material restrictions, etc.). This indicates the possibility of increased number of factors and criteria that need to be considered in future product recovery and recycling applications. The multi-criteria decision making model generated and presented in this research provides a flexible and powerful approach that allows additional considerations to be included to the three criteria already considered (i.e. environmental, economic and socio-technical) as part of this research.
11.3.4 Design and Development of a Decision Support Software Tool

Inclusion of economic, environmental and socio-technical issues necessitates a software decision support tool, as the consideration of these issues requires processing of a large amount of information and knowledge to identify the most appropriate solution. The decision support tool developed by this research provide a simple, yet very effective, instrument that systematically assess the environmental, economical and socio-technical issues using different evaluation techniques. This tool has been designed and implemented to support end-of-life activities. However, the author argues that this software tool can also provide great support for design and material selection activities in footwear industry in order to facilitate recycling and product recovery of post-consumer shoes. In fact, it is the author’s opinion that the vision of “zero waste to landfill” in footwear sector introduced by this research can only be achieved through such design and material selection improvements. The consideration of end-of-life knowledge to support the design process forms one of the possible avenues for extending of the research reported in this thesis, as it would be further described in Chapter 12.

11.3.5 Case Studies

For the purpose of validation and demonstration of the research concepts, two case studies on the implementation of the ETS methodology and its associated multi-criteria decision support model and software tool have been defined and undertaken. A clear objective of these case studies was to follow a stepwise implementation of the ETS methodology proposed by this thesis, and to show its feasibility and applicability in selecting the most appropriate end-of-life treatment option for a wide range of post-consumer shoes. For this purpose, two distinctly different case studies have been selected based on two different types of post-consumer shoes. One is based on a men’s casual shoe with a high content of leather and rubber in its composition while the other case study shoe is a women’s fashion boot with a more complex construction and a more extensive components and materials list.

These case studies have highlighted the influence of material composition, construction methods, condition of post-consumer shoe, etc., in selecting the most appropriate end-of-life treatment option. Through this research, it became apparent that there is a clear
relation between range and cost of recovery processes and the revenue that can be obtained from such shoe recycling activities. In some cases the disassembly of the upper from the sole of the shoe before shredding each part separately provide a high grade and better quality material that can be used in more valuable applications. In addition, the case studies highlighted the ease of use and effectiveness of the end-of-life footwear decision support tool developed by this research.

11.3.6 The Realisation of End-of-life Product Recovery to Support a Zero Waste to Landfill Approach in Footwear Industry

End-of-life product recovery and recycling practices must be implemented in every manufacturing application in order to achieve the vision of “zero waste to landfill”, which forms one of the major challenges of the 21st century in many industrial sectors. Investigating the realisation of end-of-life product recovery in footwear sector clearly provides an ideal case for extending the traditional scope of end-of-life product recovery to other industrial domains where currently there are not any established recovery and recycling procedures in place.

In footwear sector, the “zero waste to landfill” vision presents a very ambitious target as currently less than 1% of the 19 billion pairs of shoes consumed worldwide every year is recycled or reused. In fact, the growing amount of footwear products consumed and the very limited recycling activity in the footwear sector clearly indicate that a significant proportion of the end-of-life shoe waste currently end up in landfills. Forthcoming environmental legislative requirements and consumer pressures are expected to challenge the way the footwear industry deals with its end-of-life waste. However, past experiences in other industrial sectors (e.g. packaging, automotive) have shown that end-of-life product recovery procedures need to be not only environmentally acceptable but also economically and technologically justified.

The main research assertion presented in this thesis has been that in a rapidly growing mass-production/consumption/disposal society, which generates an enormous amount of end-of-life waste, there is an essential need to develop product recovery and recycling procedures for post-consumer products in order to prevent material resources of being landfilled, reduce the consumption of raw materials and finally capture the hidden value of
re cycl a b le m a te ri a ls in u sed p roducts. T hi s res earch h as d e vel op ed a h olis tic a pproach for
d e terminin g th e fe a si bili ty of e nd-of-life p roduct r ecovery in th e fo otwea r i ndustry. A
s yst emati c m eth odo lgy h as b ee n d eve lo p e d for p arallel (i.e. m ulti-criteria) c onsidera ti o n
of en vironm e nta l, e c on o mic a n d s ocio-t echnica l is su es r elated to s ho e r e cy clin g. Ho wever,
in c ons iderin g th e v ariou s m ateri als, c onstruc ti o n p roce sses, st yles a n d t ypes o f s hoes it
h a s b e co m e a p p ar e nt th a t th e re is a n eed t o s uppo rt th e d ecisi o n m aking p roces s th roug h a
fo rmal d ec is io m e nt s upp or t tool. T ypica ll y, suc h d ecis i o n m akin g p roces s w as tradi ti o na ll y
fo c u sed o n e ith er ec on o mic o r en v ironm en t a l m e trics w ith o ut ta k in g in to c ons id e r a ti o n th e
co m p reh en siv e n a tu re o f th e a n alys is o f co m p e tin g c riter i a o utli ne d a s p a rt o f th is
res earch. Th us, th is th e si s h a s e xpl or ed th e a pplic a tio n o f a m ulti-criteria a pproach to
co ns id e r m o re th a n o n e criter io n a n d p ro vide d e c isi o n s b a sed o n ec on o mic, en v ironm e nta l
a nd s ocio-t ecnica l a s s e ssm e nt o f e nd-o f-life p roducts.
Chapter 12

12 Conclusions and Further Work

12.1 Introduction

This chapter identifies the major conclusions drawn from the author's research, and proposes possible avenues for further extension of this work.

12.2 Conclusions from the Research

The conclusions drawn from this research are as follows:

i) The increasing amount of post-consumer waste that goes to landfill and its associated environmental concerns have led to the development of a wide range of national and international legislations that forcing governmental agencies, local authorities, and particularly manufacturers to consider the end-of-life consequences of post-consumer products. The research reported in this thesis has clearly highlighted the need for the extension of end-of-life product recovery applications within most industrial sectors in the future.

ii) The survey of the research work on implementation of end-of-life product recovery procedures within various industrial sectors has highlighted that such applications are often developed on an “ad hoc” basis and mainly due to the hidden economic value within post-consumer products. This indicates the paramount importance of economical considerations of shoe product recovery and recycling applications. The author is of the opinion that a large scale adoption of product recovery and recycling procedures in footwear sector can only be realised through establishment of a sustainable value chain for the recycled materials.

iii) Currently, more than 19 billion pairs of shoes consumed every year, and this figure continues to rise. This creates a large waste stream at the end of the
functional life of shoes that is currently disposed in landfills around the world. This research has shown that recovery of post-consumer footwear products is largely an untapped commodity with strong reuse and recycling potential. This highlights the economic and environmental benefit that can be obtained from establishing an end-of-life product recovery in footwear sector. Hence, end-of-life product recovery procedures must be developed in the footwear sector to ensure that landfilling of post-consumer shoes is reduced and hazardous substances do not enter the environment and impact human health while the economic value of the end-of-life products, materials and components is recovered.

iv) This research has highlighted a large number of criteria related to environmental impacts, economic considerations and socio-technical issues that influence the selection of an appropriate end-of-life treatment option for post-consumer shoes. This necessitates the requirement for a systematic approach of considering these criteria as proposed by the End-of-Life Treatment of Shoes (ETS) methodology generated as part of this research.

v) Consideration of various criteria involved in selecting the most appropriate end-of-life option for post-consumer shoes has indicated the need for a multi-criteria decision making process that is capable of simultaneous consideration of a number of competing, and at times, conflicting factors. Hence, this research has proposed a novel approach for integration of a number of evaluation techniques in order to support such multi-criteria decision making process.

vi) A large volume of data and knowledge related to these evaluation techniques need to be processed to support the selection of appropriate end-of-life treatment option for post-consumer shoes. The end-of-life footwear decision support tool (EF-DST) generated by this research has been shown to be an effective and powerful tool to support shoe designers, shoe manufacturers and recovery operators to design and produce environmental friendly shoes and to establish a sustainable product life cycle in footwear sector through effective management of post-consumer shoe waste.

vii) The results from the case studies undertaken as part of this research based on two distinctly different shoe types have outlined a wide range of potential markets that can be established for the various recycled materials that can be
obtained from post-consumer shoes. These results also indicated that a small increase in the cost of recycling process can lead to generation of high quality shoe recycled materials which could have potentially valuable applications in various industries.

Throughout this research it has become evident that the idealistic vision of "zero waste to landfill" cannot be achieved by consideration of reactive end-of-life management options introduced by this research. The author is of the opinion that such vision can only be realised through consideration of proactive approaches which include design and material selection improvements. It is also argued that the methodology, the multi-criteria decision making model and the decision support software tool investigated by this research can provide invaluable support for implementing such proactive approaches within the footwear sector.

12.3 Further Work

The author recognises the following areas of further work as the most valuable extensions of the current research.

12.3.1 Shoe Design Improvements to Facilitate Recycling

This research has shown that information retrieved from the application of the ETS methodology on various types of shoes could be utilised to highlight potential design improvements. Hence, a bespoke “design for recycling” approach for the footwear sector could be further investigated to facilitate the ease of disassembly and separation and to reduce the overall cost of shoe recycling. The overall objective of such design approach will be to maximise the value recovery from post-consumer shoes whilst maintaining the original functional and aesthetic requirements.

12.3.2 Disassembly, Separation and Material Recycling Processes

The first step in developing a shoe recycling process is to successfully separate post-consumer shoes into well defined mono-fraction material streams, which could be based on either mechanical or chemical processes. For example, the separation of high quality leather in the upper part of a fashion shoe from the rubber/plastic used in the sole can
make huge difference in total revenue from the recycled material market. Therefore, a range of disassembly, separation and material recycling processes need to be investigated due to the wide ranging physical qualities, appearances, service life, and hidden value of materials used in shoe manufacture. The author proposes the development of a new generation of processes that provides the technical feasibility to recycle the majority of footwear materials (either as a raw material, a chemical feedstock or as energy) in an environmental friendly manner. It is envisaged that these processes will create higher value-added recycled materials which could be used in a wide variety of applications.

12.3.3 Application of a modified ETS Methodology in other Industrial Sectors

This research has proposed an end-of-life product recovery methodology for the specific requirements of the footwear industry. The footwear sector has been selected because it provides an ideal case for extending the traditional scope of end-of-life product recovery to other industrial domains where currently no established product recovery and recycling procedures are in place. Thus, further work is encouraged to be carried out in a number of other industrial sectors with similar characteristics. However, it is recognised that application of the EST methodology and its associated decision support model and software tool in other sectors requires modification and maybe some customisation.
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References


References


Appendix I

Automated Version of micro-AHP Model

This appendix outlines the main parts of a fully automated version of the micro-AHP model that has been developed as part of this research. This program has been developed in MS-Excel and written in Visual Basic for Applications (VBA), which is the programming language incorporated in MS-Excel. The advantage of using MS-Excel as a development environment is that it provides capabilities that allow for analysis and manipulation of the data and the visualisation of the results. In addition, MS-Excel is familiar to a large majority of people.

The program starts with an explanation screen as illustrated in Figure A1.1. Clicking on the “Run the Application” button produces the dialog box in Figure A1.2, which has a combo box with a dropdown list from where the most relevant socio-technical criteria are chosen. When all desired criteria have been added, the user should click the “No More” button, which opens the dialog box in Figure A1.3. This dialog box has the same functionality with the previous dialog box, except that the user must enter all relevant end-of-life options in the text box provided. After all criteria and alternative options have been entered, several dialog boxes similar to the one shown in Figure A1.4 appear. Each of these dialog boxes ask the user to make a pairwise comparison between two of the criteria and then between pairs of end-of-life treatment options, as shown in Figure A1.5. When all pairwise comparisons have been made, the program does the calculations based on the micro-AHP model and reports the results in a report screen as depicted in Figure A1.6. The report lists the weights for the socio-technical criteria, the scores for the alternative EoL options on each criterion, and the total scores for the EoL options while provides a consistency check for each pairwise comparison. A chart of total scores for each end-of-life option is also generated as depicted in Figure A1.7.
VBA micro-AHP Model

Run the application

This application automates the micro-AHP model for calculating socio-technical criteria of end-of-life options for post-consumer shoes. You can specify any criteria and any alternative EoL options. After you make all of the pairwise comparisons, you will see the calculated weights for the criteria, the scores for the EoL options on each criterion, the total scores for each EoL option, and consistency measures for each pairwise comparison matrix.

Figure A1.1: Explanation Screen

Criteria for EoL Alternative Options

Choose a criterion from the dropdown list or type in a criterion of your choice. Then click on the Add button to add this to your criteria list. Click the No More button if you have added all you want. Click the Cancel button to exit the application altogether.

- Technical Feasibility
- Market Pressures
- Public Opinion
- Compliance with Legislation

Add
No More
Cancel

Figure A1.2: Dialog Box for Selecting Socio-Technical Criteria

EoL Options

Enter alternative EoL Options for post-consumer shoes and then click on the Add button to add it to the list of EoL options. Click the No More button if you have added all you want. Click the Cancel button to exit the application altogether.

Enter EoL Option for post-consumer shoes:

Add
No More
Cancel

Figure A1.3: Dialog Box for Adding End-of-Life Treatment Options
Pairwise comparisons for criteria

Enter your pairwise comparisons here. For each pair, check which criterion is more important, then use the scrollbar to indicate how much more important it is than the other, then click on the Next button.

- **Pair of criteria**
  - Technical Feasibility
  - Market Pressures

- **How much more important?**

  1. About equal
  2. Strongly more important
  3. Absolutely more important

- **Number of pairs of criteria left to evaluate (after this one):** 5

Next

Figure A1.4: Pairwise Comparison Dialog Box for Socio-Technical Criteria

Pairwise comparisons between EoL Options for Technical Feasibility

Enter your pairwise comparisons here. For each pair check which EoL alternative option is preferred for the criterion shown, then a number from 1 to 9 indicating how much more preferred it is than the other, then click on the Next button.

- **Criterion: Technical Feasibility**
  - Reuse Scenario
  - Recycling Scenario 1

- **How much more important?**

  1. About equal
  2. Strongly more important
  3. Absolutely more important

- **Number of pairs of EoL Options left to evaluate on this criterion (after this one):** 9

Next

Figure A1.5: Pairwise Comparison Between EoL Option on Technical Feasibility
Results from micro-AHP Model

Weights for Criteria

<table>
<thead>
<tr>
<th>Technical Feasibility</th>
<th>Market Pressures</th>
<th>Public Opinion</th>
<th>Compliance with Legislation</th>
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<td>0.418</td>
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Scores for alternative EoL Options on various criteria

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<th>Public Opinion</th>
<th>Compliance with Legislation</th>
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<td>Incineration Scenario</td>
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<td>Landfilling Scenario</td>
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Overall EoL Option scores (best score highlighted)

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<th>Recycling Scenario 2</th>
<th>Incineration Scenario</th>
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<tr>
<td>0.269</td>
<td>0.194</td>
<td>0.207</td>
<td>0.188</td>
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</table>

Relative Consistency Indexes

- Pairwise comparisons among criteria: 0.051 (adequate consistency)
- Pairwise comparisons among EoL Options on various criteria:
  - On Technical Feasibility: 0.004 (adequate consistency)
  - On Market Pressures: 0.072 (adequate consistency)
  - On Public Opinion: 0.013 (adequate consistency)
  - On Compliance with Legislation: 0.013 (adequate consistency)

Figure A1.6: Final Report Screen

Figure A1.7: Chart of Total Scores for End-of-Life Options
Appendix II

Automated Version of macro-AHP Model (Level 1)

This appendix outlines the main components of an automated version of the macro-AHP model that has been developed as part of this research. However, it should be mentioned that this program automates only the first level of the macro-AHP model, as defined in Section 9.2.4.4 of this thesis. This program has the same structure and follows a similar approach to the program presented in Appendix I.

Hence, the program starts with an explanation screen as illustrated in Figure A2.1. Clicking on the “Run the Application” button produces the dialog box in Figure A2.2, which has a combo box with a dropdown list from where the decision criteria are chosen. When all criteria have been added, the user should click the “No More” button, which opens the dialog box in Figure A2.3. This dialog box ask the user to make a pairwise comparison between two of the decision criteria. When all pairwise comparisons have been made, the program does the calculations based on the macro-AHP model and reports the results in a report screen as depicted in Figure A2.4. The report lists the weights for the decision criteria as well as provides a consistency check for the pairwise comparison.

Figure A2.1: Explanation Screen
Figure A2.2: Dialog Box for Selecting Decision Criteria

Figure A2.3: Pairwise Comparison Dialog Box for Decision Criteria

Figure A2.4: Final Report Screen
Appendix III

Questionnaires for Case Studies

This appendix contains the completed questionnaires collected from the various experts from the footwear sector that agreed to participate in this research. The questionnaires were developed in order to obtain experts' judgements on pairwise comparisons on various decision criteria that have been used in the case studies of this thesis.

In total six questionnaires were received. Based on these questionnaires, aggregated questionnaire judgements were produced for each case study shoe. The completed questionnaires are presented below. The first three questionnaires were used in the MCS case study while the latter three were applied in the WFB case study.
SHOE RECYCLING RESEARCH
QUESTIONNAIRE

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Your Background:

Name: Andrew Ogilvie
Position: Global Director of Sustainable Ventures
Company/Organisation: Nike

Research Background

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Question 1: Judgement of Waste Management Factors

Please complete the following judgement matrix. Check the judgement which indicates the dominance of the factor in the left column over the corresponding one in its row in the right column. If there is such dominance some position in the set of values to the left of equality is checked. Otherwise equality or position in the right set of values is checked.

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Question 2: Judgement of Social-Technical Criteria

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Explanation

Market Pressures: Market pressures to develop shoe recycling activities
Public Opinion: Public opinion towards shoe recycling
Technical Feasibility: Importance of technology to develop shoe recycling procedures
Compliance with Legislation: Present or future legislative requirements regarding recycling of shoes.

THANK YOU FOR YOUR HELP
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Your Background:

Name: Aykan Gulten ..........................................

Position: Corporate Responsibility Manager...........................

Company/Organisation: Nike EMEA ....................................

Research Background

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Question 2: Judgement of Social-Technical Criteria

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</tbody>
</table>

Explanation

Market Pressures: Market pressures to develop shoe recycling activities
Public Opinion: Public opinion towards shoe recycling
Technical Feasibility: Importance of technology to develop shoe recycling procedures
Compliance with Legislation: Present or future legislative requirements regarding recycling of shoes.

THANK YOU FOR YOUR HELP
SHOE RECYCLING RESEARCH
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Your Background:
Name: 
Position: 
Company/Organisation: 

Research Background
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Question 2: Judgement of Social-Technical Criteria

Please complete the following judgement matrix following the previous instructions.

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**Explanation**
Market Pressures: Market pressures to develop shoe recycling activities
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Compliance with Legislation: Present or future legislative requirements regarding recycling of shoes

THANK YOU FOR YOUR help

209
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Your Background:

Name: Kate Larsen
Position: CSR Manager Asia
Company/Organisation: ...Burberry

Research Background

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### Question 2: Judgement of Social-Technical Criteria

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Your Background:

Name: Sheetal Nischal
Position: Business Standards Officer
Company/Organisation: Pentland Brands

Research Background

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<td>Compliance with Legislation</td>
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</table>

Explanation

Market Pressures: Market pressures to develop shoe recycling activities
Public Opinion: Public opinion towards shoe recycling
Technical Feasibility: Importance of technology to develop shoe recycling procedures
Compliance with Legislation: Present or future legislative requirements regarding recycling of shoes

THANK YOU FOR YOUR HELP
SHOE RECYCLING RESEARCH QUESTIONNAIRE

This questionnaire has been created as part of a PhD research project undertaken by Mr Theodoros Staikos at Loughborough University in the UK. The aim of the project is to investigate the realisation of a sustainable recycling chain for the global footwear industry.

To complete this work and give the project stronger industrial foundation, I would be very grateful if you could spend 3 minutes giving me the benefit of your experience and judgement.

Thank you in advance for your cooperation and help.

Disclaimer: The responses of this questionnaire are confidential and are intended for research purposes only. All responses will be held on a private secure server in accordance with data protection act, and publication of any obtained results will be confined to academic publication. All opinions held there within are assumed to be that of the respondent(s), and may not be representative of the organisations you are associated with.

Your Background:

Name: Damian Peat ..............................................
Position: Brand Manager ......................................
Company/Organisation: Terra Plana/Worn Again ......................................

Research Background

A decision making model for shoe recycling has been developed to simultaneously consider quantitative (environmental, economic) and qualitative (social-technical) factors. Environmental factors include a number of well-recognised environmental impact category indicators (i.e. global warming potential, human eco-toxicity etc) while economic criteria are simply divided into costs and benefits for each shoe recycling scenario. The list of social-technical criteria is almost endless and could be easily changed by the user depending on the requirements of the analysis and the type of shoe under consideration.
Question 1: Judgement of Waste Management Factors

Please complete the following judgement matrix. Check the judgement which indicates the dominance of the factor in the left column over the corresponding one in its row in the right column. If there is such dominance some position in the set of values to the left of equality is checked. Otherwise equality or position in the right set of values is checked.

<table>
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</table>

Question 2: Judgement of Social-Technical Criteria

Please complete the following judgement matrix following the previous instructions.

<table>
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<th>Strong</th>
<th>Weak</th>
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<th>Weak</th>
<th>Strong</th>
<th>Very Strong</th>
<th>Absolute</th>
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</thead>
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<td></td>
<td>X</td>
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</tr>
<tr>
<td>Market Pressures</td>
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</tbody>
</table>

Explanation

Market Pressures: Market pressures to develop shoe recycling activities
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Compliance with Legislation: Present or future legislative requirements regarding recycling of shoes

THANK YOU FOR YOUR HELP
Appendix IV

Life Cycle Assessment Study of a Women’s Fashion Boot

This appendix presents the goal and scope definition of the study as well as some of the most important results of the streamlined LCA study of a Women’s Fashion Boot (Case Study 2) using the Sima Pro 7 LCA software package.

Goal and Scope Definition

1. Goal of the study
The primary objective of the study is to evaluate and compare the environmental impacts of alternative end-of-life treatment options for a particular type of a post-consumer shoe, namely a women’s fashion boot.

1.1 Intended application
The study will be utilised as reference information for the PhD thesis.

1.2 Intended audience
The results of this study will not be disclosed to the public.

2. Scope of the Study

2.1 Functional Unit
The functional unit is a women’s fashion boot typically used as fashion statement both at work or during spare time activities. The weight of the product is 275g. The composition of different parts and components is previously presented in Section 10.4.1.4.

2.2 System Boundaries
The whole life cycle of the product from cradle to grave including raw materials, transportation, manufacturing, use and disposal was considered.

2.3 Method of Life Cycle Inventory Analysis
Physical and chemical relevance was the basis for allocation whenever feasible. The ecoinvent 1.2 and IDEMAT 2001 databases were used for the inventory analysis.

2.4 Method of Life Cycle Impact Assessment
The EDIP 97 impact assessment method was used as previously described in Section 8.5.1.1.

2.5 Method of Life Cycle Interpretation
Contribution analysis was performed to identify environmental hot spots during the life cycle of the product based on the results of the life cycle impact assessment.

2.6 Assumption and Limitations
An initial limitation of the current study is that the data collection only included literature sources and commercial databases and not site-specific data. Furthermore, data collection efforts have been focused on life cycle stages where preliminary calculations or earlier experience indicated that the difference in environmental impacts could be significant. It should also be mentioned that the boundary conditions and system definitions have great influence on the study results. Desired results could be achieved by simply choosing the “right” system boundaries. For this reason, the issue of clearly defining and documenting the system boundaries is quite important to an LCA’s transparency and credibility.

Major Results of LCA Study

Some of the major results of the life cycle assessment study are presented in the following figures. Figure A4.1 shows the characterisation results of the analysis for the different end-of-life treatment options.
Figure A4.1: Characterisation Results of LCA Study

Figure A4.2 presents the normalisation results of the analysis while Figure A4.3 shows the weighting results.

Figure A4.2: Normalisation Results of LCA Study
Figure A4.3: Weighting Results of LCA Study

Finally, the single score of the streamline life cycle assessment study is illustrated in Figure A4.4.

Figure A4.4: Single Score of LCA Study
Appendix V

Post-Consumer Waste Management Issues in the Footwear Industry

This paper has been published in the Journal of Engineering Manufacture (Part B of the Proceedings of the Institution of Mechanical Engineers), Vol. 221(2), pp. 363-368.
Abstract: Currently, 17 billion pairs of shoes are produced worldwide every year, and this figure continues to rise. This creates an enormous amount of post-consumer (end-of-life) shoe waste that is currently being disposed of in landfill sites around the world. The research reported in this paper is an initial investigation into realization of a holistic approach to application of recovery and recycling in the footwear industry. The paper provides a brief review of the trends in the footwear sector regarding the amount of end-of-life waste produced, together with existing reuse and recycling activities. It also presents an integrated waste management framework by combining a mix of design and material improvements, as well as reuse, recycling, and energy recovery activities, and concludes by examining the challenges in establishing end-of-life product recovery procedures for post-consumer shoes.

Keywords: end-of-life management, shoe recycling, product recovery, footwear industry

1 INTRODUCTION

The footwear industry over the last 20 years has placed significant effort in improving material efficiency during the production phase, as well as eliminating the use of hazardous materials in shoe production. However, the environmental gains made in production are being overtaken by the considerable increase in the demand for footwear products. Moreover, the useful life of shoes is relatively short and progressively decreasing as a result of rapid market changes and consumer fashion trends. This creates a large waste stream at the end of the functional life of shoes, which are often being disposed of in landfills. Producer responsibility and other forthcoming environmental legislation, as well as increasingly environmental consumer demands, are expected to challenge the way the footwear industry deals with its end-of-life waste. Thus, an investigation into a holistic approach to shoe recovery and recycling is being undertaken, as reported in this paper.

The initial part of the paper provides a review of current trends regarding the amount of end-of-life waste produced by the footwear industry. The latter sections present an integrated waste management framework for shoes and discuss the challenges in establishing end-of-life product recovery procedures for post-consumer shoes.

2 SCALE OF POST-CONSUMER SHOE WASTE

From 1990 to 2004, worldwide footwear production increased by a staggering 70 per cent to more than 17 billion pairs of shoes per year [1]. In fact, worldwide footwear production and consumption are being doubled every 20 years, from 2.5 billion pairs in 1950 to an expected 2 billion pairs of shoes in 2010 [2]. In the European Union, footwear consumption increased by 22 per cent from 2002 to 2005 to reach 2.3 billion pairs of shoes [3]. Additionally, the worldwide per capita consumption of footwear has also been considerably increased, from one pair of shoes for every person in the world in 1950 to almost 2.6 pairs of shoes in 2005. However, footwear consumption differs significantly between countries. Although China, owing to its large population, has the highest footwear consumption in the world, the
There are a number of environmental concerns linked with the footwear industry. These occur both in the production of raw materials and within footwear manufacturing itself and include the use of hazardous materials and chemicals in shoes, the air and water emissions, and the solid waste generated during the production process. In particular, the use of chromium as a tanning agent, which is highly toxic and a suspected carcinogen, has been a major environmental concern for the footwear industry over the last few decades.

However, the most important environmental challenge that the footwear industry is currently facing is the enormous amount of waste generated at the end-of-life phase, with most shoes being disposed of in landfills. Landfill sites can result in serious environmental pollution of groundwater and rivers, caused by landfill leachate (the liquid produced from the decomposition of waste within the landfill). The landfill restrictions introduced by Article 5 of the EU Landfill Directive are very important, in particular the reduction in the amount of biodegradable waste going to landfill and the prohibition of landfilling for certain waste types [7]. Since 1 June 2005, German and Austrian landfills have only accepted biodegradable municipal waste that has been either incinerated or undergone mechanical and biological treatment. Furthermore, the UK Landfill Allowances and Trading Scheme Regulations (LATS) introduced in 2004 determine the percentage of certain waste types that are regarded as biodegradable municipal waste. These biodegradable materials range from paper, card, and vegetable oils (potentially 100 per cent biodegradable) through to footwear, furniture, and textiles (50 per cent biodegradable) to batteries, glass, and metal waste (0 per cent biodegradable) [8]. This means that certain types of biodegradable material such as leather, natural textiles, natural rubbers, etc., which are extensively used by the footwear industry, will soon be required to be reused or recycled instead of directly disposed of in landfill sites.

### Table 1 Per capita footwear consumption in different countries

<table>
<thead>
<tr>
<th>Countries</th>
<th>Population (million inhabitants)</th>
<th>Footwear consumption (1000 pairs)</th>
<th>Footwear consumption per capita/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU-25</td>
<td>456.5</td>
<td>2,054,571</td>
<td>4.5</td>
</tr>
<tr>
<td>Germany</td>
<td>82.5</td>
<td>320,800</td>
<td>3.9</td>
</tr>
<tr>
<td>France</td>
<td>59.6</td>
<td>335,502</td>
<td>5.5</td>
</tr>
<tr>
<td>UK</td>
<td>59.3</td>
<td>312,802</td>
<td>5.3</td>
</tr>
<tr>
<td>Italy</td>
<td>57.3</td>
<td>385,302</td>
<td>6.8</td>
</tr>
<tr>
<td>Spain</td>
<td>41.5</td>
<td>136,202</td>
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<td>16.1</td>
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<td>4.6</td>
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<tr>
<td>USA</td>
<td>289</td>
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<tr>
<td>China</td>
<td>1,287.1</td>
<td>2,900,000</td>
<td>2.2</td>
</tr>
<tr>
<td>Brazil</td>
<td>195.0</td>
<td>490,000</td>
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</tr>
<tr>
<td>India</td>
<td>1,041.9</td>
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<td>0.6(^*)</td>
</tr>
<tr>
<td>Vietnam</td>
<td>84.2</td>
<td>N/A</td>
<td>0.5(^\alpha)</td>
</tr>
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</table>


\(^\alpha\) Footwear Market Survey, 2004 [4].

\(^\beta\) http://www.apparellandfootwear.org/data/shoestats2005.pdf [5].

\(^\gamma\) Footwear Markets Predictions, 2003 [6].

United States is the country with the highest per capita shoe consumption, since each inhabitant purchases an average of 6.9 pairs of shoes every year. In Europe, and in the case of the 25 member states of the European Union (including the new member states), the yearly per capita shoe consumption in 2003 was 4.5 pairs of shoes, while in the United Kingdom the average was slightly higher at 5.3 pairs. At the other extreme, in the less developed countries, the per capita shoe consumption is 0.6 pairs for India and 0.5 pairs of shoes for Vietnam (all types of shoe included). Table 1 presents the per capita shoe consumption in a number of different countries.

### 3 ENVIRONMENTAL CONCERNS IN THE FOOTWEAR INDUSTRY

There are a number of environmental concerns linked with the footwear industry. These occur both in the production of raw materials and within footwear manufacturing itself and include the use of hazardous materials and chemicals in shoes, the air and water emissions, and the solid waste generated during the production process. In particular, the use of chromium as a tanning agent, which is highly toxic and a suspected carcinogen, has been a major environmental concern for the footwear industry over the last few decades.

However, the most important environmental challenge that the footwear industry is currently facing is the enormous amount of waste generated at the end-of-life phase, with most shoes being disposed of in landfills. Landfill sites can result in serious environmental pollution of groundwater and rivers, caused by landfill leachate (the liquid produced from the decomposition of waste within the landfill). The landfill restrictions introduced by Article 5 of the EU Landfill Directive are very important, in particular the reduction in the amount of biodegradable waste going to landfill and the prohibition of landfilling for certain waste types [7]. Since 1 June 2005, German and Austrian landfills have only accepted biodegradable municipal waste that has been either incinerated or undergone mechanical and biological treatment. Furthermore, the UK Landfill Allowances and Trading Scheme Regulations (LATS) introduced in 2004 determine the percentage of certain waste types that are regarded as biodegradable municipal waste. These biodegradable materials range from paper, card, and vegetable oils (potentially 100 per cent biodegradable) through to footwear, furniture, and textiles (50 per cent biodegradable) to batteries, glass, and metal waste (0 per cent biodegradable) [8]. This means that certain types of biodegradable material such as leather, natural textiles, natural rubbers, etc., which are extensively used by the footwear industry, will soon be required to be reused or recycled instead of directly disposed of in landfill sites.

### 4 CURRENT REUSE AND RECYCLING ACTIVITIES IN THE FOOTWEAR SECTOR

The footwear industry's response to the increasing problem of post-consumer shoe waste has been negligible. In fact, only one major shoe manufacturer, Nike, has taken measures to manage its waste. Nike's recycling programme 'NikeGO Places' (formerly 'Reuse-A-Shoe') is the only product take-back and recycling scheme currently established by a shoe manufacturer. According to Nike [9], since its inception in 1993, the 'Reuse-A-Shoe' programme has recycled more than 16 million pairs of worn-out and defective athletic shoes in total.

Another form of reuse activity in the footwear sector is the collection and distribution of worn or
unwanted shoes to developing countries. Reuse schemes are mainly supported by charity organizations, local authorities, and municipalities such as the Salvation Army Trading Company Ltd (SATCOL), Oxfam, and others. However, there is a strong debate about such reuse activities in terms of their overall environmental impact and their economic consequences for local communities. According to Wicks and Bigsten [10], redistribution of second-hand products into developing countries may also lead to net economic damage to the local economies as a result of ‘dumping’ of cheap used footwear. In the case of Uganda, the import of a large volume of second-hand shoes in recent years has significantly reduced the size of the local footwear industry. About 7 million pairs of second-hand shoes are imported into Uganda annually, while only 240 000 pairs are produced by the local footwear industry [11]. However, as the cost of producing new shoes is coming down and the markets are flooded with lower-quality shoes, it is expected that the price difference between new shoes and second-hand shoes will shrink in less developed countries. The demand for second-hand shoes might then drop in these countries, leading to more post-consumer shoes needing to be recycled and disposed of in the developed world.

5 WASTE MANAGEMENT FRAMEWORK FOR SHOES

An integrated waste management framework for footwear products has been developed and is presented in Fig. 1. This proposed framework divides the waste management options for shoes into two major approaches: proactive and reactive. Proactive approaches include all measures that are taken with the aim of minimizing waste during both the production and the end-of-life phase. On the other hand, reactive approaches include all the other waste management options which act in response to the waste problem when the useful life of the product has ended, and are hence referred to as end-of-life management.

5.1 Proactive approaches

Although there is a wide range of proactive waste management activities, there are two major improvement methods that could be applied in the footwear industry in order to minimize waste at the source, namely design and material improvements. Design improvements include activities at the beginning of a product’s life cycle, i.e. in the product design phase through the application of ecodesign.
5.2 Reactive approaches (end-of-life management)

Where waste material is produced, an optimal treatment option must be selected with the lowest possible risks to human health and the environment. Direct reuse of shoes with minimal processing is a possible option, but there are a few variables that need to be considered such as the condition of the shoe at the end of its life, the collection and distribution system, as well as the purpose of its reuse. Recycling involves the reprocessing of end-of-life footwear products, parts, or materials, either into the same product system (closed loop) or into different ones (open loop). The end-of-life waste is therefore reintroduced back into the market through a series of recycling processes that can be divided into two major methods: destructive and non-destructive. Destructive methods, mainly through the shredding process, could be used to transform shoes into other useful materials. Shredded materials can be directly used in secondary applications such as surfacing of roads, playgrounds, and sound insulation. On the other hand, non-destructive recycling methods involve the dismantling of shoes to isolate materials for further recycling in order to obtain a high grade of quality of recycled materials that can be used in a wider range of applications. Non-destructive methods generally include sorting, inspection, disassembly, and then shredding of separated materials. However, disassembly of shoes is not an easy task owing to the large amount of adhesive typically used to join shoe parts together, along with stitching techniques. A number of disassembly experiments related to different types of shoe have been performed as part of this research work, as depicted in Fig. 2. The development of a semi-automated shoe disassembly system is one of the authors’ research goals.

An additional reactive waste management option for post-consumer shoes is to generate heat and electricity through energy recovery. This includes a number of established and emerging technologies such as incineration, gasification, and pyrolysis. In the case of leather waste, gasification technology has been applied for heat generation and chromium recovery. Finally, disposal of waste in landfills is often regarded as the last-resort waste management option with the highest environment impact. However, disposal of post-consumer waste may present difficulties in the future owing to recently introduced legislation that bans landfilling of certain waste streams (see section 3).

6 CHALLENGES IN ESTABLISHING END-OF-LIFE PRODUCT RECOVERY IN THE FOOTWEAR INDUSTRY

Forthcoming legislation and market pressures are expected to force the footwear industry towards measures to deal with its end-of-life waste. Hence, the authors argue that an end-of-life product recovery system for post-consumer shoes needs to be established to minimize the environmental impacts of end-of-life shoes while taking advantage of the economic value of end-of-life materials, components, and products. This highlights a number of
challenges for developing such a product recovery chain for post-consumer shoes, which are discussed in the following sections.

6.1 Establishing sustainable reverse logistics in the footwear sector
Reverse logistics and collection of post-consumer shoes are already happening, but on a very small scale and mainly for reuse purposes. The standard shoe collection process includes a number of specially designed ‘shoe banks’ based at recycling stations, schools, charity shops, and other participating outlets. Other possible shoe collection options include kerbside collection (as part of already existing door-to-door municipal waste collection) and recycling point collection systems (where consumers bring all kinds of shoe to containers located in recycling stations). However, at present the lack of an appropriate infrastructure results in a small proportion of post-consumer shoes being collected for recycling, while the majority end up in the normal waste stream for landfill or incineration. Financial incentives could also be considered as an option to facilitate the collection of a greater volume of post-consumer shoes, i.e. a discount on new shoes when you bring back a pair of used shoes. Clearly, establishing sustainable reverse logistics in the footwear industry is one of the key drivers for successful end-of-life product recovery.

6.2 New generation of recycling processes in the footwear industry
The consideration of shoe composition clearly indicates that a pair of shoes may contain various recycled materials such as leather (chromium tanned or chromium free), polymers (PU, PVC, etc.) as well as natural and synthetic textiles. The challenge is, therefore, to develop a new generation of recycling processes that provides the technical feasibility to recycle the majority of these materials (either as a raw material, a chemical feedstock, or as energy) in an environmental friendly manner (low emissions and less use of non-renewable energy and other natural resources). The cost of such an environmentally friendly approach to shoe recycling may be higher than the cost of the present waste management method (landfilling) but could become competitive in the longer term as new market opportunities develop for recoverable materials.

The first step in developing a shoe recycling process is successfully to separate post-consumer shoes into well-defined monofraction material streams, which could be based on either mechanical or chemical processes. The research is also exploring the use of such materials in low-grade applications, i.e. equestrian surfacing for horseriding arenas, sound insulation, etc., and possible use in shoe manufacturing.

6.3 Establishing a value recovery chain for post-consumer shoes
Once end-of-life shoe waste is collected, separated, and converted into a form that can be used either by the footwear industry or by other industrial sectors, it must compete with virgin materials both on price and performance. A sustainable footwear recycling application depends heavily on establishing a successful value recovery chain. Issues that need to be considered include the size and the value of the end market, the current and predicted buying trends, as well as the range and price of competing materials and products. Furthermore, possible legislative requirements can play an important role in developing economically feasible value recovery chains for post-consumer shoes. Such legislation can take the form of business-centred legislation, i.e. the recycling fee imposed by the car industry and the white goods sector in certain European countries, or consumer-centred legislations, i.e. the introduction of a recycling fee for newly sold shoes. The revenues created through such legislation can be used to develop and sustain successful end-of-life product recovery for post-consumer shoes.

7 CONCLUSIONS
The large amount of post-consumer shoe waste produced every year, the legislative pressures to divert waste from landfills, as well as the hidden value of recyclable materials in post-consumer shoes have led to the investigation of post-consumer waste management issues in the footwear industry. Past experience in other industrial sectors, i.e. automotive and electrical/electronic equipment, has shown that end-of-life product recovery procedures need to be not only environmentally acceptable but also economically and technologically justified.

Many of the technical, economical, and environmental issues raised in this paper have highlighted the need to overcome the barriers that exist in establishing end-of-life recovery procedures in the footwear industry. Collection of post-consumer shoes, separation into well-defined material streams, and, finally, value recovery of recyclable materials are among the crucial factors in establishing sustainable end-of-life product recovery in the footwear industry. The next phase of the research is exploring these crucial factors to ensure that shoe recovery and recycling is commonplace across the globe in the near future.
REFERENCES


4 EU market survey 2004: footwear, Centre for the Promotion of Imports from Developing Countries (CBI), December 2004.


Appendix VI

A Decision Making Model for Waste Management in Footwear Industry

This paper has been accepted for publication at the Special Issue on Sustainable Production in the International Journal of Production Research, September 2007.
A Decision Making Model for Waste Management in Footwear Industry
Theodoros Staikos* and Shahin Rahimifard
Centre for Sustainable Manufacturing and Reuse/Recycling Technologies (SMART)
Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, UK
*T.Staikos@lboro.ac.uk

Abstract
The footwear industry, over the last years, has placed significant effort to improving energy and material efficiency, but in comparison little effort has been directed at the recovery and recycling of shoes at the end of their functional life. In reality, most worn and discarded (end-of-life) shoes are disposed off in landfills. Producer responsibility issues and forthcoming legislations as well as increasingly environmental consumer demands are expected to challenge the way the global footwear industry deals with the its End-of-Life waste. This paper presents an investigation into the steps required to consider the end-of-life implication of shoes and promote post-consumer recycling practices in the footwear industry. The paper describes the design and specification of a decision making model to identify the most appropriate reuse, recovery and recycling option for post-consumer shoes. Such tool in addition to supporting design and material selection processes could also provide benchmark information for the selection of a best End-of-Life practice for a selected range of shoe types. The paper concludes by providing a case study for shoe waste management to demonstrate the practicality of this decision making model.

Keywords: Footwear Industry, End-of-Life Management, Decision Making Model

1 Introduction
The footwear industry is a diverse manufacturing sector which employs a wide variety of materials to make products ranging from different types and styles of shoes to more specialised footwear. Leather, synthetic materials, rubber and textile materials are amongst the basic materials most commonly used in shoe manufacture; each material having its own specific characteristics. These differ not only in their appearance but also in their physical qualities, their service life, the different treatment needs as well as their recycling and recovery options at the end of their useful life. Design and material selection activities significantly influence not only the life of the footwear, but also its end-of-life treatment.

In the recent past, a consumer would own a few pairs of shoes, some for exercising and others for work or fashion. But today's consumer demands a larger variety of shoes including options for specialised footwear. To meet the needs of customers and be competitive, footwear companies face two key challenges: to be responsive to market changes and to establish efficient product development in order to identify or establish new consumer trends. Responsiveness to customer demands leads to a shorter life cycle of shoes, and an increasingly shorter product development cycle. A shorter life cycle means that more shoes will be produced over the years, so leading to a higher level of post-consumer waste. From 1990 to 2004, worldwide footwear production has increased by 70% to around 17 billion pairs of shoes while by 2010 experts in the sector expect the global footwear output to reach 20 billion
pairs (World Footwear 2005). In the European Union, footwear consumption has increased by a staggering 22% from 2002 to 2005 to reach 2.3 billion pairs of shoes (EC 2006). Additionally, the footwear per capita consumption has increased considerably, from 1 pair of shoes for every person in the world in 1950 to almost 2.6 pairs of shoes in 2005. However, footwear consumption differs significantly per country. Although China, due to its large population, has the highest footwear consumption in the world, the United States has the highest per capita shoe consumption with each inhabitant purchasing an average of 6.9 pairs of shoes every year (AAfA 2006). In Europe (including new Member States), the yearly per capita shoe consumption in 2003 was 4.5 pairs of shoes, while in the United Kingdom the average is slightly higher at 5.3 pairs of shoes/person/year (CBI 2004). At the other extreme, in less developed countries the per capita shoe consumption is only 0.6 pairs for India and 0.5 pairs of shoes for Vietnam (all types of shoes included) (SATRA 2003).

In any product recovery application, there are a number of possible end-of-life treatment options with different environmental impacts, economic values and technical requirements. Hence, there is a need for a decision making process to evaluate these factors and provide support to decision making. This paper has proposed such a decision making model for end-of-life waste management in footwear industry. The initial part of the paper provides a review of relevant literature on product recovery and investigates current reuse and recycling practices for post-consumer shoes. The main section describes the design and specification of a decision making model for shoe waste management. Finally, a case study of a selected shoe type is presented at the last part of the paper.

2 Overview of Relevant Research

The increasing significance of product recovery has brought a corresponding growth in research covering the various stages of the product life cycle (Gupta and Gungor 1999). Therefore, many definitions and categorisations exist in the literature regarding product recovery activities. Thierry et al. (1995) present a categorisation of product recovery options into repair, refurbish, remanufacture, cannibalisation and recycling while Johnson et al. (1995) define the product recovery process simply as a combination of remanufacture, reuse and recycling. On the other hand, Moyer and Gupta (1997), Brennan et al. (1994), and US EPA (1997), simply classify the recovery of end-of-life products into material recovery (recycling) and product recovery (remanufacturing).

Additionally, a number of studies have investigated a range of different factors such as economic, environmental, technical and social criteria, which influence product recovery options (Krikke et al. 1998, Goggin et al. 2000, Lee et al. 2001, Erdos et al. 2001 and Bufardi et al. 2003). Different methodologies have also been developed to find a balance between the time and money invested in product recovery operations and value gained from the recovered products and materials. Johnson et al. (1995) suggest a methodology which aims to identify a preferred sequence of disassembly steps whilst maximising the value gained from recovery products while Hentschel et al. (1995) present an approach to recycling system planning for used products at their end-of-life phase. Also, Rahimifard et al. (2004) suggested a novel systematic five-stage methodology,
called PRIME, to support product end-of-life management in different manufacturing applications based on an integrated view of a product supply and recovery chain.

3 Current Reuse and Recycling Practices in the Footwear Industry

In the UK, more than 330 million pairs of shoes are consumed every year (SATRA 2003). It is estimated that the amount of waste generated from post-consumer shoes in the UK could reach 200,000 tonnes per year, with most of it end up in landfills. The figure for the European Union is almost 1.5 million tonnes per year. Footwear industry's response to this increasing problem of post-consumer shoe waste has been negligible. In fact, only one major shoe manufacturer, Nike\textsuperscript{®}, has taken measures to manage its waste. Nike's recycling programme "NikeGO-Places\textsuperscript{®}" (formerly "Reuse-A-Shoe\textsuperscript{®}") is the only product take-back and recycling scheme currently established by a shoe manufacturer. This programme has been operating for over a decade in the United States and has just started operating in the UK, Australia and Japan Nike (2006). Their reuse and recycling programme involves a series of collection points in retail centres where people can deposit their worn-out and discarded athletic shoes. The shoes are then collected and taken to a central recycling facility where they are shredded, producing a material called "Nike-Grid\textsuperscript{®}", which can be used in the surfacing of tennis and basketball courts, playgrounds and running tracks. According to Nike (2006), since its inception in 1993, the "Reuse-A-Shoe" programme has recycled more than 16 million pairs of worn-out and defective athletic shoes in total.

Another form of reuse activity in the footwear sector is the collection and distribution of worn or unwanted shoes to developing countries. Reuse schemes are mainly supported by charity organisations, local authorities and municipalities such as the Salvation Army Trading Company Ltd. (SATCOL\textsuperscript{®}), Oxfam and others. In the UK, SATCOL alone, with its 2,300 banks and door-to-door collections and donations, have managed to collect around 971 tonnes of worn or unwanted shoes during the year 2000-2001 (Woolridge et al. 2006). However, there is a strong debate about such reuse activities in terms of their overall environmental impact and the economic consequences for the local communities. It has been argued that collection and distribution of worn or unwanted shoes in developing countries diverts post-consumer waste from the developed world to poor countries with no infrastructure to deal with. According to Wicks et al (1996), re-distribution of second hand products into developing countries may also lead to net economic damage to the local economies due to 'dumping' of cheap used footwear. In the case of Uganda, the import of large volume of second hand shoes in recent years has significantly reduced the size of the local footwear industry. About 7 million pairs of second hand shoes are imported into Uganda annually while only 240,000 pairs of shoes are produced by the local footwear industry (Temsch et al. 2002). However, as the cost of producing new shoes reduces and the markets are flooded with lower quality shoes, it is expected that the price difference between new shoes and second-hand shoes will shrink in less-developed countries. The demand for second-
hand shoes might then drop in these countries, leading to an increase in post-
consumer shoe recycling and disposal in the developed world.

However, not all materials used in footwear manufacturing can be recycled or
reused. Once post-consumer waste is collected, separated and converted into
a form that can be used by either the footwear industry or other industrial
sectors, it must compete with virgin materials both on price and performance.
Although in the case of other industrial sectors (i.e. metal and glass industry)
established recycling markets already exist, in other material markets such as
leather, textiles and plastics the situation is more complex.

4 Decision Making Model for Shoe Waste Management

This study presents a decision making model for end-of-life shoe waste
management. This model has been developed to simultaneously consider
quantitative and qualitative waste management factors. For this reason, the
analytic hierarchy process (AHP), which is a multi-criteria decision making
(MCDM) method, has been applied to construct the basic framework for
analysing these factors. Additionally, a number of other decision making
techniques have been utilised to calculate economic and environmental criteria
such as Cost-Benefit Analysis (CBA) and Life Cycle Assessment (LCA), as
described in Figure 1.

Multi-criteria decision making is a scientific field which has seen a considerable
development during the last decades. As its name indicates, multi-criteria
decision making aims to give decision-makers tools to enable them to advance
in solving problems where several, often contradictory, criteria must be taken
into account (Vincke 1992). The AHP method, developed by Saaty (1980), is
one of the most widely used MCDM methods and has been applied in a variety
of applications in different fields such as planning, selecting the best alternative
option, resources allocation, and optimisation (Vaidya et al. 2006). In addition, a
number of researchers have investigated the combined application of AHP and
LCA in various industrial case studies (Hermann et al. 2006, Daniel et al. 2004
and Huang et al. 2004). According to Henson et al. (2002) the AHP is consistent
with the LCA concept because the environmental factors can be hierarchically
structured into impacts and improvement options.

The proposed decision making model for end-of-life shoe waste management,
as depicted in Figure 1, outlines of the main steps, and the decision aid method
that has been applied in each step. Economic criteria are calculated using Cost-
Benefit Analysis (CBA) to identify cost and benefits for each end-of-life
management scenario, while environmental impacts are calculated by a
streamlined Life Cycle Assessment (LCA).
4.1 Design Shoe Waste Management Model

A waste management model for post-consumer shoes determines the different end-of-life management options, giving priority to recycling and reuse and minimising cost and environmental impacts. The output of such a model would identify potential treatments for post-consumer shoes depending on the type of shoe. However, a shoe waste management model does not optimise the waste management treatments for each type of shoe; it simply lists the options available for treating the post-consumer waste as well as identifying potential applications for recycled materials.

In general, a shoe waste management model consists of the following end-of-life management options (Staikos et al. 2006):

i) Reuse
ii) Recycling
iii) Energy recovery
iv) Disposal

Figure 1: Decision Making Model for Shoe Waste Management
Reuse of post-consumer shoes is a possible option but there are variables that need to be considered such as the condition of the shoe at the end of its functional life, the collection and distribution system as well as the purpose of its reuse (see Section 3). Recycling involves the reprocessing of post-consumer shoes, parts or materials, either into the same product system (closed loop) or into different ones (open loop). The waste is, therefore, re-introduced back into the market through a series of destructive and non-destructive recycling processes. Energy recovery is another possible waste management option for post-consumer shoes and includes a number of established and emerging technologies such as incineration, gasification and pyrolysis. Finally, disposal of waste to landfills is currently the most common waste management option for post-consumer shoes.

4.2 Identify Waste Management Factors
This decision making model takes into consideration both quantitative (environmental and economic criteria) and qualitative (technical criteria) factors. Environmental criteria include a number of well-recognized environmental impact category indicators (i.e. global warming potential, human eco-toxicity etc). Economic criteria are simply divided into costs and benefits for each end-of-life management scenario (i.e. resale price of reused shoe, cost of landfilling etc). The list of technical criteria is almost endless and could be easily changed by the user depending on the requirements of the analysis and the type of shoe under consideration.

4.3 Prioritise Alternatives
Although many multi-criteria decision making methods can be applied to prioritise alternatives, AHP is considered as one of the most comprehensive MCDM methods (Triantaphyllou 2000). In general, the AHP method decomposes a complex decision problem into a hierarchy and allows the consideration of both quantitative and qualitative (objective and subjective) factors in selecting the best alternative option (Saaty 1980). It also provides a methodology to calibrate the numeric scale for the measurement of quantitative and qualitative performances. Application of the AHP method requires the following steps: structuring of the problem into a hierarchy, making pairwise comparisons, calculating criteria weights, and synthesising the priorities (Saaty and Vargas 2001).

4.3.1 Structuring the problem into a decision hierarchy
In applying the AHP method, the first step is decomposition or the structuring of the problem into a hierarchy. Decomposition requires that the decision problem be decomposed into a hierarchy that captures the essential variables (factors, criteria, sub-criteria) of the problem. The decision hierarchy is structured so that the top level represents the overall objective or goal of the problem. Factors, criteria and sub-criteria upon which this goal is dependent are assigned to the lower levels of the hierarchy. The lower level contains the alternatives or options through which the goal may be achieved.
4.3.2 Making pairwise comparisons

The next step is to make pairwise comparisons of any two decision variables belonging to the same hierarchical level. The pairwise comparison of the decision variables is performed using the fundamental Saaty scale shown in Table 1.

<table>
<thead>
<tr>
<th>Numerical Rating</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Both criteria equally important</td>
</tr>
<tr>
<td>3</td>
<td>Very slight importance of one criterion over the other</td>
</tr>
<tr>
<td>5</td>
<td>Moderate importance of one criterion over the other</td>
</tr>
<tr>
<td>7</td>
<td>Demonstrated importance of one criterion over the other</td>
</tr>
<tr>
<td>9</td>
<td>Extreme or absolute importance of one criterion over the other</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values between two adjacent judgements</td>
</tr>
</tbody>
</table>

*Table 1: The AHP Pairwise Comparison Scale (Saaty 1980)*

The relative weights or priorities of decision criteria and alternatives need to be identified. From the set of pairwise comparison of the variables, a judgment matrix $A$ is generated with $n$ rows and $n$ columns, where $n$ is the number of variables being considered.

$$A = \begin{bmatrix} A_{11} & \ldots & A_{1n} \\ \vdots & \ddots & \vdots \\ \vdots & \ddots & \vdots \\ A_{n1} & \ldots & A_{nn} \end{bmatrix}$$

4.3.3 Calculate waste management criteria weights

Based on the developed judgement matrix $A$, a series of calculations are then performed in order to identify the relative weight of each waste management criterion.

4.3.3.1 Environmental Criteria

Environmental criteria for end-of-life management scenarios are calculated using the Life Cycle Assessment (LCA) methodology. The environmental impact ($EI$) score of each scenario is expressed in eco-indicator points (mPt) and computed as follow:

$$EI_j = \sum_{i=1}^{n} IC_{ii}$$  \hspace{1cm} (1)

where

$I_{Ci} = $ impact category indicator $i$

$n = $ number of impact category indicators

$j = $ number of waste management scenarios
The Life Cycle Inventory (LCI) data is derived from a streamlined LCA study of average shoes, which was based on generalised manufacturing data found in commercial databases. The LCI calculations and the Life Cycle Impact Assessment (LCIA) phase are conducted in SimaPro 7 LCA software using recognised impact assessment methods.

Finally, the environmental impact score ($E_{lj}$) of each scenario need to be normalised and expressed in unit-free numbers for consistency purposes. The normalised environmental impact score ($NE_{lj}$) for each scenario is calculated as follows:

i) calculate the reciprocal of each environmental impact score ($RE_{lj}$)

ii) divide the reciprocal of each environmental impact score ($RE_{lj}$) by the sum of all reciprocal scores.

\[
NE_{lj} = \frac{RE_{lj}}{\sum_s RE_{lj}} \quad (2)
\]

where

\[RE_{lj} = \frac{1}{E_{lj}}\]

$E_{lj} = $ environmental impact score of each scenario ($s$)

4.3.3.2 Economic Criteria

Economic values for each end-of-life management scenario are calculated using the benefit to cost ratio approach. The benefit to cost ratio (BCR) must be greater than or equal to 1 i.e. $B/C > 1$, where B is the benefit and C is the cost of each alternative. The end-of-life economic value and benefit/cost ratio are calculated based on the following methods:

i) Reuse Benefit/Cost Ratio (BCR$_{RE}$)

The revenue of the reuse scenario ($B_{RE}$) derived from the resale value of the shoe ($B_{resale}$) while the costs ($C_{RE}$) arise from collection costs ($C_{collection}$), transportation costs ($C_{trans}$) and refurbishing costs ($C_{refurb}$). Therefore, the Reuse Benefit/Cost Ratio (BCR$_{RE}$) can be obtained as follows:

\[
BCR_{RE} = \frac{B_{resale}}{\sum C_{RE}} = \frac{B_{resale}}{C_{collection} + C_{trans} + C_{refurb}} \quad (3)
\]

ii) Recycling Benefit/Cost Ratio (BCR$_{RC}$)

The revenues of the recycling scenario ($B_{RC}$) is a function of the weight of the recovered material ($B_{weight}$) and the market value of the material ($B_{value}$). The costs ($C_{RC}$) arise from collection costs ($C_{collection}$), transportation costs ($C_{trans}$), separation costs ($C_{separation}$) and shredding costs ($C_{shred}$). Therefore, the Recycling Benefit/Cost Ratio (BCR$_{RC}$) can be obtained as follows:

\[
BCR_{RC} = \frac{B_{weight} * B_{value}}{\sum C_{RC}} = \frac{B_{weight} * B_{value}}{C_{collection} + C_{trans} + C_{separation} + C_{shred}} \quad (4)
\]
iii) Energy Recovery Benefit/Cost Ratio (BCR\textsubscript{ER})

The revenues of the energy recovery scenario (B\textsubscript{ER}) is a function of the net energy produced (B\textsubscript{energy}) and the unit price of the produced energy (B\textsubscript{price}). The costs (C\textsubscript{ER}) arise from collection costs (C\textsubscript{collection}) and transportation costs (C\textsubscript{trans}). Therefore, the Energy Recovery Benefit/Cost Ratio (BCR\textsubscript{ER}) can be obtained as follows:

\[
BCR\textsubscript{ER} = \frac{\sum B\textsubscript{ER}}{\sum C\textsubscript{ER}} = \frac{B\textsubscript{energy} \times B\textsubscript{price}}{C\textsubscript{collection} + C\textsubscript{trans}}
\]  

(5)

iv) Disposal Benefit/Cost Ratio (BCR\textsubscript{DS})

There are no projected revenues in the disposal scenario (B\textsubscript{DS}). The costs (C\textsubscript{DS}) arise from transportation costs (C\textsubscript{trans}) and landfilling costs (C\textsubscript{land}). Landfilling cost (C\textsubscript{land}) is a function of the weight of the shoe (W\textsubscript{shoe}) and the actual cost of landfilling per tonne of material (C\textsubscript{ai}). Therefore, the Disposal Benefit/Cost Ratio (BCR\textsubscript{DS}), which is always zero, can be obtained by the following formula:

\[
BCR\textsubscript{DS} = \frac{\sum B\textsubscript{DS}}{\sum C\textsubscript{DS}} = \frac{0}{C\textsubscript{trans} + (W\textsubscript{shoe} \times C\textsubscript{ai})} = 0
\]  

(6)

The benefit to cost ratio (BCR\textsubscript{j}) for each shoe waste management scenario is then normalised for consistency purposes. The Normalised Benefit/Cost Ratio (NBCR\textsubscript{j}) is calculated by dividing each Benefit/Cost Ratio by the sum of all Benefit/Cost ratios as given in Eq. (3):

\[
NBCR\textsubscript{j} = \frac{BCR\textsubscript{j}}{\sum BCR\textsubscript{j}}
\]  

(7)

where 

- NBCR\textsubscript{s} = Normalised Benefit/Cost Ratio for each scenario
- BCR\textsubscript{s} = Benefit/Cost Ratio for each scenario
- \( j = \) number of waste management scenarios

4.3.3.3 Technical Criteria

The technical criteria are calculated by using the AHP method. In fact, a micro-AHP analysis is performed to calculate these criteria weights as part of a macro-AHP method for the overall analysis. In this respect, the same AHP steps are performed as described before (see Section 4.3): structuring the problem into a hierarchy, making pairwise comparisons, calculating criteria weights and synthesising the priorities.

It should be mentioned that the weight value of the technical criteria relies less on numbers and statistics but more on interviews, questionnaires, subjective reports and case studies. In this respect, the technical criteria and their weights can be easily changed by the user depending on the requirements of the analysis.
4.3.4 Synthesise the Priorities

The final step in applying the AHP method is to calculate the composite weight factor \( W_j \) of each alternative shoe waste management scenario. A simple additive method is utilised to synthesise the AHP priorities \( (P_i) \) and the weights of the alternatives with respect to each decision variable \( (K_{ij}) \).

\[
W_j = \sum P_i \times K_{ij} \tag{8}
\]

where

- \( i = 1, \ldots, n \) decision variables (factors, criteria, sub-criteria)
- \( W_j \) = composite weight of alternative option \( j \)
- \( P_i \) = relative weight of variable \( i \) with respect to the overall goal
- \( K_{ij} \) = relative weight of alternative \( j \) with respect to variable \( i \)

5 Illustrative Example of Decision Making Model

The proposed decision making model is applied to evaluate a real shoe waste management problem. The selected shoe is a Men Casual Shoe (MCS), as depicted in Picture 1, with the following characteristics:

- MCS Upper: Leather
- MCS Lining: Leather
- MCS Sole: Rubber
- MCS Weight: 350gr

This type of shoe has been selected because it is made of leather and rubber, two of the most common materials used in shoes. This illustrative example demonstrates the practicality of the decision making model for shoe waste management.

5.1 MCS Waste Management Model

Figure 2 presents the MCS waste management model. Five end-of-life management scenarios have been selected for this type of shoe:

1. Reuse Scenario: Reuse of shoe to less-developed countries.
2. Recycling Scenario 1: Shredding of shoe as a whole
3. Recycling Scenario 2: Disassembly of shoe to isolate materials and then shredding of separated materials.
4. Incineration Scenario: Incineration of shoe in municipal solid waste incinerators to generate heat and electricity.

5.2 MCS Waste Management Factors
Quantitative (environmental and economic) and qualitative factors are being considered in this case study. Environmental criteria include a number of well-recognised impact category indicators such as global warming potential, human eco-toxicity, ozone depletion etc. Economic criteria are simply divided into costs and benefits for each end-of-life management scenario. Finally, the technical factors comprise of technical feasibility, compliance with legislation, market pressures and public opinion.

5.3 Prioritise Alternatives
As previously described (see Section 4.3), the application of the AHP method requires the following steps: structuring of the problem into a decision hierarchy, making pairwise comparisons, calculating criteria weights and, finally, synthesising the priorities.
5.3.1 Structuring the problem into a decision hierarchy

Figure 3 presents the AHP hierarchy of the MCS waste management problem.

The hierarchy is structured into four levels:

i) At the first (or top) level is the overall goal of the decision making problem. In our case, the goal is to identify optimal end-of-life management option for MCS.

ii) At the second level, the goal is broken down using Quantitative and Qualitative factors.

iii) At the third level, the Quantitative and Qualitative factors are divided into criteria and sub-criteria.
iv) At the forth (or bottom) level are the five MCS end-of-life management options that are to be evaluated in terms of the criteria and sub-criteria of the third level.

5.3.2 Making pairwise comparisons
To estimate the significance of each end-of-life management scenario (Level 4) in achieving the overall goal (Level 1), pairwise comparisons of the decision variables within a lower level of the hierarchical structure with respect to the variables in the next higher level are performed. These decision variable weights could be determined by using questionnaires to obtain stakeholders (governmental, experts, public, business etc) opinions.

The judgement matrix of pairwise comparisons of the factors in the upper level of the hierarchy is shown in Table 2, along with the resulting weight of priorities. This weight gives the relative priority of the factors measured on a ratio scale. In our case, Environmental factors have the highest priority, with 0.559.

<table>
<thead>
<tr>
<th>Economic</th>
<th>Environmental</th>
<th>Technical</th>
<th>Priority Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>1</td>
<td>1/2</td>
<td>3</td>
</tr>
<tr>
<td>Environmental</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Technical</td>
<td>1/3</td>
<td>1/4</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 2: Pairwise Comparison Matrix for Level 2*

Note for example that in comparing the economic factors row with the environmental factors column, a value of 1/2 is assigned. However, when comparing it with technical factors it is preferred, and a value of 3 is entered in the first row. At the same time, the reciprocal value 1/3 is automatically entered in the third row under technical factors.

In the same way, analysis can be done at the lower level. Pairwise comparisons of each end-of-life management scenario is performed with respect to each of the decision variables. For example, the five end-of-life management scenarios are compared to one another, first relative to economic criteria, then relative to environmental criteria and, finally, relative to technical criteria.

5.3.3 Calculate criteria weights

5.3.3.1 Environmental Criteria
Sixteen (16) potential impact category indicators (I/Cl) have been selected (i.e. global warming potential, acidification potential, eco-toxicity factors in water etc), as depicted in Table 3. The Life Cycle Inventory (LCI) data is derived from a streamlined LCA of a men’s casual shoe, which was based on generalised manufacturing data. The total environmental impact (EI) of each MCS waste management scenario and the score of each impact category indicator (I/Cl), are calculated by using Eq. (1), and presented in Table 3.
### Table 3: Total Environmental Impact (EI) of Each Scenario

<table>
<thead>
<tr>
<th>Impact Category Indicator (ICl)</th>
<th>Unit</th>
<th>Reuse Scenario</th>
<th>Recycling Scenario 1</th>
<th>Recycling Scenario 2</th>
<th>Incineration Scenario</th>
<th>Landfill Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (EI)</td>
<td>mPt</td>
<td>29.33</td>
<td>23.16</td>
<td>23.26</td>
<td>221.88</td>
<td>282.59</td>
</tr>
<tr>
<td>Global warming (GWP 100)</td>
<td>mPt</td>
<td>1.10</td>
<td>0.61</td>
<td>0.61</td>
<td>0.81</td>
<td>0.70</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>mPt</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Acidification</td>
<td>mPt</td>
<td>0.64</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>mPt</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.11</td>
</tr>
<tr>
<td>Photochemical smog</td>
<td>mPt</td>
<td>0.71</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.22</td>
</tr>
<tr>
<td>Ecotoxicity water chronic</td>
<td>mPt</td>
<td>7.60</td>
<td>6.67</td>
<td>6.68</td>
<td>102.00</td>
<td>121.00</td>
</tr>
<tr>
<td>Ecotoxicity water acute</td>
<td>mPt</td>
<td>7.33</td>
<td>6.39</td>
<td>6.40</td>
<td>99.90</td>
<td>130.00</td>
</tr>
<tr>
<td>Ecotoxicity soil chronic</td>
<td>mPt</td>
<td>2.66</td>
<td>1.64</td>
<td>1.65</td>
<td>3.62</td>
<td>1.63</td>
</tr>
<tr>
<td>Human toxicity air</td>
<td>mPt</td>
<td>1.66</td>
<td>1.15</td>
<td>1.15</td>
<td>1.16</td>
<td>1.15</td>
</tr>
<tr>
<td>Human toxicity water</td>
<td>mPt</td>
<td>1.50</td>
<td>1.49</td>
<td>1.50</td>
<td>8.05</td>
<td>20.80</td>
</tr>
<tr>
<td>Human toxicity soil</td>
<td>mPt</td>
<td>2.86</td>
<td>2.20</td>
<td>2.20</td>
<td>2.54</td>
<td>3.22</td>
</tr>
<tr>
<td>Bulk waste</td>
<td>mPt</td>
<td>1.52</td>
<td>1.02</td>
<td>1.08</td>
<td>1.05</td>
<td>1.99</td>
</tr>
<tr>
<td>Hazardous waste</td>
<td>mPt</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>Radioactive waste</td>
<td>mPt</td>
<td>0.71</td>
<td>0.64</td>
<td>0.64</td>
<td>0.68</td>
<td>0.68</td>
</tr>
<tr>
<td>Slags/ashes</td>
<td>mPt</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.71</td>
<td>0.00</td>
</tr>
<tr>
<td>Resources (all)</td>
<td>mPt</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The Disposal scenario has the highest environmental impact score with 282.59 mPt while Recycling Scenario 1 (shredding of the shoe as a whole) has the lowest impact score of 23.16 mPt. The LCA calculations were conducted in SimaPro 7 using the EDIP (Environmental Design of Industrial Products) impact assessment method (Wenzel et al. 1997). The total environmental impact (EI) score for each scenario is, then, normalised, by using Eq.(2), and expressed in unit-free numbers as shown in Table 4.
Appendix VI

Environmental Impact Normalised Results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Score (mPt)</th>
<th>Normalised Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>29.33</td>
<td>0.2656</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>23.16</td>
<td>0.3367</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>23.26</td>
<td>0.3351</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>221.88</td>
<td>0.0351</td>
</tr>
<tr>
<td>Disposal Scenario</td>
<td>282.59</td>
<td>0.0273</td>
</tr>
</tbody>
</table>

Table 4: Normalised Environmental Impact (NEI) Score

5.3.3.2 Economic Criteria

An experimental data set based on average values for costs and benefits has been used to calculate the benefit/cost ration for each MCS end-of-life management scenario. Each scenario is calculated as follows:

i) Reuse MCS Scenario

Calculations are based on Eq. (3) taking into consideration the following values:

\[ B_{RE} = B_{resale} \]
\[ C_{RE} = C_{collection} + C_{trans} + C_{refurb} \]

ii) Recycling MCS Scenario 1

Calculations are based on Eq. (4) taking into consideration the following values:

\[ B_{RC1} = (B_{weight}) * (B_{value}) \]
\[ C_{RC1} = C_{collection} + C_{trans} + C_{shred} \]

iii) Recycling MCS Scenario 2

Calculations are based on Eq. (4) taking into consideration the following values:

\[ B_{RC2} = (B_{weight}) * (B_{value}) \]
\[ C_{RC2} = C_{collection} + C_{trans} + C_{separation} + C_{shred} \]

iv) Incineration MCS Scenario

Calculations are based on Eq. (5) taking into consideration the following values:

\[ B_{ER} = (B_{energy}) * (B_{price}) \]
\[ C_{ER} = C_{collection} + C_{trans} \]

v) Disposal MCS Scenario

Calculations are based on Eq. (6) taking into consideration the following values:

\[ B_{DS} = \text{nil} \]
\[ C_{DS} = C_{trans} + [(W_{shoe}) * (C_{land})] \]

Benefit to cost ratio is then normalised, by using Eq.(7), in order to be used by the AHP method. Table 5 presents the benefit to cost ratio and the normalised results for each end-of-life management scenario.
<table>
<thead>
<tr>
<th>Benefit/Cost Ratio</th>
<th>Normalised Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>2.00</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>1.66</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>1.75</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.83</td>
</tr>
<tr>
<td>Disposal Scenario</td>
<td>0</td>
</tr>
</tbody>
</table>

*Table 5: Normalised MCS Benefit/Cost Ratio*

5.3.3.3 **Technical Criteria**

The technical criteria are calculated by applying the AHP method in a local scale. Once again, a series of pairwise comparisons are performed in order to identify the weight of each criterion. The MCS waste management scenarios are then compared to each other with respect to each criterion, again by making a series of pairwise comparisons. The final result is a score (composite weight) for each alternative MCS waste management scenarios with respect to technical criteria. The results of the pairwise comparison of alternative scenarios with respect to each technical criterion as well as the final composite weight of each scenario are presented in Table 6.

<table>
<thead>
<tr>
<th>Technical Criteria</th>
<th>Technical Feasibility</th>
<th>Public Opinion</th>
<th>Market Pressures</th>
<th>Compliance with Legislation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Weight of Technical Criteria</td>
<td>0.07</td>
<td>0.15</td>
<td>0.43</td>
<td>0.35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>End-of-Life Management Scenarios</th>
<th>Relative Weight of Scenarios with respect to Criteria</th>
<th>Composite Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse Scenario</td>
<td>0.16 0.18 0.26 0.26</td>
<td>0.2415</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.44 0.33 0.33 0.32</td>
<td>0.3353</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.29 0.37 0.26 0.29</td>
<td>0.2882</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.08 0.09 0.11 0.09</td>
<td>0.0969</td>
</tr>
<tr>
<td>Disposal Scenario</td>
<td>0.04 0.03 0.04 0.04</td>
<td>0.0381</td>
</tr>
</tbody>
</table>

*Table 6: Synthesis of Technical Criteria Weights*

1 An experimental data set has been used for these values
5.3.4 Synthesise the priorities

Finally, the composite weight factor \( W_j \) of each MCS waste management option need to be calculated. The results of the pairwise comparison of the five end-of-life management scenarios with respect to each decision variable as well as the final composite weight of each scenario are presented in Table 7. This table synthesises the results of both the relative weights of decision variables with respect to the overall goal \( (P_i) \), and the relative weights of alternative with respect to each decision variable \( (K_{ij}) \). To calculate the composite weight \( W_j \) for each scenario the equation (1) has been utilised as described in Section 4.3.4.

<table>
<thead>
<tr>
<th>Decision Variables for Men's Casual Shoe</th>
<th>Environmental</th>
<th>Economic</th>
<th>Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Weight of Decision Variables  ( (P_i) )</td>
<td>0.5584</td>
<td>0.3196</td>
<td>0.1220</td>
</tr>
<tr>
<td>End-of-life Management Scenarios</td>
<td>Relative Weight of Scenarios with respect to Variables ( (K_{ij}) )</td>
<td>Composite Weight ( (W_j) )</td>
<td></td>
</tr>
<tr>
<td>Reuse Scenario</td>
<td>0.2656</td>
<td>0.3200</td>
<td>0.2415</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.3367</td>
<td>0.2667</td>
<td>0.3353</td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.3351</td>
<td>0.2800</td>
<td>0.2882</td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.0351</td>
<td>0.1333</td>
<td>0.0969</td>
</tr>
<tr>
<td>Disposal Scenario</td>
<td>0.0273</td>
<td>0.0000</td>
<td>0.0381</td>
</tr>
</tbody>
</table>

Table 7: Synthesis of Priorities

The composite weight \( W_j \) indicates the overall significance of each end-of-life management option after considering the importance of the decision variables. In fact, composite weight represents the cumulative weights of each alternative option throughout the entire AHP hierarchy, as described in Figure 3. For example, the composite weight of reuse scenario after considering the entire hierarchy is 0.2800. This is the cumulative weight after considering the relative weight of reuse scenario with respect to each decision variable and the relative weight of the decision variables to overall goal. This is calculated in equation [8] as follows:

\[
W_{MCS \text{ Reuse Scenario}} = \sum P_{MCS \text{ Reuse Scenario}} \times K_{ij \text{ MCS Reuse Scenario}} \\
= (0.2656 \times 0.5584) + (0.3200 \times 0.3196) + (0.2415 \times 0.1220) \\
= 0.2800
\]
The graphical representation of the aggregated results for each MCS end-of-life management scenario is shown in Figure 4.

![Figure 4: Aggregated Results for MCS End-of-life Management Scenarios](image_url)

Results indicate that Recycling Scenario 1 (shedding the shoe as a whole) is the most preferable option for a men casual shoe, whereas Disposal Scenario (landfilling) is the least. However, the priority weight given to each decision variable clearly influence the final results. If a waste management option received the least weight with respect to most of the criteria, then it will most likely be the least preferable option, as in the case of disposal. Based on the results, the priority weight given to environmental criteria (0.5584) as the most important factor in evaluating the end-of-life management options of a men casual shoe corresponds to the high composite weight given to MCS reuse and recycling scenarios.

6 Conclusion

Growing number of post-consumer shoes and the wide range of materials and construction methods used in shoe manufacturing, highlight the need for a systematic approach to deal with the end-of-life shoe waste. However, the viability of recovery and recycling scenarios have always been subject to a number of factors including economical, environmental and technical considerations. This paper has presented a decision making model to identify the most appropriate end-of-life management option for a selected range of shoe types. The decision making model provides an integrated approach to evaluate a number of related factors which influence the final decision for a shoe waste management option. Although this decision making model has been applied in the footwear industry, it can also be utilised in other industrial sectors. However, a holistic approach to waste management requires
commitment by various actors within the supply chain including material suppliers, manufacturers, retailers and even consumers. The Authors further research will focus on a number of specific challenges in establishing a sustainable shoe recovery and recycling chain which includes consideration on sustainable reverse logistics, identifying new generation of recycling processes in footwear industry and, finally, establishing value recovery chains for shoe recycled materials.

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Appendix VII

End-of-Life Decision Support Tool for Product Recovery
Considerations in the Footwear Industry

This paper has been accepted for publication in the International Journal of Computer Integrated Manufacturing, August 2007.
An End-of-Life Decision Support Tool for Product Recovery

Considerations in the Footwear Industry

Theodoros Staikos* and Shahin Rahimifard

Centre for Sustainable Manufacturing and Reuse/Recycling Technologies (SMART)

Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, UK

*T.Staikos@lboro.ac.uk

Abstract

The footwear industry is a manufacturing sector which utilises a wide variety of materials and processes to produce a range of distinctly different products, from sandals to more specialised footwear. Currently, more than 17 billion pairs of shoes are produced worldwide every year. This creates a large waste stream at the end of the functional life of shoes, which are often being disposed in landfills. Producer responsibility concerns and forthcoming legislations as well as increasingly environmental consumer demands expected to challenge the way the global footwear industry is dealing with its end-of-life products. This paper highlights the potential benefits of developing a footwear product recovery methodology and an associated software tool to support decision-making regarding the determination of the most suitable (in environmental, economic and social-technical terms) manner in which to treat post-consumer shoe waste. Such methodology in addition to supporting design and material selection processes could also provides benchmark information for the selection of the best end-of-life practise for a selected range of different shoe types. The paper concludes by providing a computational viewpoint of an end-of-life shoe recovery decision support tool.
Keywords: Shoe Recycling, Footwear Industry, End-of-Life Management, Decision-Support

1. Introduction

Unsustainable consumption and production patterns in the developed world have led to an increased generation of waste over many decades. Although local and national authorities, governmental agencies, manufacturers and the general public have come to recognise the importance of controlling waste at source, total waste elimination is not feasible. There will always be some waste that cannot be prevented at source and so need to be treated at the end of its functional life. Considering the amount of end-of-life (EoL) waste generated every year, understanding and developing methods for end-of-life management are a major part of the overall waste management concern.

The footwear industry over the last 20 years has placed significant effort in improving energy and material efficiency, as well as eliminating the use of hazardous materials during the production phase. However, the environmental gains and energy efficiency made in production are being overtaken by the considerable increase in the demand for footwear products. Several billions of shoes consumed each year worldwide and many end up in landfills when their functional life has ended. Moreover, the useful life of shoes is relatively short and progressively decreasing as a result of rapid market changes and consumer fashion trends. This creates a large waste stream of worn and discarded shoes. Producer-responsibility issues and forthcoming environmental legislations, as well as increasingly environmental consumer demands, are
expected to challenge the way the footwear industry deals with its EoL products.

This paper has proposed a footwear product recovery methodology together with an associated software tool to support the decision-making process regarding the determination of the most appropriate end-of-life management option for post-consumer shoes. The initial part of the paper provides a review of materials, processes, styles and types of shoes, which is needed in order to construct alternative end-of-life scenarios. The latter sections present the footwear product recovery methodology and provide a computational viewpoint of the proposed software tool for decision support.

2. Review of Shoe Manufacturing and Materials

In any product recovery and recycling application, there are a number of alternative options with different environmental impacts, economic values and social-technical requirements. There is, therefore, a need for a end-of-life decision making process to evaluate these factors in order to identify the best alternative option. However, the value of the results obtained thought the decision making process rests in the quality of information entered by the user in the first place. Therefore, before considering these issues in further details it is important to first consider the materials and processes used to make shoes. Based on these background information regarding materials, processes, styles and types of shoes, the footwear product recovery methodology has been developed, as described in Section 4.
Although there are many different styles and categories of shoes, most of them can be described as having a subset of parts and components that are generally common to all type of shoes. In this context, the basic parts of a shoe can be grouped broadly into three categories (Clarks 1976):

- The Upper, which includes all parts of the shoe above the sole, such as vamp and quarters, that are stitched or joined together to become a unit and then attached to the insole and outsole of the shoe.
- The Lower, which refers to the whole bottom of a shoe but not the upper including the insole, the sole and the outsole of the shoe.
- The Grindery, which includes items that incorporated into the shoe and do not belong either to the Upper or the Lower part of the shoe such as toe puff, stiffener materials and eyelets.

Some of the major parts and components of a men's formal shoe are depicted in Figure 1.
Alternatively, shoes can be divided using a supply or demand point of view. From the supply point of view, shoes can be subdivided by upper material, for example rubber/plastic, leather and textile-based shoes. On the other hand from the demand point of view, shoes can be divided by activity, for example sports, casual, formal and outdoor shoes. Other categorisations can also be made based on age and gender (i.e. men’s, women’s and children’s). For the purpose of this research, footwear products have been categorised into six different types based on their purpose of use:

- Men’s formal shoes
- Men’s casual shoes
- Women’s court shoes
- Women’s fashion shoes
- Children’s shoes
- Adult sports trainer shoes
Table 1 presents the basic shoe types and the most commonly used materials in their manufacture. Upper components, shoe soles and grindery items are presented according to their material of choice.

<table>
<thead>
<tr>
<th>Types of shoes</th>
<th>Men's Formal</th>
<th>Men's Casual</th>
<th>Women's Court</th>
<th>Women's Fashion</th>
<th>Children's</th>
<th>Adult Sports Trainer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Part</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leather</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Synthetic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canvas</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyurethane</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVC</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Lower Part (Soles)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leather</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leather/Polymer</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Vulcanise Rubber</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPR</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Polyurethane’s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>TPU</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>EVA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Grindery Items</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shanks</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nails</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
2.1 Shoe Manufacturing

The production of footwear starts with the supply of materials. These materials include both raw materials (such as leather) and semi-finished products and components. These materials need to be inspected and modified in order to meet the quality requirements of the footwear industry. Often upper, lower and grindery components are manufactured separately by using different construction methods. Cutting, machining and pre-stitching operations are applied in order to fabricate these components. The next phase of manufacturing is the assembly of the components into finished products. The completed upper and lower parts are united using different assembling techniques. Usually the upper is stretched over the last (a fixture which represents the shape of the foot) and attached at the bottom part of the shoe in
a process called lasting. There are typically three major assembling techniques used by the footwear industry (Harvey 1982):

- Cementing, where the upper and lower part assembled using adhesives
- Injection, where the sole material is injected directly to the upper part of the shoe
- Stitching, where the upper and lower part assembled together with threads.
- Finally, finishing processes determined by the materials that have been used during the manufacturing process. Usually leather materials are stained, polished and waxed before tagged and delivered to the market.

### 2.2 Shoe Materials

Leather, synthetic materials, rubber and textile materials are counted among the most commonly used materials in shoe manufacturing. These materials differ not only in their appearance but also in their physical qualities, their service life, the different treatment needs as well as their recycling and recovery options at the end of their useful life. According to Weib (1999) there are around 40 different materials used in the manufacturing of a shoe. Figure 2 represents the average composition of a typical shoe which has been measured after grinding.
Leather has ideal characteristics for use in the upper part of shoes, is soft with very good absorption ability and able to adjust to the individual shape of the foot. However, leather is a natural material made from animal hides and therefore there is a limited and variable supply depending on stock levels in the meat industry of which hides are a by-product. For this reason, synthetic materials that designed to look or function like leather have been developed such as fabrics coated with Poly Vinyl Chloride (PVC) and Polyurethane (PU).

Leather has also been largely superseded by other materials in the lower part of shoes such as rubber or plastics. In the 1950's only four materials were used as soling materials namely leather, rubber, vulcanised rubber and resin rubber (World Footwear 2005). Since then the choice of has been extended to include a number of different plastics and polymers such as PVC, TR, EVA etc. Polymeric and plastic materials currently dominate the production of shoe soles, outsoles and insoles, especially thermoplastic materials and rubbers. Table 2
presents the percentage of the major materials used in the construction of lower parts in shoes.

<table>
<thead>
<tr>
<th>Soling Materials</th>
<th>Percentage (%wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin Rubber</td>
<td>20</td>
</tr>
<tr>
<td>PVC and blends</td>
<td>19</td>
</tr>
<tr>
<td>Thermoplastic Rubber (TR)</td>
<td>15</td>
</tr>
<tr>
<td>Direct Vulcanised (DV) Rubber</td>
<td>8</td>
</tr>
<tr>
<td>Direct Injection Moulded (DIM) PVC and blends</td>
<td>8</td>
</tr>
<tr>
<td>Leather</td>
<td>7</td>
</tr>
<tr>
<td>Micro Ethylene Vinyl Acetate (EVA)/ Rubber</td>
<td>7</td>
</tr>
<tr>
<td>Polyurethane (PU)</td>
<td>7</td>
</tr>
<tr>
<td>Other (wood, cork, textile etc)</td>
<td>5</td>
</tr>
<tr>
<td>Vulcanised Rubber</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2: Use of Soling Materials in Shoes (Wilson et al. 1997)

Finally, grindery components include items that incorporated into the shoe and not belong to the upper or the lower part of the shoe. These items could be made by a variety of materials depending on their purpose of use. Toe puffs can be made of rubber or thermoplastic resins, stiffener components from leather, EVA and polyester while shank and eyelets can be made of metal (carbon steel). Finally, the heel of the shoe is usually made of Polystyrene (PS), Acrylonitrile Butadiene Styrene (ABS), or wood (Harvey 1982).
3. Magnitude of Shoe Waste Problem

Worldwide footwear production and consumption has been doubled every 20 years, from 2.5 billion pairs in 1950 to more than 17 billion pairs of shoes in 2006 (World Footwear 2006). In the European Union, footwear consumption has been increased by 22% from 2002 to 2005 to reach 2.3 billion pairs of shoes (EC 2006). Additionally, the worldwide per capita consumption of footwear has also been considerably increased, from 1 pair of shoes for every person in the world in 1950 to almost 2.6 pair of shoes in 2005. However, shoe consumption differs significantly per country. Although China has the highest footwear consumption in the world, the United States is the country with the highest per capita shoe consumption, since each inhabitant purchase an average of 6.9 pairs of shoes every year (AAfA 2006). At the other extreme, in the less developed countries, the per capita shoe consumption is 0.6 pairs for India and 0.5 pairs of shoes for Vietnam (all types of shoes included) (SATRA 2003). Figure 3 presents the overall shoe consumption as well as the per capita shoe consumption in a number of different countries.
In the UK, more than 330 million pairs of shoes consumed every year (BFA 2006). It is estimated that the waste amount arising from post-consumer shoes in the UK could reach 165,000 tonnes per year. A Department of Trade and Industry (DTI) study has estimated that the total arising of textile waste is between 550,000 and 900,000 tonnes per year in the UK, while the amount of textile waste reused or recycled annually is estimated to be 250,000 tonnes (ERM 2006). Based on the same study, about 9% of all recovered post-consumer textiles are sold as second-hand shoes. This means that around 22,500 tonnes of post-consumer shoes are collected in the UK each year for direct reuse in less developed counties. Such reuse schemes are mainly supported by charitable organisations such as the Salvation Army Trading Company (SATCOL™), Oxfam™ and others in collaboration with local authorities and municipalities. SATCOL™ alone with its 2,300 banks, door-to-
door collections and donations, has managed to collect around 971 tonnes of worn or unwanted shoes during the year 2000-2001 (Woolridge et al. 2006). However, approximately 10% of the collected shoes are not suitable for direct reuse due to their condition and, consequently end up in landfills (Barry 2006). Based on this estimations, approximately 12% (20,250 tonnes) of post-consumer shoes in the UK are collected and re-distributed as second hand shoes while the rest (88% or 145,200 tonnes) disposed in landfills.

The standard practice of dumping waste in landfills led to soil, surface and groundwater contamination. Landfill sites can result in serious environmental pollution of groundwater and rivers, due to landfill leachate\(^1\). Furthermore, landfill space is becoming extremely limited, while the number of landfill sites in the European Union has considerable decreased over the last years. In early 90's, in Germany, there were over 8000 landfill sites in use, while the number of currently operating landfill sites is below 300 (Hempen 2005). The EU Landfill Directive clearly promotes the diversion of waste from landfills towards products and materials recycling using a variety of measures (Council Directive 1999). The landfill restrictions introduced by the Article 5 of this Directive are very important, in particular the reduction in the amount of biodegradable waste going to landfill and the prohibition of landfilling for certain waste types. Since 1st June 2005, German landfills only accept biodegradable municipal waste that has been either incinerated or undergone mechanical and biological treatment while in Austria strict limits on the landfilling of organic wastes has also been introduced (Hempen 2005). Additionally, the UK Landfill Allowances and

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\(^1\) the liquid produced from the decomposition of waste within the landfill
Appendix VII

Trading Scheme Regulations (LATS) introduced in 2004, determines the percentage of certain waste type that regarded as biodegradable municipal waste. These biodegradable percentage range from paper, card and vegetable oils (potentially 100% biodegradable) through to footwear, furniture and textiles (50% biodegradable) to batteries, glass and metal waste (0% biodegradable) (LATS 2004). This means that certain types of biodegradable materials such as leather, natural textiles, natural rubbers etc, which are extensively used by the footwear industry, will be soon required to be reused or recycled instead of directly disposed in landfill sites.

Footwear industry's response to this increasing problem of post-consumer shoe waste has been negligible. In fact, only one major shoe manufacturer, Nike™, has been taken measures to manage its waste. Nike's recycling programme "NikeGO-Places™" (formerly "Reuse-A-Shoe™") is the only product take-back and recycling scheme currently established by a shoe manufacturer (Nike 2006). This programme has been operating for over a decade in the United States and also just started operating in the UK, Australia and Japan. Their reuse and recycling programme involves a series of collection points in retail centres where people can deposit their worn-out and discarded athletic shoes. The shoes are then collected and taken to a central recycling facility where they are shredded, producing a material called "Nike-Grid™", which can be used in surfacing of tennis and basketball playgrounds or running tracks. According to Nike (2006), since its inception in 1993, "Reuse-A-Shoe™" programme has recycled more than 16 million pairs of worn-out and defective athletic shoes in total.
The limited activities in shoe recycling across the footwear industry highlights the paramount importance of investigating alternative approaches to footwear product recovery and recycling, as outlined in the remaining section of this paper.

4. Footwear Product Recovery Methodology

The footwear product recovery methodology aims to assist shoe designers, shoe manufacturers and recovery and recycling organisations in determining appropriate end-of-life scenarios for post-consumer shoes. The methodology enable the definition of alternative end-of-life scenarios to a level of detail that will allow economic, social-technical and environmental factors to be calculated, analysed and compared. The most appropriate EoL option recommended through the application of this methodology should minimise overall environmental impacts in a technically feasible way and at a reasonable cost. An integrated approach is therefore needed in order to incorporate all the potential decision criteria and take into consideration both quantitative and qualitative factors. The methodology provides a systematic way of considering all these factors in an attempt to identify optimal waste management options for post-consumer shoes. Figure 3 provides a visual representation of the phases included in the footwear product recovery methodology for post-consumer shoes.
These phases start with consideration of a set of input data regarding the type of the post-consumer shoe. In the first phase, the condition, value and type of shoe are assessed together with the construction methods and the materials used for each part of the shoe. Identification of potential product recovery
scenarios and their related decision factors forms the next steps in the decision making process. Finally, quantitative (cost/benefits and environmental criteria) and qualitative (social-technical criteria) factors are calculated and an optimal product recovery scenario for a selected range of post-consumer shoes is proposed. The four phases of this methodology are further described below.

4.1 Product Characterisation

The first phase of the methodology identifies the main characteristics of the footwear product. This step is needed in order to classify the product into its basic attributes and identify the crucial factors that determine the choice of a recovery option. This is performed in four steps, also referred to as screening levels. The first screening level determines basic characteristics of worn or discarded shoes such as the condition (e.g. suitable or unsuitable for reuse), the value (based on material content) and the type of the shoe (men's casual, sports trainers etc). This screening level is very important for the selection of a suitable product recovery option. For example, worn shoes in a relatively good condition can be refurbished and then reused while in the case of damaged or destroyed shoes, reuse is simply not considered. The second and third screening levels provide the necessary background information regarding the structure of the shoe and the construction methods that have been used to produce the shoe. The construction method, in particular, and the adhesives or stitching operations that have been applied to create a shoe can significantly influence the choice of appropriate destructive (shredding or granulating) or non-destructive (disassembly of upper and sole) recycling options. Finally, at the fourth screening level, materials used in shoe construction are classified.
according to their properties and then grouped into four major groups: leather, textiles, plastics and others. The major output of the first phase is a general categorisation of shoes based on their specific attributes and identification of important factors that influence the choice of a end-of-life management option.

4.2 Recovery Scenario Selection

In the second phase of the methodology, a waste management model constructed based on the output from the first phase. This waste management model for post-consumer shoes determines the different end-of-life management options, giving priority to recycling and reuse to minimise cost and environmental impacts. The output of such model would identify potential treatments for post-consumer shoes depending on the shoe type. The shoe waste management model consists of the following end-of-life management options; reuse, recycling, energy recovery and disposal (Staikos et al. 2006). Reuse of post-consumer shoes is a possible option but there are few variables that need to be considered such as the condition of the shoe at the end of its functional life, the collection and distribution system as well as the purpose of its reuse. Recycling involve the reprocessing of post-consumer shoes, parts or materials to be used either into the same product system (closed loop manufacture) or into different ones. In this approaches, the waste is re-introduced back into the market through a series of destructive and non-destructive recycling processes. Energy recovery is another possible waste management option for post-consumer shoes which includes a number of established and emerging technologies such as incineration, gasification and
pyrolysis. Finally, disposal of waste to landfills is currently the most common waste management option for post-consumer shoes.

4.3 EoL Scenario Assessment

In phase 3, decision factors that influence the EoL treatment options need to be identified. These factors should take into consideration both quantitative (environmental and economic) and qualitative (social-technical) criteria. Environmental criteria include a number of environmental impact category indicators i.e. global warming potential, human eco-toxicity etc. Economic criteria are simply represent the costs and revenues for each end-of-life scenario (e.g. resale price of reused shoe, cost of landfilling etc). The list of social-technical criteria is almost endless and includes technical feasibility, market pressures, compliance with legislation etc. This list could be easily changed depending on the requirements of the analysis and the type of shoe under consideration.

Once the decision factors have been selected, these are then analysed for each recovery scenario in order to measure the impacts associated with all of the processes within the scenario. Information and data are collected and analysed in order to provide guidance on which is the optimal waste management solution for the selected type of shoe. The basic output of this phase is an assessment value for each recovery scenario based on social-technical, economic and environmental considerations. A number of decision making aid techniques have been utilised to analyse the decision criteria. The Analytic Hierarchy Process (AHP), however, has been used as the basic framework for simultaneous consideration of all these factors. AHP is a multi-criteria decision
making (MCDM) method that has been used successfully in a variety of applications in different fields such as planning, resource allocation, optimisation and in general selecting the best alternative option (Vaidya et al. 2006). The AHP method decomposes a complex decision problem into a hierarchy and allows the consideration of both quantitative and qualitative (objective and subjective) factors in selecting the best alternative option (Saaty 1980). Economic criteria are calculated using Cost-Benefit Analysis (CBA) to identify cost and benefits for each recovery scenario while environmental impacts of various scenarios are calculated using a streamlined Life Cycle Assessment (LCA). Finally, social-technical criteria are calculated by applying the AHP method in a local scale. Figure 4 displays the framework for shoe recovery scenario assessment, including the different decision making methods that have been utilised.
4.4 Recovery Value Chain

The final step in the methodology aims to identify a recovery value chain for the alternative scenarios and make sure that a market exists for such recovered products or materials. Once post-consumer shoes collected, sorted and converted into a form that can be used by either the footwear industry or other industrial sectors, then it must compete with virgin materials both on price and performance. A sustainable footwear recycling application heavily depends on
establishing a successful value shoe recovery chain. In this respect, a product recovery value chain can be described as the service of recovery and reuse of resources across a number of different sectors. Hence, this step of the footwear product recovery methodology is to identify suitable applications for each scenario. This can be achieved by establishing procedures that identify, within a broader context, value-added activities and benefits and seeking out the best recycling practices along different industrial sectors. Figure 6 presents a product recovery value chain for alternative end-of-life scenarios for shoes.

Value-Added Activities

![Diagram of Value-Added Activities]

**Figure 6: Recovery Value Chain for End-of-Life Scenarios for Shoes**

However, not all post-consumer shoes can be considered to be suitable for recycling or reuse and, therefore, landfilling and even incineration without energy recovery of such materials could be considered as a practical option. Other issues that also need to be considered include the size and the value of the end market, the current and predicted buying trends as well as the range
and price of competing materials and products. The basic output of this phase is a list of potential applications for shoe recycled materials.

5. EoL Decision Support Tool for Footwear Products

The determination of the most suitable (in environmental, economic and social-technical terms) manner in which to treat post-consumer shoe waste, as described in previous sections, is a complex process involving a wide range of materials, construction methods and recycling processes. Therefore, to support the implementation of the proposed footwear product recovery methodology, a prototype end-of-life (EoL) decision support tool has been developed. The prototype model was developed as a three-tier architecture as presented in Figure 7.

![Figure 7: System Architecture of Prototype EoL Decision Support Tool](image-url)
The presentation module acts as a user interface environment to receive and control user’s input as well as to present the output. The database module provides a data repository in which information is stored and retrieved while the assessment module comprise the assessment/logic element of the system that support the decision–making process.

5.1 Presentation Module

The user interface environment has been developed in Visual Basic for Applications (VBA) and integrated with a MS-Access environment. The main interface controls and integrates the major components of the proposed system and contains seven options to indicate the user selection. The main menu containing the EoL decision support system which includes most of the major functions of the tool are depicted in Figure 8. Each of these options lead to further a software module that support a specific function with in the system.

![Figure 8: The Main Interface of the EoL Decision Support Tool](image-url)
5.2 Database Module

The database module provides a back end database, comprising both data sets and the software system that manages and provides access to the data. This knowledge-based element supplies the required expertise for solving specific aspects of the problem domain. The core database of the model is constructed to provide essential information in order to generate product recovery and recycling scenarios. The core database is being developed on commercial software (MS-Access), and is still under development. The relational database model includes 16 tables in total. A pictorial representation of the database model is illustrated in Figure 9.

![Database Model Structure](image-url)
5.3 Assessment Module

The third module comprise the assessment element, the so-called logic of the system that support the decision-making process. As previously described, each recovery scenario is assessed in terms of its environmental, economical, and social-technical criteria. These assessment processes are based on the various phases of the footwear product recovery methodology, as presented in Section 4.3.

5.3.1 Calculate Environmental Criteria

Environmental criteria for alternative end-of-life scenarios for shoes are calculated using a simplified Life Cycle Assessment (LCA) methodology. The Environmental Impact ($E_l$) score of each scenario is computed as follow (Wenzel et al. 1997):

$$E_{lj} = \sum_{i=1}^{n} IC_{li}$$

where

- $IC_{lj}$ = impact category indicator $i$
- $n$ = number of impact category indicators
- $j$ = number of end-of-life scenarios

The Life Cycle Inventory (LCI) data has been derived from a streamlined LCA study of average shoes, which was based on typical manufacturing data found in commercial databases. The LCI calculations and the Life Cycle Impact Assessment (LCIA) phase are conducted in SimaPro 7 LCA software using the EDIP (Environmental Design of Industrial Products) impact assessment method.
The environmental impact score (Elj) of each scenario need to be normalised and expressed in unit-free numbers for consistency purposes. The normalised environmental impact score (NElj) for each scenario is calculated as follows:

i) calculate the reciprocal of each environmental impact score (RElj)
ii) divide the reciprocal of each environmental impact score (RElj) by the sum of all reciprocal scores.

\[ NElj = \frac{RElj}{\sum s RElj} \]

where \( RElj = \frac{1}{Elj} \)

\( Elj = \) environmental impact score of each scenario(s)

### 5.3.2 Calculate Economic Criteria

Economic values for each end-of-life scenario are calculated using the benefit to cost ratio approach. The benefit to cost ratio (BCR) must be greater than or equal to 1 i.e. B/C>1, where B is the benefit and C is the cost of each alternative. The end-of-life economic value and benefit/cost ratio are calculated based on the following methods (Lee et al. 2001):

i) **Reuse Benefit /Cost Ratio (BCRRE)**

The revenue of the reuse scenario (BRE) derived from the resale value of the shoe (B_resale) while the costs (C_RE) arising form collection costs (C_collection), transportation costs (C_trans) and refurbishing costs (C_refurb). Therefore, the Reuse Benefit/Cost Ratio (BCR_RE) can be obtained as follows:
ii) Recycling Benefit/Cost Ratio (BCR_{RC})

The revenues of the recycling scenario \( (B_{RC}) \) is a function of the weight of the recovered material \( (B_{\text{weight}}) \) and the market value of the material \( (B_{\text{value}}) \). The costs \( (C_{RC}) \) arising from collection costs \( (C_{\text{collection}}) \), transportation costs \( (C_{\text{trans}}) \), separation costs \( (C_{\text{separation}}) \) and shredding costs \( (C_{\text{shred}}) \). Therefore, the Recycling Benefit/Cost Ratio \( (BCR_{RC}) \) can be obtained as follows:

\[
BCR_{RC} = \frac{\sum B_{RC}}{\sum C_{RC}} = \frac{B_{\text{weight}} \cdot B_{\text{value}}}{C_{\text{collection}} + C_{\text{trans}} + C_{\text{separation}} + C_{\text{shred}}}
\]  

(2)

iii) Energy Recovery Benefit/Cost Ratio (BCR_{ER})

The revenues of the energy recovery scenario \( (B_{ER}) \) is a function of the net energy produced \( (B_{\text{energy}}) \) and the unit price of the produced energy \( (B_{\text{price}}) \). The costs \( (C_{ER}) \) arising from collection costs \( (C_{\text{collection}}) \) and transportation costs \( (C_{\text{trans}}) \). Therefore, the Energy Recovery Benefit/Cost Ratio \( (BCR_{ER}) \) can be obtained as follows:

\[
BCR_{ER} = \frac{\sum B_{ER}}{\sum C_{ER}} = \frac{B_{\text{energy}} \cdot B_{\text{price}}}{C_{\text{collection}} + C_{\text{trans}}}
\]  

(3)
iv) **Disposal Benefit/Cost Ratio (BCR<sub>DS</sub>)**

There are no projected revenues in the disposal scenario (B<sub>DS</sub>). The costs (C<sub>DS</sub>) arising form transportation costs and landfilling costs. Landfilling cost is a function of the weight of the shoe and the actual cost of landfilling per tonne of material. Therefore, the Disposal Benefit/Cost Ratio (BCR<sub>ER</sub>), is always zero:

\[
BCR_{DS} = \sum \frac{B_{DS}}{C_{DS}} = 0 \quad (4)
\]

The benefit to cost ratio (BCR<sub>j</sub>) for each end-of-life scenario is then normalised for consistency purposes. The Normalised Benefit/Cost Ratio (NBCR<sub>j</sub>) is calculated by dividing each Benefit/Cost Ratio by the sum of all Benefit/Cost ratios as given in Eq. (1), (2), (3) and (4):

\[
NBR_{j} = \frac{BCR_{j}}{\sum_{j} BCR_{j}}
\]

where \( NBR_{j} = \) Normalised Benefit/Cost Ratio

\( BCR_{j} = \) Benefit/Cost Ratio for each scenario

\( j = \) number of waste management scenarios
5.3.3 Calculate Social-Technical Criteria

Social-technical criteria (e.g. technical feasibility, public opinion, market pressures, compliance with legislation) are calculated by using the AHP method. The same AHP steps are performed as described in Section 4.3: structuring the problem into a hierarchy, making a series of pairwise comparisons to identify the weight of each criterion, calculate criteria weights and, finally, synthesize the priorities into a composite weight. The final result is a score (composite weight) for each alternative end-of-life scenario with respect to each social-technical criterion. Figure 11 shows graphically the composite weight of five alternative end-of-life scenarios, namely shredding the shoe as a whole (Recycling Scenario 1), disassembly of upper and sole before shredding to gain higher quality of recycled material (Recycling Scenario 2), together with Reuse, Incineration and Disposal scenarios for a selected type of shoe (men’s casual shoe).
The results presented in Figure 10 indicate that Recycling Scenario 1 (shredding the shoe as a whole) is the most preferable option with respect to the social-technical criteria for a men casual shoe. However, it should be mentioned that the weight value of the social-technical criteria rely less on numbers and statistics but more on interviews, questionnaires, subjective reports and case studies. In this respect, the social-technical criteria and their weights can be easily changed by the user depending on the requirements of the analysis.
5.3.4 Synthesis of Overall Results

The final step of the assessment process, as part of the AHP method, is to synthesize the overall results in order to produce a global priority vector for each end-of-life scenario. The global priority vector indicates the preference (or the composite weight) of each alternative option. Figure 11 shows graphically the preference of the five alternative end-of-life scenarios, as previously presented in Section 5.3.3, for a men’s casual shoe.

### Table: Synthesis of Overall Results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Quantitative Factors</th>
<th>Qualitative Factors</th>
<th>Global Priority Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Environmental</td>
<td>Economic</td>
<td>Social-Technical</td>
</tr>
<tr>
<td></td>
<td>0.350424543</td>
<td>0.303616264</td>
<td>0.121557193</td>
</tr>
<tr>
<td>Recycling Scenario 1</td>
<td>0.266666667</td>
<td>0.320</td>
<td></td>
</tr>
<tr>
<td>Recycling Scenario 2</td>
<td>0.268237619</td>
<td>0.370</td>
<td></td>
</tr>
<tr>
<td>Reuse Scenario</td>
<td>0.2415356</td>
<td>0.250</td>
<td></td>
</tr>
<tr>
<td>Incineration Scenario</td>
<td>0.096304588</td>
<td>0.041</td>
<td></td>
</tr>
<tr>
<td>Disposal Scenario</td>
<td>0.026087450</td>
<td>0.019</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 11: Final Output of EoL Decision Support Tool](image)
The final output of the analysis, as presented in Figure 11, indicate that Recycling Scenario 2 (disassembly of shoe) is the most preferable option for a men casual shoe, whereas Disposal Scenario (landfilling) is the least. It should be mentioned that this demonstration of the AHP method is only an example of how this multi-criteria decision making technique could be used by the EoL decision support tool in order to identify optimal solutions.

6. Conclusion

The large amount of post-consumer shoe waste produced every year, the legislative pressures to divert waste from landfills as well as the hidden value of recyclable materials in post-consumer shoes have led to the development of a end-of-life decision support tool and methodology to support the determination of the most suitable treatment option for post-consumer shoes. The key to success in establishing product recovery and recycling procedures is to identify economically justified end-of-life options with the lowest possible risk to the environment. Additionally, the new innovative product recovery value chains must be created that recognize value and benefits within a broader context and seeking out for best recycling practices along the same or different industrial sectors. The most appropriate end-of-life product recovery option, however, often depends on the nature of the product itself and largely depends on weather the objective is to minimise environmental impacts or maximise economic benefits. Therefore, there is clearly a need to identify a systematic way of considering all these factors in an attempt to reach decisions that are environmentally, technically and economically justified.
This paper describes a four-step methodology for reaching end-of-life management decisions for footwear products. This methodology could be used to find optimal product recovery and recycling procedures for footwear products based on the combination of material content, recycling feasibility, recycling application and cost, social-technical and environmental considerations. However, the identification of optimal product recovery and recycling practices for every footwear material group can be a very complex task due to the wide range of materials and processes involved in footwear production. This creates the need for developing knowledge-based approaches that can provide understanding of the relationship and their trade offs among various end-of-life options. Based on this methodology, an end-of-life decision support tool has been developed to facilitate the process of decision making. Design and specification of the prototype EoL decision support tool are provided in this paper. This tool could be used by a number of end users including footwear designers, material suppliers, shoe manufacturers, as well as recycling and product recovery organisations.

One of the primary conclusions of the research on application of the product recovery in footwear industry has been the paramount importance of the role of footwear designers to promote sustainable design practices along the footwear industry. In this context, the footwear recovery methodology and tool presented in this paper can be used to support the material selection based on the recyclability factors of footwear materials while enabling other design optimisation activities to make the reuse and recycling of footwear materials,
components and parts easier, thus reducing the amount of waste disposed into landfills.

References


CBI, EU Market Survey 2004: Footwear, Centre for the Promotion of Imports form Developing Countries (CBI), 2004.


Appendix VII


Appendix VIII

End-of-life Management of Shoes and the Role of Biodegradable Materials

End-of-Life Management of Shoes and the Role of Biodegradable Materials

Theodoros Staikos¹, Richard Heath², Barry Haworth², Shahin Rahimifard¹
¹Centre for Sustainable Manufacturing and Reuse/Recycling Technologies (SMART), Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, UK
²Institute of Polymers Technology and Materials Engineering (IPTME), Loughborough University, UK

Abstract
The paper reviews the trends in the footwear sector regarding the amount of end-of-life waste produced and ways in which it is tackled. Existing reuse and recycling activities in the footwear sector are examined, and the use of biodegradable materials is investigated. The paper presents an integrated waste management framework by combining a mix of design and material improvements as well as reuse, recycling and energy recovery activities. The paper also discusses the implications of using biodegradable materials as a means of reducing the amount of end-of-life waste in the footwear industry and how this proactive approach compares against traditional end-of-life management approaches.

Keywords
End-of-Life Management, Shoes, Biodegradable Materials

INTRODUCTION
Insustainable consumption and production patterns in the developed world have led to an increased generation of waste over many decades. Although local and national authorities, governmental agencies, manufacturers and the general public have come to recognise the importance of controlling waste at source, total waste elimination is not possible. There will always be some waste that cannot be prevented at source and so need to be treated at the end of its functional life. Considering the amount of end-of-life (EoL) waste generated every year, understanding and developing methods for EoL management are a major part of the overall waste management concern.

The footwear industry over the last years has placed significant effort in improving energy and material efficiency, as well as eliminating the use of hazardous materials during the production phase. However, the environmental gains and energy efficiency made in reduction are being overtaken by the considerable increase in the demand for footwear products, the so-called rebound effect [1]. Moreover, the useful life of shoes is relatively short and progressively decreasing as a result of rapid market changes and consumer fashion ends. This creates a large waste stream of worn and discarded shoes at the time their functional life has ended, and most of them are being disposed in landfills.

RESEARCH BACKGROUND

1 Review of the Footwear Industry
The footwear industry is a diverse manufacturing sector which employs a wide variety of materials to make products ranging from different types and styles of footwear to more specialised shoes. Leather, synthetic materials, rubber and textile materials are amongst the basic materials most commonly used in shoe manufacture; each material has its own specific characteristics. Materials significantly influence, not only the life of the footwear but also the end-of-life treatment of the product. Approximately 40 different materials can be used in the manufacturing of a shoe [2]. However, the common material composition of a typical shoe is presented in Table 1.

<table>
<thead>
<tr>
<th>Footwear Materials</th>
<th>Percentage (%wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leather</td>
<td>25</td>
</tr>
<tr>
<td>Polyurethane (PU)</td>
<td>17</td>
</tr>
<tr>
<td>Thermoplastic Rubber (TR)</td>
<td>16</td>
</tr>
<tr>
<td>Ethylene Vinyl Acetate (EVA)</td>
<td>14</td>
</tr>
<tr>
<td>Poly (Vinyl Chloride) (PVC)</td>
<td>8</td>
</tr>
<tr>
<td>Rubber</td>
<td>7</td>
</tr>
<tr>
<td>Other (adhesives, metals, etc.)</td>
<td>7</td>
</tr>
<tr>
<td>Textiles and Fabrics</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 1: Materials composition of a typical shoe. [3]

Nowadays, the shoe industry is facing many of the same challenges as the consumer products and food industries. To meet the needs of customers and be competitive, footwear companies must face two key challenges: being quick to market changes and stay relevant in order to identify or establish new consumer trends. This leads to a shorter life cycle of shoes, and an even increasingly shorter product development cycle for the footwear industry. A shorter life cycle of shoes means that more shoes have been produced over the years, so leading to a higher level of EoL waste by the footwear industry. From 1990 to 2004, worldwide footwear production has increased by 70% to around 17 billion pairs of shoes while by 2010 experts in the sector expect the global footwear output to reach 20 billion pairs [4]. Shoe production and consumption is definitely rising. Western Europe and United States consume 2 billion pairs of shoes each every year [4]. In the UK alone, more than 330 million pairs of shoes, with a total market value of more than £5 billion are consumed every year [5].
shoes, and the air, water and solid waste emissions generated during the shoe production process. In fact, the most serious risks to the environment are to be found with suppliers of semi-finished products and components such as leather, which is produced by tanning. Especially, the use of chromium as tanning agent, which is highly toxic and a suspected carcinogen, has been a major environmental issue for the footwear industry over the last few decades [6]. The use of PVC also, has been reduced in the footwear manufacturing sector because it is claimed that when burned at low temperatures, it has the potential to form organo-chlorine substances, which are extremely toxic both for the environment and for human beings. Finally, solvents and other volatile organic compounds (VOCs), used in synthetic upper materials, leather finishing, adhesives and cleaners, are of major importance for the footwear industry since they contribute to the formation of ground-level ozone, an air pollutant harmful to human health as well as plant life [7]. Table 1 presents some of the major pollutants that linked with footwear materials and their processes.

<table>
<thead>
<tr>
<th>Footwear Materials</th>
<th>Environmental Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leather</td>
<td>Chromium, Aldehydes, Solvents</td>
</tr>
<tr>
<td>Synthetic Materials</td>
<td>Solvents, VOCs</td>
</tr>
<tr>
<td>Textiles</td>
<td>Process Chemicals, Biocides</td>
</tr>
<tr>
<td>Rubbers</td>
<td>Rubber Fume</td>
</tr>
<tr>
<td>PVC</td>
<td>Vinyl Chloride Monomer, Cadmium, Plastisolers</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>Styrene Monomer</td>
</tr>
<tr>
<td>Polurethane</td>
<td>Isocyanates, (CFCs)</td>
</tr>
<tr>
<td>Adhesives</td>
<td>Solvents, VOCs, Chlorine</td>
</tr>
</tbody>
</table>

Table 1: Major Pollutants in the Footwear Industry [7]

In order to promote footwear products which have lower environmental impacts, the European Union (EU) has recently established the European Footwear Eco-Label scheme as a marketing and publicity tool for environmentally-friendly shoes [8]. To be able to use the footwear eco-label some determined ecological criteria must be fulfilled. These criteria aim, in particular, at limiting the levels of toxic residues, limiting the emissions of VOCs and promoting a more durable footwear product. However, the major environmental challenge that footwear industry is currently facing, is the enormous amount of waste generated at the end-of-life phase. Some 12 billions pairs of shoes produced worldwide every year, with most of them being disposed in landfills. Landfill sites can result in serious environmental pollution of groundwater and rivers, due to landfill leachate. Landfill space is also becoming extremely limited, especially in some European countries where available landfill space is non-existent. Finally, forthcoming product-related environmental legislation is expected to change the approach of the footwear industry regarding its EoL waste.

**Landfill Restrictions**

The EU Landfill Directive is the major driving force for the development of European waste management policies. This Directive clearly promotes the diversion of waste from landfills towards products and materials recycling using a variety of measures. The landfill restrictions introduced by the Article 5 of this Directive are very important, in particular the reduction in the amount of biodegradable waste going to landfill and the prohibition of landfilling for certain waste types [9]. According to a recently published report by the European Commission, most of the EU countries have introduced landfill restrictions and taken measures to reduce biodegradable waste going to landfills [10]. For example, since 1st June 2005, German landfills only accept biodegradable municipal waste that has been either incinerated or undergone mechanical and biological treatment. Austria has also introduced strict limits on the landfilling of organic wastes and no waste with an organic carbon content of more than 5% is going to landfill [11].

Furthermore, the UK Landfill Allowances and Trading Scheme Regulations (LATS) introduced in 2004, determines the percentage of certain waste type that regarded as biodegradable municipal waste. These biodegradable percentage range from paper, card and vegetable oils (potentially 100% biodegradable) through to footwear, furniture and textiles (60% biodegradable) to batteries, glass and metal waste (0% biodegradable) [12]. This means that certain types of materials such as leather, natural textiles, natural rubbers etc. which are extensively used by the footwear industry, will be soon required to be reused or recycled instead of disposal in landfill sites.

**Producer Responsibility Issues**

In most countries, managing EoL waste has long been and, in most cases, still is the responsibility of governmental agencies and local authorities. Once products reach the end of their functional lives, producers play no role in collection, recycling or disposal of those EoL products. This approach has started to change with the emergence of a producer responsibility concept. This concept was first introduced in Germany with the 1991 Packaging Ordinance which required manufacturers and distributors to take back packaging from consumers and ensured that a specified percentage is recycled. Producer responsibility legislation was introduced into the EU waste policy with the 1994 Packaging Directive and since then has spread to most industrialised countries. In 2000, the European Commission passed a Directive requiring its Member States to institute a producer responsibility program for end-of-life vehicles (ELV) while an additional Directive for Waste Electronics and Electrical Equipment (WEEE) is expected to be adopted soon by all EU Member States. This concept of broadening manufacturer's responsibility for products beyond their useful life into the post-consumer phase, also concerns closing the loop with respect to materials use and waste management at the end-of-life phase, while providing a source of financing to offset the cost disadvantage of recycling versus disposal and energy recovery. In this context, take-back and producer responsibility legislation is expected to affect the footwear sector similarly to what has happen in other consumer product sectors, e.g. with the implementation of the ELV and WEEE Directives.

**1.1 Reuse and Recycling Activities in the Footwear Industry**

Footwear industry's response to increasing problem of EoL waste has been negligible. In fact, only one major shoe manufacturer, Nike Inc, has been taken measures to manage its waste. Nike's "Reuse-A-Shoe" programme is the only product take-back and recycling scheme established by a shoe manufacturer. This programme has been operating for over a decade in the United States and also just started operating in the UK, Australia and Japan [13]. Their reuse and recycling programme involves a series of collection points in retail centres where people can deposit their worn-out and discarded athletic shoes. The shoes are then collected and taken to a central
It is quite clear from the examination of older landfill sites, that unless carefully designed, built and having the necessary environmental “reagents” present to promote breakdown of materials, waste organic materials can remain in an inert, unchanged state over long periods of time.

RESEARCH ACTIVITIES

1. Waste Management Framework for Shoes

Effective management of EoL waste is a rather complex issue made up of many components. Although there is no blueprint that can be applied in every industrial sector, the European Commission has set up a waste hierarchy framework which specifies the order in which waste management options should be considered, based on environmental impact. Based on this hierarchy, an integrated waste management framework for footwear products has been developed and presented in Figure 1.

This proposed framework divides the waste management options for shoes into two major approaches: proactive and reactive. Proactive approaches include all measures that are taken with the aim to reduce or minimise waste at the source. Reduction of waste, also referred to as waste minimisation, is a proactive approach because simply, waste which is avoided needs no management and has no environmental impact. On the other hand, reactive approaches include all the other waste management options which act in response to the waste problem when the useful life of the product has ended. Reactive waste management approach is also referred as End-of-Life Management.

The key difference between proactive and reactive approaches is timing. EoL management is an after-the-event approach while proactive approaches have an “anticipate and prevent” philosophy to deal with waste.

1.1 Proactive Approaches

In general, it makes far more sense to reduce or even minimise waste than to develop extensive treatment schemes and techniques to ensure that the waste poses no threat to the environment. Waste minimisation activities range from product and material changes, to process changes, to changes in methods of operations [18]. Although there is a wide range of proactive waste management activities, there are two major improvement methods that could be applied in the footwear industry in order to reduce or even minimise waste at the source, design and material improvements.

Design Improvements

Waste minimisation strategies should start at the beginning of a product’s life cycle, here in the product design phase using eco-design improvements. Eco-design improvements in the footwear sector could have significant impact on environmental quality and could reduce the amount of materials needed, thus reducing the amount of waste that need to be handled at the end of the lifecycle. Also a footwear product which is designed for ease of disassembly will make reuse and recycling of its components and parts easier, thus reducing the amount of materials disposed into landfill.

Figure 1: Waste Management Framework For Footwear Products
Material Improvements
The environmental properties of a product can be improved by simply choosing different materials. Material substitution is a proactive approach which can achieve significant reduction of waste, under certain circumstances. In the case of the footwear industry, biodegradable materials can substitute conventional materials in order to improve the environmental properties of shoes. The two most important features that distinguish biodegradable materials from conventional petrochemical materials are their potential biodegradability or compostability at the EoL phase and the use of renewable resources in their manufacture as further discussed in section 3.4.

1.1 Reactive Approaches (End of Life Management)
Total waste elimination is not possible. There will always be some waste that cannot be prevented at the source. Where waste material is produced, an optimal EoL treatment option must be selected with the lowest possible risks to human health and the environment. Each EoL management option brings different impacts to different parts of the environment.

Reuse
Reuse can be practised with the use of products that designed to be used a number of times. Direct reuse of shoes with minimal processing is a possible EoL option but there are a few variables that need to be considered such as the condition of the shoe at the end of their life, the collection and distribution system as well as the purpose of its use.

Recycling
Recycling involves the reprocessing of end-of-life footwear products, parts or materials, either into the same product system (closed loop) or into different ones (open-loop). The end-of-life waste is therefore re-introduced back into the market through a series of processes that can be divided into two major methods: destructive and non-destructive. Destructive methods, like shredding, could be used to transform shoes into other useful materials. End-of-life shoes are being collected and taken to recycling facilities where they are shredded without separation into material types, in order to produce materials that used in secondary applications such as surfacing for roads, playgrounds and running trucks. Nike's "Reuse-A-Shoe" programme, see above, is the most recognized, and probably the only destructive recycling programme in the shoe industry. Non-destructive methods involve the dismantling of shoes to recover saleable and reusable components and to isolate materials for further recycling and disposal. Non-destructive methods generally include inspections, disassembly, replacing and repairing shoe parts and components and finally re-assembling into a new product that could be used inside or outside the footwear sector. However, disassembly of EoL shoes is not an easy task due typically to the large amount of adhesive used to join shoe parts together along with stitching techniques. New technologies must be employed to aid the eventual disassembly process, for example the use of water-soluble adhesives and the use of construction techniques that require less stitching.

Energy Recovery from Waste
EoL waste can be recovered in order to generate heat and electricity. Energy recovery from waste includes a number of established and emerging technologies such as incineration, gasification and pyrolysis. In the case of leather waste, gasification technology has been applied for heat generation and chromium recovery. For example, a 50kg/h leather waste gasification unit has been installed at Pittards plant in Leeds, UK with good results [19]. At the moment, however, such gasification units accept only raw solid waste directly form the tannery production and not finished leather products such as shoes.

Disposal
Disposal of waste is often regarded as the last resort waste management option with the highest environment impact. Most of the EoL footwear waste is going to landfill sites in which are deposited. However, not all waste can be prevented or recycled and there will always be some waste to finally be disposed off in landfills or even just thrown away.

1.2 End-of-Life Management Options for Biodegradable Materials
There are two established methods for the end of life management of biodegradable materials: biological treatment and conventional methods. Biological treatment includes both aerobic (composting) and anaerobic digestion. Aerobic composting of biodegradable materials generates carbon dioxide, water and methane as some form of compost, which can be used as a fertilizer. Whilst all three are greenhouse gases, carbon dioxide and water do not contribute to additional atmospheric loading, while it is argued methane does. Indeed some biodegradables may also produce hazardous by-products as soil contaminants. It has also been recently recognised for fast cycle composting, the biodegradables have to be held at 50 to 60°C. So if biodegradable products are to be composted, they must meet stringent quality criteria. Dedicated standards and certification schemes have been established for verifying the compostability of biodegradable products. Anaerobic digestion, on the other hand, is a process where biodegradable material is broken down in the absence of oxygen in an enclosed vessel. The process produces carbon dioxide, a biogas and solids/liquors known as digestate which can also be used as fertiliser. However, anaerobic digestion can be problematic as some of the biodegradable materials are known to be non-biodegradable under anaerobic conditions, another possible problem with PLA [20]. It should be noted that the EU Landfill Directive recognises biological treatment activities as a form of recycling.

Biodegradable waste materials can also be treated using conventional methods, such as incineration and landfilling. Incineration may be a solution in the case of no available biological treatment. Mass burn incineration of biodegradable materials generates carbon dioxide, water, and ash, with the release of thermal energy. However, in the case where renewable resources used, thermal recovery is carbon dioxide neutral. There is the possibility with the combustion of composite structures that metals may be concentrated and recovered. Biodegradable materials also could be send to landfill, where broke down to produce a powerful greenhouse gas, methane. As previously mentioned, the EU Landfill Directive requires a considerable reduction to the volume of biodegradable materials being sent to landfill and even such materials are being excluded from landfilling by law.

2 CONCLUSIONS
Forthcoming legislative requirements and market pressures are expected to force the footwear industry towards measures to deal with its end-of-life waste. Recycling and product recovery activities for footwear products need to be identified to ensure that landfilling is
economic value of the end-of-life materials, components and products is recovered. Proactive waste management activities such as material substitution will not, in the short term, be able to solve the issues connected to current EoL waste generation. This highlights the need to direct considerable efforts on reactive end of life management initiatives improving the treatment of waste currently generated, especially those focusing on the encouragement of reuse, recycling and energy recovery of footwear products.

In this context, this paper presented an integrated waste management framework for the footwear industry based on proactive and reactive waste management options, the composition of which is determined by the availability of end-of-life shoes and by access to recycling facilities. The use of biodegradable materials and their end-of-life implications are also being discussed. Compostability of biodegradable materials together with the use of renewable resources, of animal or plant origins, in their manufacture provide some positive aspects in terms of their end-of-life management consequences. On the other hand, if landfilled, biodegradable materials produce methane, a powerful greenhouse gas. In fact, when send to landfill, biodegradable materials lose their environmental benefit and become a non-benefit in terms of the EU Landfill Directive objectives. Furthermore, climatic variations play an important role in the biodegradability of materials which makes the application in the footwear industry not suitable for every type of shoes. Therefore, it the authors opinion that the use of biodegradable materials is a viable solution for certain types of shoes and components but they cannot be used in all the types of shoes and, definitely do not provide the ultimate solution to solve the EoL waste problem of the footwear industry. The use of biodegradable materials in shoe manufacturing is a long-term solution compared with recycling and product recovery which is a short-term end of life management option. However, the use of biodegradable materials needs to be further examined, especially with many types of biomaterials at the research and development stages at present.

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CONTACT

Theodoros Staikos
Centre for Sustainable Manufacturing and Reuse/Recycling Technologies (SMART), Wolfson School of Mechanical and Manufacturing Engineering, LE11 3TU, Loughborough University, UK, T.Staikos@lboro.ac.uk