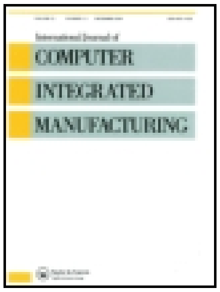

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An end-of-life decision support tool for product recovery considerations in the footwear industry

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The footwear industry is a manufacturing sector that utilizes a wide variety of materials and processes to produce a range of distinctly different products, from sandals to more specialized footwear. Currently, more than 19 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 disposed of in landfills. Producer responsibility concerns, forthcoming legislation and increasingly environmentally conscious consumers are expected to challenge the way the global footwear industry is dealing with its end-of-life (EoL) products. This paper highlights the potential benefits of developing a footwear product recovery methodology and an associated software tool to support decision-making to determine the most suitable (in environmental, economic and social–technical terms) manner in which to treat post-consumer shoe waste. Such a methodology, in addition to supporting design and material selection processes, could also provide benchmark information for the selection of the best EoL practice for a selected range of different shoe types. The paper concludes by providing a computational viewpoint of an EoL 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 recognize the importance of controlling waste at the source, total waste elimination is not feasible. There will always be some waste that cannot be prevented at the source and so must 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 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 are 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 legislation, as well as increasingly

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environmental consumer demands, are expected to challenge the way the footwear industry deals with its EoL products.

This paper proposes a footwear product recovery methodology together with an associated software tool to support the decision-making process regarding the determination of the most appropriate EoL 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 EoL scenarios. Later 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 an EoL decision-making process to evaluate these factors in order to identify the best alternative option. However, the value of the results obtained through 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 detail, it is important to first consider the materials and processes used to make shoes.

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 shoes. In this context, the basic parts of a shoe can be grouped broadly into three categories (Clarks Ltd 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; this includes the insole, the sole and the outsole;
- the grindery, which includes items that are incorporated into a shoe but do not belong either to the upper or the lower (e.g. toe puffs, stiffener materials, eyelets).

Some of the major parts and components of a man'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 categorizations can also be made based on age and gender (i.e. men's, women's and children's shoes). For the purpose of this research, footwear products have been categorized 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.

2.1. Shoe manufacturing

The production of footwear starts with the supply of materials. These materials include both raw materials (such

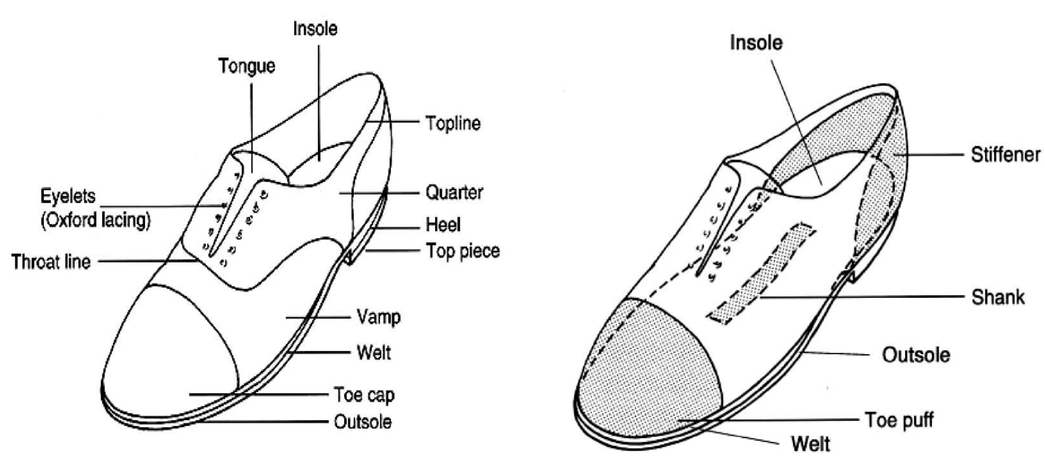

Figure 1. Major parts and components of a man's formal shoe (Rossi 2000).

Table 1. Component breakdown of different shoe types.

	Men's formal	Men's casual	Women's court	Women's fashion	Children's	Adult sports trainer
Upper part						
Leather	✓	✓	✓	✓	✓	
Canvas		✓		✓	✓	
Polyurethane		✓		✓		✓
PVC		✓		✓		✓
Lower part (soles)						
Leather	✓					
Leather/polymer	✓	✓	✓	✓		
Vulcanized rubber		✓		✓		
TPR		✓		✓	✓	
Polyurethanes		✓		✓	✓	✓
TPU		✓		✓	✓	✓
EVA		✓		✓		✓
Grindery items						
Shanks	✓		✓			
Nails	✓		✓			
Eyelets	✓	✓		✓	✓	
Laces	✓	✓		✓		✓
Threads	✓	✓	✓	✓	✓	✓
Velcro/catches					✓	
Textile backers & linings	✓	✓	✓	✓	✓	✓
Foams (padding)	✓	✓	✓		✓	✓
Heel backing supports	✓	✓	✓	✓	✓	✓
Toe cap reinforcement.	✓	✓	✓	✓	✓	✓
Heels	✓	✓	✓	✓		

as leather) and semi-finished products and components. The 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 a last (a fixture that 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—the upper and lower part are assembled using adhesives;
- injection—the sole material is injected directly to the upper part of the shoe;
- stitching—the upper and lower part are assembled together with thread.

Finally, finishing processes are carried out and these are determined by the materials used during manufacture, for example, leather materials are usually stained, polished and waxed before being tagged and delivered to the market.

2.2. *Shoe materials*

Leather, synthetic materials, rubber and textile materials are among the most commonly used materials in shoe manufacturing. These materials differ not only in their appearance but also in their physical qualities, service life, differing treatment needs, and 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, measured after grinding.

Leather has ideal characteristics for use in the upper part of shoes—it is soft with very good absorption ability and is 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 are designed to look or function like leather have been developed (e.g. fabrics coated with polyvinylchloride (PVC) or polyurethane (PU)). Leather has also been largely superseded by other materials such as rubber and plastics in the lower part of shoes. In the 1950s only four materials were used as soling materials, namely leather, rubber, vulcanized rubber and resin rubber (*World Footwear* 2005). Since then, the choice has been extended to include a number of different plastics and polymers such as PVC, thermoplastic rubber (TR), micro ethylene vinyl acetate (EVA), etc. Polymeric and plastic materials currently dominate the production of shoe soles, outsoles and insoles, especially thermoplastic materials and rubbers. Table 2 lists the major materials used in the construction of shoe lowers.

Finally, grindery components can be made of a variety of materials depending on their purpose of use. Toe puffs can be made from rubber or thermoplastic resins, stiffener components from leather, EVA and polyester, while shanks 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 doubled every 20 years, from 2.5 billion pairs in 1950 to more than 19 billion pairs of shoes in 2006 (*World Footwear* 2007). In the European Union, footwear consumption increased by 22% from 2002 to 2005 to reach 2.3 billion pairs of shoes (EC 2006). Additionally, worldwide *per capita* consumption of footwear has also 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, shoe consumption differs significantly per country. Although China has the highest footwear consumption in the world, the USA has the highest *per capita* shoe consumption with each inhabitant purchasing an average 6.9 pairs of shoes every year (AAfA 2005). At the other extreme, in less developed countries, the *per capita* shoe consumption is 0.6 pairs in India and 0.5 pairs in Vietnam (all types of shoes included) (SATRA 2003). Figure 3 shows overall shoe consumption as well as the *per capita* shoe consumption in a number of different countries.

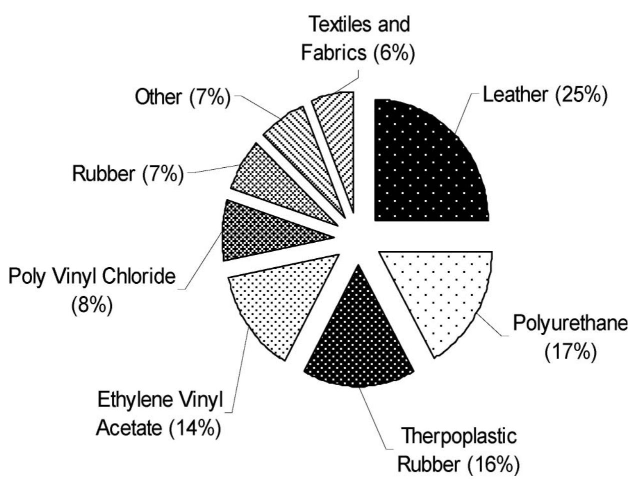

Figure 2. Material composition in an average shoe (%wt) (Weib 1999).

Table 2. Use of soling materials in shoes (Wilson *et al.* 1997).

Soling materials	Percentage (%wt)
Resin rubber	20
PVC and blends	19
Thermoplastic rubber (TR)	15
Direct vulcanized (DV) rubber	8
Direct injection moulded (DIM) PVC and blends	8
Leather	7
Micro ethylene vinyl acetate (EVA)/rubber	7
Polyurethane (PU)	7
Other (wood, cork, textile etc.)	5
Vulcanized rubber	4

In the UK, more than 320 million pairs of shoes are consumed every year (SATRA 2003). It is estimated that the waste 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 organizations such as the Salvation Army Trading Company (SATCOL^{TM}), Oxfam^{TM} and others in collaboration with local authorities and municipalities. SATCOL^{TM} alone, with its 2300 shoe banks, door-to-door collections and donations, managed to collect around 971 tonnes of worn or unwanted shoes during 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 these estimations, approximately 12% (20 250 tonnes) of post-consumer shoes in the UK are collected and re-distributed as second-hand shoes with the remainder (88% or 145 200 tonnes) disposed to landfill.

The standard practice of dumping waste in landfills has led to soil, surface and groundwater contamination. Landfill sites can result in serious environmental pollution of groundwater and rivers due to landfill leachate (the liquid produced from the decomposition of waste within the landfill). Furthermore, landfill space is becoming extremely limited, with the number of landfill sites in the European Union considerably decreased over recent years. In early 1990s, there were over 8000 landfill sites in use in Germany; the number of currently operating landfill sites is below 300 (Hempen 2005). The EU Landfill Directive (European Union 1999) clearly promotes the diversion of waste from

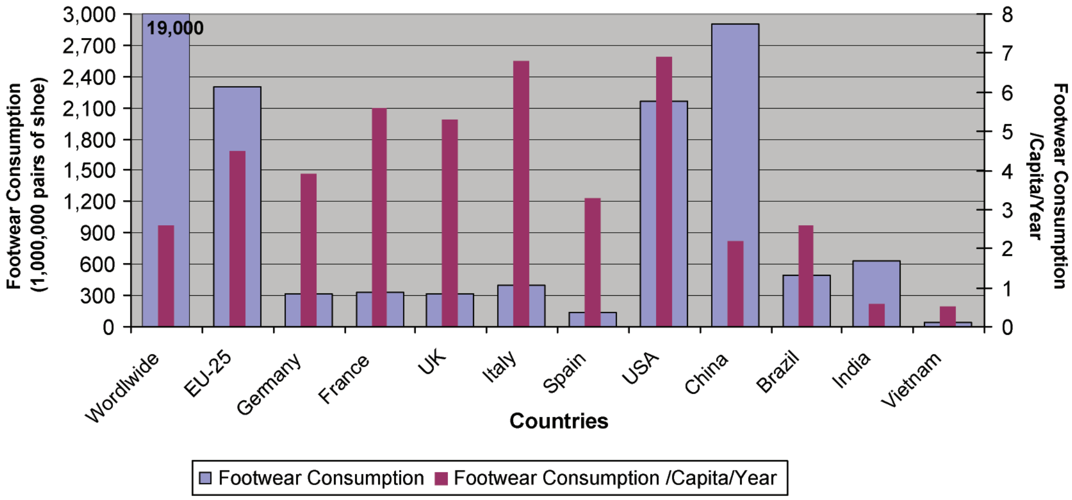

Figure 3. *Per capita* footwear consumption in different countries (SATRA 2003, CBI 2004, AAfA 2006, EC 2006).

landfills towards products and materials recycling using a variety of measures. The landfill restrictions introduced by Article 5 of the Directive are very important, in particular the requirements for reduction in the amount of biodegradable waste going to landfill and prohibition of landfilling certain waste types. Since 1 June 2005, German landfills only accept biodegradable municipal waste that has been either incinerated or undergone mechanical and biological treatment; in Austria, strict limits on the landfilling of organic wastes have also been introduced (Hempen 2005). Additionally, the UK Landfill Allowances and Trading Scheme (LATS) regulations introduced in 2004, determine the percentage of certain waste types that are regarded as biodegradable municipal waste. These biodegradable percentages range from paper, card and vegetable oils (potentially 100% biodegradable) through footwear, furniture and textiles (50% biodegradable) to batteries, glass and metals (0% biodegradable) (Defra 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.

The footwear industry's response to this increasing problem of post-consumer shoe waste has been negligible. In fact, only one major shoe manufacturer, Nike^{TM}, has been taking measures to manage its waste. Nike's recycling programme 'NikeGO-Places^{TM}' (formerly 'Reuse-A-Shoe^{TM}') 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 USA and has 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^{TM} that can be used in the surfacing of tennis and basketball courts or running tracks. According to Nike (2006), since its inception in 1993, the Reuse-A-Shoe^{TM} programme has recycled more than 16 million pairs of worn-out and defective athletic shoes.

The limited activities in shoe recycling across the footwear industry highlight the paramount importance of investigating alternative approaches to footwear product recovery and recycling, as outlined in the remainder of this paper.

4. Footwear product recovery methodology

The footwear product recovery methodology aims to assist shoe designers, manufacturers and recovery and recycling organizations in determining appropriate EoL scenarios for post-consumer shoes. The methodology enables the definition of alternative EoL 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 minimize 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 4 shows a visual representation of the phases included in the footwear product recovery methodology for post-consumer shoes.

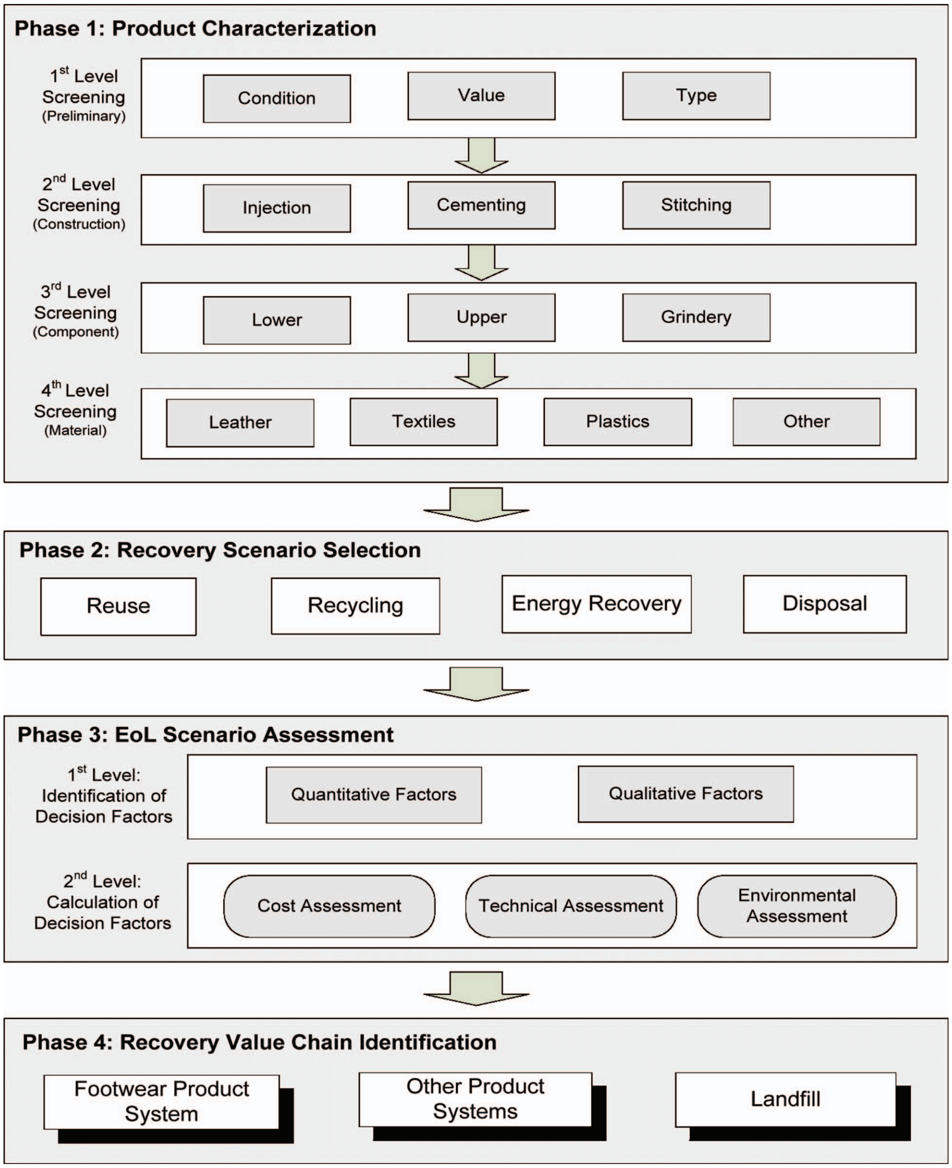

Figure 4. Footwear product recovery methodology.

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.

4.1. Product characterization

This first phase identifies the main characteristics of the footwear product. This step is needed in order to classify the product into its basic attributes and to 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 shoe (men's casual, sports trainers, etc.). This screening level is very important for selection of a suitable product recovery option. For example, worn shoes in 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, others. The major output of the first phase is a general categorization of shoes based on their specific attributes and identification of important factors that influence the choice of an EoL management option.

4.2. *Recovery scenario selection*

In the second phase of the methodology, a waste management model is constructed based on output from the first phase. This waste management model for post-consumer shoes determines the different EoL management options, giving priority to recycling and reuse to minimize cost and environmental impacts. The output of such a model would identify potential treatments for post-consumer shoes depending on the shoe type. The shoe waste management model consists of the EoL management options of reuse, recycling, energy recovery or disposal (Staikos *et al*. 2006). Reuse of post-consumer shoes 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 functional life, the collection and distribution system, and the purpose of its reuse. Recycling involves the reprocessing of post-consumer shoes, parts or materials to be used either into the same product system (closed-loop manufacture) or different ones. In this approach, 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 simply represent the costs and revenues for each EoL 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 were utilized to analyse the decision criteria. The analytic hierarchy process (AHP), however, was used as the basic framework for simultaneous consideration of all these factors. The 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, resources allocation, optimization and generally selecting the best alternative option (Vaidya and Kumar 2006). The AHP decomposes a complex decision problem into a hierarchy and allows 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 costs 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 at a local scale. Figure 5 shows the framework for shoe recovery scenario assessment, including the different decision-making methods that have been utilized.

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 are 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 depends heavily on establishing a successful value shoe

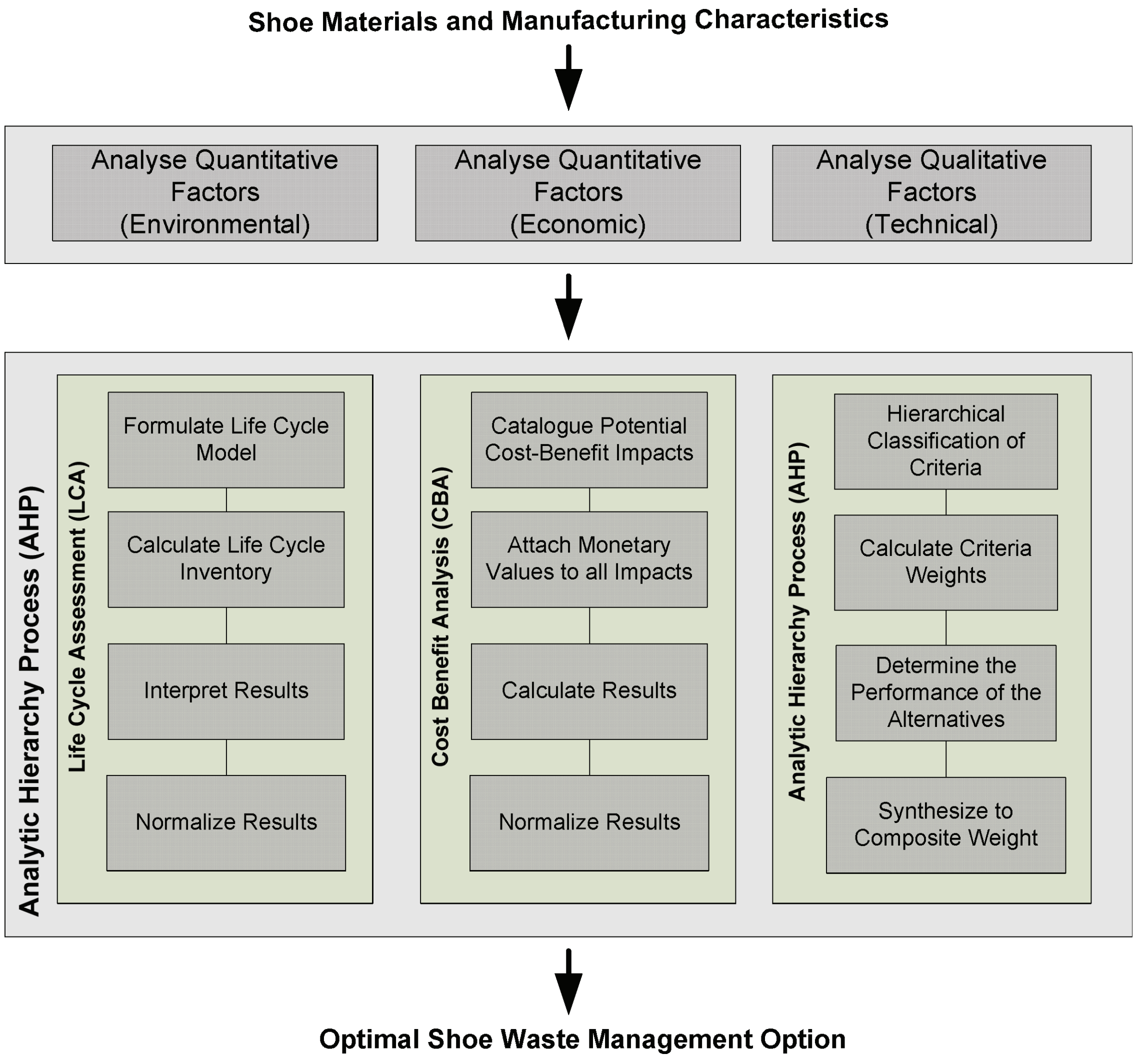

Figure 5. Framework for scenario assessment.

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 EoL scenarios for shoes.

However, not all post-consumer shoes are suitable for recycling or reuse and, therefore, landfilling or even incineration without energy recovery must be considered practical options. Other issues that also need to be considered include the size and the value of the end market, current and predicted buying trends, and the range and price of competing materials and products. The basic output of this phase is a list of potential applications for recycled shoe materials.

5. EoL decision support tool for footwear products

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 EoL decision support tool was developed. The prototype model was developed as a three-tier architecture (figure 7).

The presentation module acts as a user interface environment to receive and control user input as well as to present the output. The database module provides a data

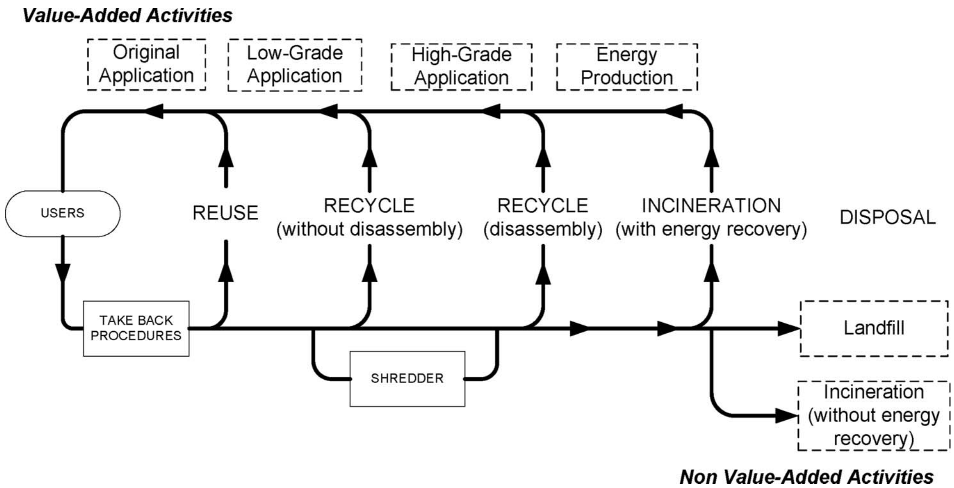

Figure 6. Recovery value chain for EoL scenarios for shoes.

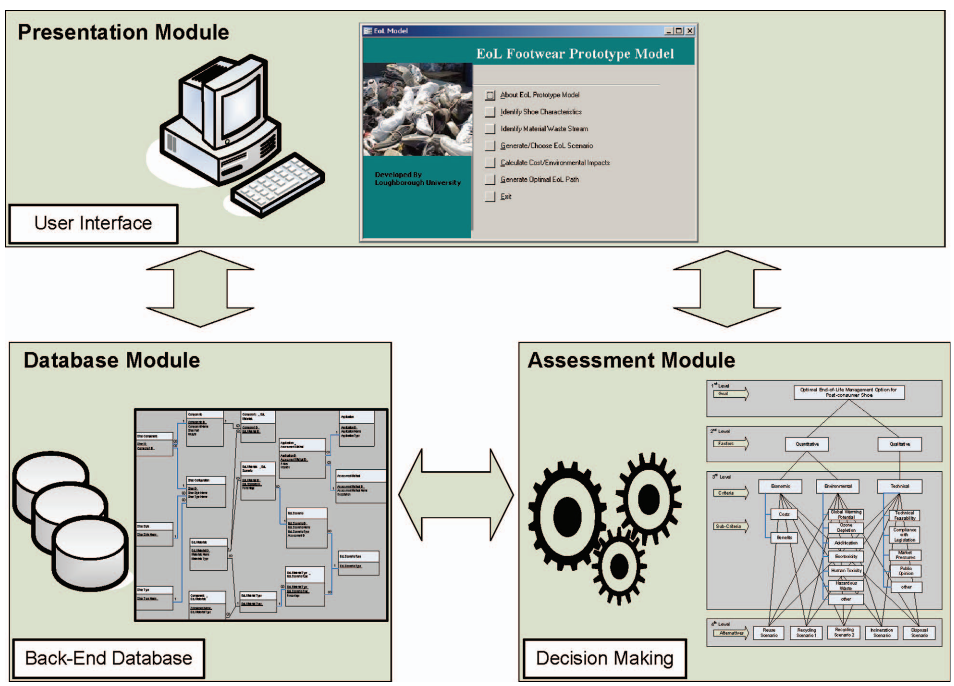

Figure 7. System architecture of prototype EoL decision support tool.

repository in which information is stored and retrieved while the assessment module comprises the assessment/logic elements of the system that support the decision-making process.

5.1. Presentation module

The user interface environment was 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, is depicted in figure 8. Each of these options leads to a further software module that supports a specific function within the system.

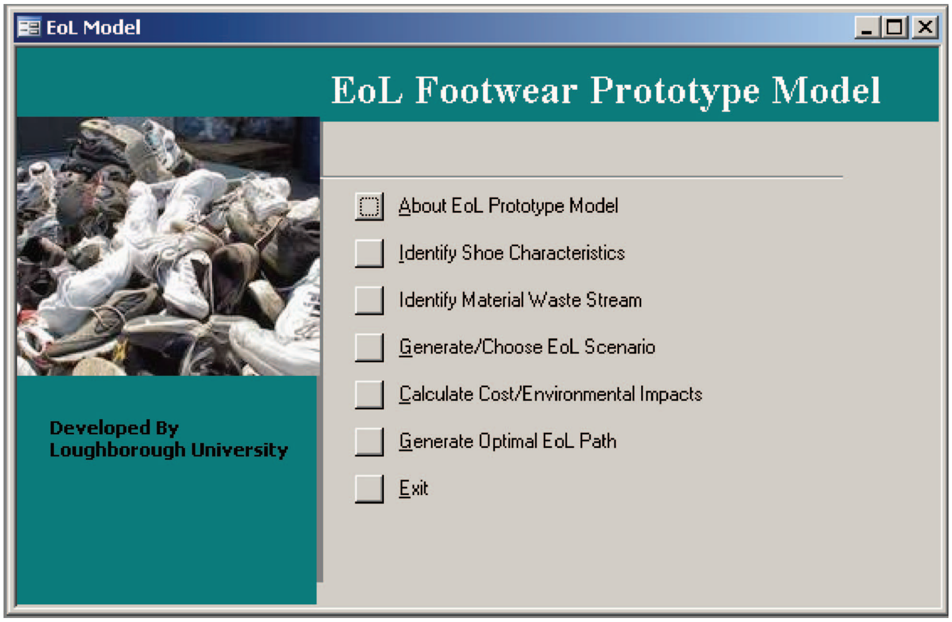

Figure 8. The main interface of the EoL decision support tool.

5.2. *Database module*

The database module provides a back-end database, comprising both datasets 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 currently being developed on commercial software (MS-Access). The relational database model includes 16 tables in total. A pictorial representation of the database model is illustrated in figure 9.

5.3. *Assessment module*

The third module comprises the assessment element, the so-called logic of the system that supports the decision-making process. As previously described, each recovery scenario is assessed in terms of 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.

5.3.1. Calculate environmental criteria. Environmental criteria for alternative EoL scenarios for shoes are calculated using a simplified LCA methodology. The environmental impact (*EI*) score of each scenario is computed as follows (Wenzel *et al.* 1997)

$$EI_j = \sum_{i=1}^{n} ICI_i$$

where IC_i = impact category indicator, n = number of impact category indicators and j = number of EoL scenarios.

The life cycle inventory (LCI) data were derived from a streamlined LCA study of average shoes, 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 (Wenzel *et al.* 1997). The environmental impact score (EI_j) of each scenario needs to be normalized and expressed in unit-free numbers for consistency purposes. The normalized environmental impact score (NEI_j) for each scenario is calculated as follows:

(i) calculate the reciprocal of each environmental impact score (REI_j);
(ii) divide the reciprocal of each environmental impact score (REI_j) by the sum of all reciprocal scores;
(iii)

$$NEI_j = \frac{REI_j}{\sum_s REI_j}$$

where $REI_j = 1/EI_j$ and EI_j = environmental impact score of each scenario, s.

5.3.2. Calculate economic criteria. Economic values for each EoL 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 EoL

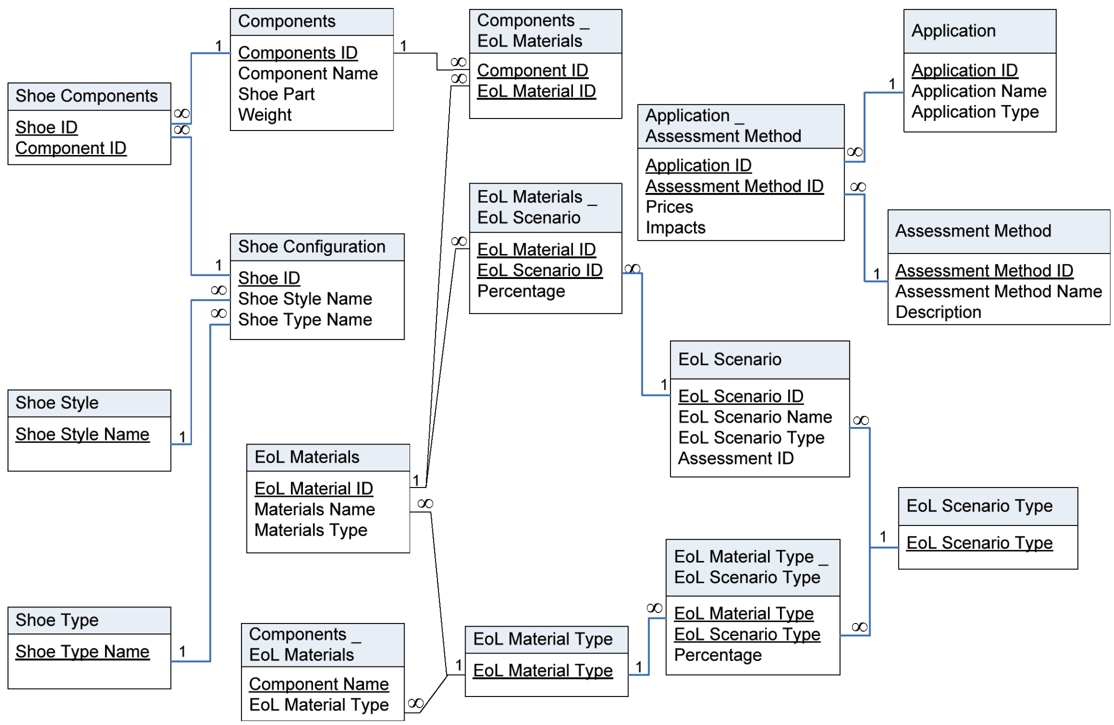

Figure 9. Database model structure.

economic value and *BCR* are calculated based on the following methods (Lee *et al*. 2001).

- *Reuse benefit/cost ratio* (BCR_{RE})

The revenue of the reuse scenario (B_{RE}) is 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, BCR_{RE} can be obtained as

$$BCR_{RE} = \frac{\sum B_{RE}}{\sum C_{RE}} = \frac{B_{resale}}{C_{collection} + C_{trans} + C_{refurb}} \tag{1}$$

- *Recycling benefit/cost ratio* (BCR_{RC})

The revenue 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}):

$$BCR_{RC} = \frac{\sum B_{RC}}{\sum C_{RC}} = \frac{B_{weight} \times B_{value}}{C_{collection} + C_{trans} + C_{separation} + C_{shred}} \tag{2}$$

- *Energy recovery benefit/cost ratio* (BCR_{ER})

The revenue of the 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_{ER}) are collection costs ($C_{collection}$) and transportation costs (C_{trans}):

$$BCR_{ER} = \frac{\sum B_{ER}}{\sum C_{ER}} = \frac{B_{energy} \times B_{price}}{C_{collection} + C_{trans}} \tag{3}$$

- *Disposal benefit/cost ratio* (BCR_{DS})

There are no projected revenues in the disposal scenario (B_{DS}). The costs (C_{DS}) arise from 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, BCR_{ER} is always zero:

$$BCR_{DS} = \frac{\sum B_{DS}}{\sum C_{DS}} = 0 \tag{4}$$

The benefit to cost ratio (BCR_j) for each EoL scenario is then normalized for consistency purposes. The normalized benefit/cost ratio ($NBCR_j$) is calculated by dividing each *BCR* by the sum of all *BCR*s as given in equations (1)–(4):

$$NBCR_j = \frac{BCR_j}{\sum_j BCR_j} \tag{5}$$

where $NBCR_j$ = the normalized benefit/cost ratio, BCR_j = the benefit/cost ratio for each scenario and j = the 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 using the AHP. 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 EoL scenario with respect to each social–technical criterion. Figure 10 shows graphically the composite weight of five alternative EoL 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 man's 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, is to synthesize the overall results in order to produce a global priority vector for each EoL scenario. The global priority vector indicates the preference (or the composite weight) of each alternative option. Figure 11 shows the preference of the five

Social-Technical Criteria					
	Technical Feasability	Public Opinion	Market Pressures	Compliance with Legislation	**Composite Weight**
Relative Weight of Decision Variables	0.07	0.15	0.43	0.35	
End-of-Life Management Scenarios	*Relative Weight of Scenarios with respect to Variables*				
Recycling Scenario 1	0.44	0.33	0.33	0.32	**0.34**
Recycling Scenario 2	0.29	0.37	0.26	0.29	**0.29**
Reuse Scenario	0.16	0.18	0.26	0.26	**0.24**
Incineration Scenario	0.08	0.09	0.11	0.09	**0.10**
Disposal Scenario	0.04	0.03	0.04	0.04	**0.04**

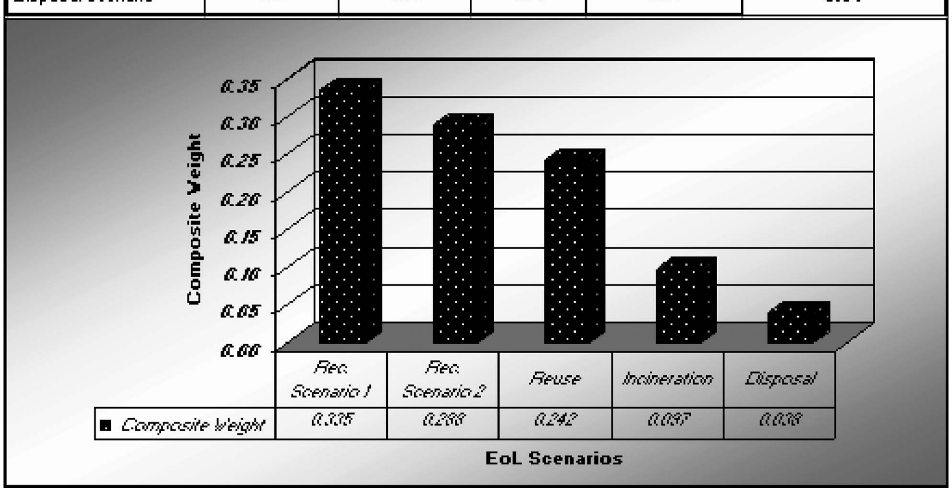

Figure 10. Calculation of social–technical criteria.

SYNTHESIS OF OVERALL RESULTS

	Quantitative Factors		*Qualitative Factors*	
	Environmental	**Economic**	**Social-Technical**	**Global Priority Vector**
	0.56	0.32	0.12	
Recycling Scenario 1	0.32	0.27	0.34	**0.32**
Recycling Scenario 2	0.31	0.28	0.29	**0.37**
Reuse Scenario	0.31	0.32	0.24	**0.25**
Incineration Scenario	0.03	0.13	0.10	**0.04**
Disposal Scenario	0.03	0.00	0.04	**0.02**

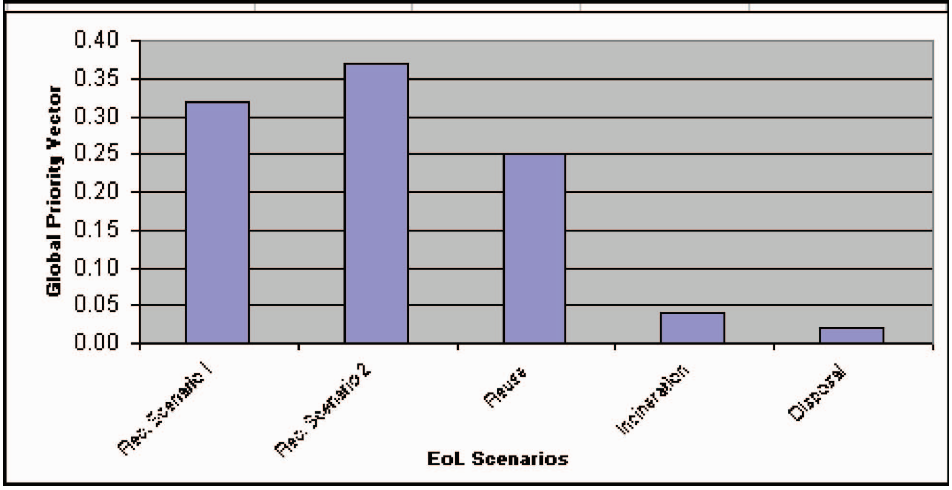

Figure 11. Final output of EoL decision support tool.

alternative EoL scenarios, as presented in section 5.3.3, for a man's casual shoe.

The final output of the analysis, as presented in figure 11, indicates that Recycling Scenario 2 (disassembly of shoe) is the most preferable option for a man's casual shoe and Disposal (landfilling) is the least. It should be mentioned that this demonstration of the AHP 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. Conclusions

The large amounts of post-consumer shoe waste produced every year, legislative pressures to divert waste from landfills and the hidden value of recyclable materials in post-consumer shoes have led to the development of an EoL 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 EoL options with the lowest possible risk to the environment. Additionally, new innovative product recovery value chains must be created that recognize value and benefits within a broader context and seek out the best recycling practices in the same or different industrial sectors. The most appropriate EoL product recovery option, however, often depends on the nature of the product itself and largely depends on whether the objective is to minimize environmental impacts or maximize 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 EoL 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, and social–technical and environmental considerations. However, the identification of optimal product recovery and recycling practices for every footwear group can be a very complex task due to the wide range of materials and processes involved in shoe production. This creates the need to develop knowledge-based approaches that can provide an understanding of the relationships and trade-offs among various EoL options. Based on this methodology, an EoL decision support tool has been developed to facilitate the decision-making process. 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 and shoe manufacturers, as well as recycling and product recovery organizations.

One of the primary conclusions of the research on the application of product recovery in the footwear industry has been the paramount importance of the role of footwear designers to promote sustainable design practices in the footwear industry. In this context, the footwear recovery methodology and tool presented in this paper could be used to support material selection based on the recyclability factors of footwear materials while enabling other design optimization activities to make the reuse and recycling of footwear materials easier, thus reducing the amount of waste disposed to landfill.

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