Development of an Economically Sustainable Recycling Process for the Footwear Sector

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Abstract

The worldwide consumption of footwear is estimated to be in excess of 20 billion pairs of shoes per year. At present less than 5% of these are recycled or reused, with most being disposed of in landfill sites around the world. In fact, the majority of current footwear recycling schemes are led by charitable organisations, for the purpose of reusing the shoes in developing countries. However, not all of the collected shoes are deemed suitable for reuse, with a sizeable amount of these old shoes more suited for material recycling due to their poor conditions. Material recycling of footwear products is however a challenging problem with most modern shoes containing a complex mixture of rubber, textile, polymers and metallic materials. Furthermore due to the relatively low value of recoverable materials, the cost of the shoe recycling processes has to be kept to a minimum. This paper discusses a four step methodology that has been developed to create a market driven material recycling approach for footwear products. A key point presented in the paper is that for products with relativity low hidden value at end-of-life such as footwear product, it is not presently economically feasible to obtain recycled materials that can compete with virgin materials in the market place. Therefore, for footwear products a more realistic level of material recycling is proposed, using commercially available automated recycling technologies, with the reclaimed materials limited to a range of down-cycled, yet useful and viable applications.

Keywords

End-of-Life Management, Footwear Recycling, ...

1 INTRODUCTION

Rapid market changes and consumer fashion trends coupled with an increased availability of cheap mass produced goods, has resulted in a sharp increase in the consumption of products over the last five decades.

In the footwear sector the per capita consumption has increased considerably, from one pair of shoes for every person in the world in 1950 to almost 2.5 pairs of shoes in 2005. It is predicted that the global footwear consumption will reach 20 billion pairs by 2010 [1]. Most of these shoes are currently being disposed of in landfill sites around the world, often after a short use life-cycle. However, producer-responsibility issues and forthcoming environmental legislations are expected to challenge the way the footwear industry deals with its end-of-life (EoL) products.

The work by Staikos and Rahimifard [5] has already established a comprehensive range of possible end-of-life options for footwear, including reuse, material recycling incineration and gasification, each of which have different environmental impacts, economic values and technical requirements. According to the waste hierarchy, reuse should be the first priority. However, not all shoes can be reused. In such situations, material recycling is seen as the most suitable means of dealing with these discarded shoes. For long-term sustainability of such footwear recovery activities, however, an economically viable material recycling process must be established.

In the automotive and electrical/electronic industry, where European Producer Reasonability directives, such as the ELV and the WEEE have been introduced, a number of material recycling value chains have now been established. This has been feasible because these products typical contain a large percentage of metallic parts and so their recovery will typically generate a high commercial value to facilitate an economically sustainable value chain. However, footwear products typically contain a large mixture of materials that have relatively low economic value. Therefore understanding and developing methods for economically sustainable footwear recycling is of major concern to the footwear sector for their overall waste management strategy.

In this paper a methodology for the development of an economically sustainable recycling process is presented. This consists of four main steps: product analysis; the definition of recycling scenarios; a cost benefit analysis of the different scenarios; and the development of a recycling process plan. The authors argue that this approach is not just limited to the footwear sector and due to its generic nature it can be applied to other industrial sectors.

2. Research Background

A number of EoL options have been defined for the management and reduction of post-consumer footwear waste, these are: reuse, material recycling, incineration and gasification, and landfilling [5]

Landfilling is considered the most undesirable options, due to the obvious negative environmental impact, depletion of resources; increasing landfill taxes and in some countries the limited availability of landfill space. Incineration is still considered a controversial technology with environmental concerns over the release of polluting emissions. The other promising technology referred to as gasification, can mainly be applied to leather and other organic materials, and still provides an expensive option for large scale energy recovery from footwear products.

Reuse involves the collection of worn or unwanted shoes for distribution mainly within developing countries. Charity organisations, local authorities and municipalities such as the Salvation Army Trading Company Ltd. (SATCOL) and Oxfam are the main supporters of reuse schemes in the UK. However not all shoes that are collected can be reused, and in such situations material recycling is seen as the most suitable option. Nike is currently the only footwear manufacturer engaging in post-consumer footwear recycling on a commercial scale. Their scheme has been labelled the Nike 'reuse A-shoe' programme and has been developed to recycle worn and defective athletic shoes[3]. Consumers can return any brand of unwanted athletic shoes via Nike's worldwide network of collection points placed within retail stores. The collected shoes end up in one of two central recycling plants - in the US or in Belgium. In these plants the shoes are shredded and put through a series of mechanical recycling processes to separate them into three material streams: Nike grind (rubber), Nike foam and Nike Fluff (textiles). These materials are then used for various sports related applications such as running track underlay, playground surfacing and basketball court underlay. The Nike 'reuse-a-shoe' scheme has been operating for over a decade and Nike claims to have recycled around 24 million pairs of shoes to date [3]. However, the scheme is not designed to deal with the recycling of other non-athletic types of post-consumer footwear. Therefore, a more generic approach as outlined in this paper, is required to deal with various types and styles of footwear product.

3 A METHODLOGY FOR SUSTAINBLE RECYCLING PROCESS FOR FOOTWEAR PRODUCTS

Material recycling scenarios for footwear have already been discussed in the previous works of Staikos and Rahimifard [5]. The work was however largely theoretical, driven by the 'technology push' scenario, where high levels of material liberation and purity were deemed possible. For example, no-destructive disassembly of footwear products to their component level was considered to achieve a high grade of material recycling.

However, in order to establish a large scale holistic footwear recovery and recycling scheme in the UK, there is now a strong need to develop a technologically feasible and commercially viable recycling system for post-consumer footwear waste, thus the material recycling approach presented in this paper is based upon the 'market pull' principles, as depicted in figure 1.

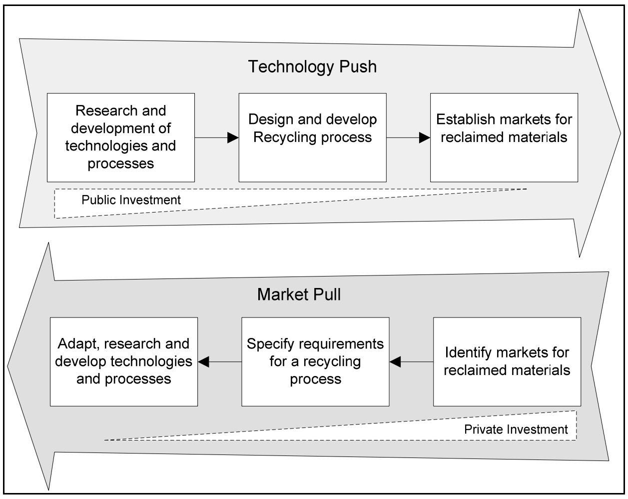

Figure 1: Technology push versus market pull

The proposed market pull based material recycling methodology (see Figure 2) starts with the analysis of the product and the definition of a number of feasible material recycling scenarios. The costs and revenues are then analysed for each option to highlight the most economically viable alternative. In this way, only when the recycling scenario is deemed feasible from the market perspective, will the technology be developed to enable liberation of the materials. The four steps in this methodology are further described below.

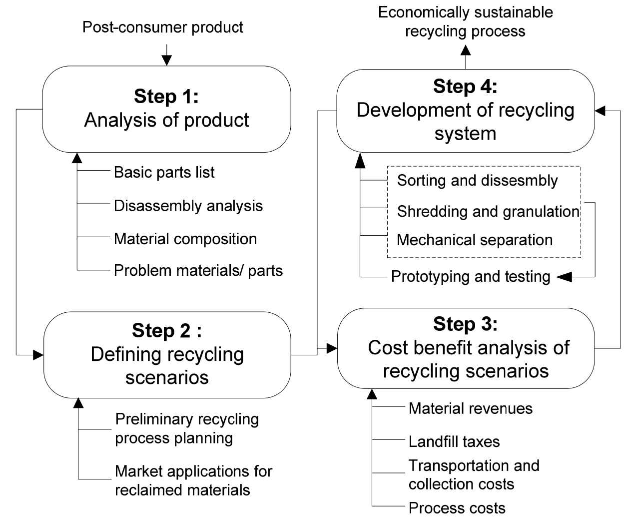

Figure 2: Methodology for development of economically sustainable recycling process.

3.1 Step 1: Analysis of Product

The analysis of various footwear types has shown that the material recycling of mixed footwear products is a challenging problem [5]. The footwear industry employs a wide variety of materials to make a diverse range of different types and styles of 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. A particular problem is however that these commonly used footwear materials have similar/ overlapping density ranges; as shown in figure 3. This causes problems for the automated recovery of footwear materials as most commercially available material recycling technologies utilise material density based separation to reclaim the different types of materials present in the product.

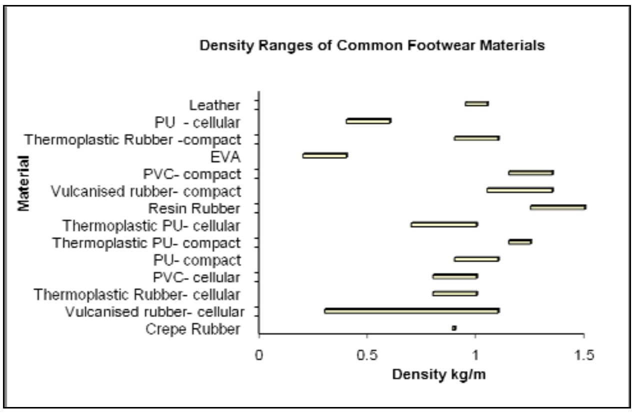

Figure 3: Density range of common footwear materials

3.2. Step 2: Definition of Recycling Scenarios

The second step in this methodology is to define a number of material recycling scenarios. These scenarios must be deemed feasible from both a technology perspective and more importantly there must be potential markets and applications for the various reclaimable materials. For post consumer footwear waste, three possible material recycling scenarios have been defined, namely high grade recycling, medium grade recycling and low grade recycling. For each of these scenarios a number of preliminary recycling process plans have been created. The majority of these process plans include granulation followed by some kind of mechanical separation. These processes are at present considered the most economically feasible means to recycle footwear products. For the mechanical separation, commercially available density based separation technologies are currently advocated. Although other more complex technologies such as electrostatic and hydrophobic based separation are also being considered to enable a higher grade of material recycling. These footwear material recycling scenarios are further described below.

3.2.1. High Grade Recycling Scenarios

For the high grade material recycling scenario, the aim is to obtain almost pure materials that can then be reused for new manufactured product applications e.g. new shoes. For this high grade recycling almost complete separation of material types will be needed. For example, the separation of the footwear products into different types of rubbers and polymers (vulcanised rubbers, thermoplastic rubbers, PVC) the textiles (nylon, polyester), the foams (PU foam, EVA foam), the leather and the metals (ferrous and non-ferrous). Achieving such a high grade of material recycling will require either: a number of disassembly operations to separate the shoes into individual component parts or; a complex automated separation process using a variety of different technologies.

3.2.2. Medium Grade Recycling Scenarios

Medium grade recycling, does not aim to reclaim such a high level of material separation. The reclaimed materials will primarily be used for down-cycled applications such as surfacing materials, underlay and insulation materials. For this category of recycling a primarily recycling process involves granulation followed by material separation using a mixture of air and water based density separation technologies.

Medium grade recycling is therefore less technically demanding and aims to reclaim just the primary material types: leather, foam, rubber, textile and rubber. There are in fact a number of both potential applications for each of these four reclaimed material.

A possible application of leather is the reforming of the leather fibres to produce leather sheets. E-leather is currently doing this with pre-tannery scrap leather. But the process may also be feasible for post consumer leathers.

Profit (£/ tonne)	**Revenue**
$P = R_{Total} - C_{fixed} + C_{variable}$ **(1)**	$R_{total} = \left[\sum_{i}^{n} (MR_i \ x \ MQ_i)\right] + \left[(LF_{tax} + T_{landfill}) \times LF_{quanity}\right]$ **(2)**
Fixed costs	**Variable Costs**
$C_{fixed} = \frac{C_{process} + C_{buidling}}{QP_{total}}$ **(3)**	$C_{varible} = T_{collection} + \left[\frac{E_{cost} \times E_{consumption}}{QP_{hour}}\right] + \left[(L_{sorting} + L_{dissasembly} + L_{operator}) \ x \ L_{wage}\right]$ **(4)**
Key	*L* = Labour
R = Revenue	*QP* = Quantity of product processed
C = Cost	*LF* = Landfill
T = Transportation	*MR* = Material revenue
E = Energy	*MQ* = Material quantity

Figure 4: Cost modelling equations for recycling process

Leather granules can be also treated to remove the chromium and used as fertilizer. If the reclaimed leather is of sufficient purity is it also possible to extract the gelatine for use as glues and animal food stock.

Reclaimed rubber also has a variety of uses such as surfacing product, matting and decking and use as an underlay material. In fact recycled rubber is already being used for a number of applications. Nike has established sports based applications - including the surfacing of athletic tracks, football and baseball pitches. And Play-top has an established use as a surfacing material for playgrounds.

Recycled foam can be used as an underlay for laminate floors and carpets and for sports pitches. Again Nike already has an established sports based applications - for example as an underlay for basketball courts

The mixed textile reclaimed from the footwear could be used for a variety of applications. These include: a filler (mixed with cement) for construction work, insulation materials for buildings and sound proofing material.

3.2.3. Low Grade Recycling Scenarios

The aim of low grade recycling is to reclaim one or two types of materials which can be used for a low grade down-cycled application. For low grade recycling, two process plans have been defined. The first involves the simple granulation of the shoe with the mixture being used for a low grade insulation material. The second plan involves granulation followed by one simple separation process to reclaim the rubbers. The rubbers could then be used as a surfacing material, whilst the remaining textile/leather mix is used as insulation.

3.3. Step 3: Cost Analysis of Recycling Scenarios

To understand the financial implications of the different material recycling scenarios a cost model has been developed using the equations shown in figure 4. The results of the model can be used to guide the selection of the most economically sustainable material recycling scenario for the product.

The overall profit (equation 1) is seen as the revenue minus the costs. There are two primary types of costs; these are the fixed costs (equation 3) and variable costs (equation 4).The fixed costs are the capital equipment costs and the building lease costs. The capitol equipment costs are based upon the purchase of the various different recycling technologies that are needed for the recycling process scenario.

In the equation the profit per tonne of material is being sought. Therefore the fixed costs are divided by the expected quantity of shoes processed over the estimated lifecycle of the recycling machinery. For the variable costs there are three aspects: energy costs, labour costs and transportation costs. Energy costs are calculated from the estimated energy usages of the plant multiplied by the energy unit cost (per KW), which are then converted into a per tonne cost by dividing by the quantity of shoes processed per hour. Labour costs are based upon the sorting costs, the disassembly costs and the plant operator costs. Transportation costs are based upon the transport of shoes from collection point to recycling plant.

The revenues are calculated using equation 2 and are based upon the reclaimed material revenues and the money saved from landfill taxes and transportation. For the material revenues data has been collected from numerous sources, however due to the lack of data on some of the recycled materials streams, estimates have had to be used in some cases. For example, for the mixed material types such as mixed rubbers and mixed foams no exacting data exits. In such cases where limited data exists, a largely conservative estimate of revenue has been used. Thus actual revenues gained from some reclaimed materials may actually be higher than stated in the reported results.

The cost modelling results for the various recycling scenarios can be seen in table 1 and confirm that there are in fact quite small profits available for footwear recycling. Thus each of the recycling scenarios must be carefully considered before embarking on the development of a prototype footwear recycling system

Table 1 - Cost benefit analysis for various grades of material recycling

Recycling scenerio	Recyling Process	Reclaimed material and applications	Costs (£/ tonne)	Revenue (£/ tonne)	Profit (£/ tonne)
High grade 1	Manual dissembly to componnet level, Metal removal, granualtion.	primary material types: to be used as per virgin materials	£400	£310	-£90
High grade 2	Metal removal, granualtion, Complex 8 stage seperation process	primary material types: to be used as per virgin materials	£295	£300	£5
Medium grade	Metal removal, granualtion, air seperation and dense medium seperation	Rubber (surfacing) and foam (underlay) leather (reformed), textile (isulation)	£170	£275	£105
Low grade 1	Metal removal, granualtion, no seperation	Mixed matrial (low grade isulation applications)	£120	£130	£10
Low grade 2	Metal removal, granualtion and dense medium seperation	Rubber (surfacing) and textile/foam/leather mix (insualtor)	£130	£165	£35

The first high grade recycling scenario, is based upon the manual disassembly of footwear to component level and the modelling results confirm that this will be a costly process, leading to financial losses. The second high grade recycling scenario is based upon the hypothetical possibility that almost complete separation of material is possible using a complex mixture of separation technologies. It is however unlikely that complete liberation of each material type will actually be possible with currently available technologies. Moreover, the benefit gained from high grade recycling is not significant enough to outweigh the costs and make any form of profit from the recycling activities.

The medium grade recycling option seen in table 1, is based upon the liberation of four primary material types. Although the material revenues will be lower than the purer materials reclaimed by high grade recycling, the technological process will be far simpler and less costly. As seen in table 1 the potential profits are estimated to be in the region of £105 per tonne.

For the low grade recycling scenarios it can be seen that profits are small – around one third that of medium grade recycling. Moreover the reclaimed materials will be extremely limited to low grade down-cycled applications.

Upon comparison of the different cost modelling results (in table 1) it is clear that high grade and low grade recycling scenarios are not at this present time economically sustainable. Therefore it is recommended that the current focus should be on the development of a suitable material recycling process for the medium grade recycling scenario.

However, the automated high grade recycling scenario may actually become a profitable option in the future. When a number of factors are likely to change, such as: higher environmental and landfill taxes, the increased scarcity of virgin material, and the improvement of processing technologies. From the purely environmental view point the high grade recycling scenario will generally be the preferable option because the reclaimed materials can complete with virgin materials and create high value applications.

For all of the proposed recycling process the transportation, sorting and manual labour are major costs that need to be reduced for economic footwear recycling. Furthermore, there must be a large enough number of shoes collected and processed to generate the revenues in which to offset plant investment and running costs.

Due to the small profits involved in footwear recycling coupled with the complex nature of footwear design it can also be concluded that there is a strong need for environmentally focused design of footwear. For example, reducing the material mixtures within footwear will improve post-fragmentation separation.

3.4. Step 4: Development of Recycling System

A generic process plan for the medium grade material recycling scenario can be seen in figure 5. The process has been designed to recycle the vast majority of footwear types and styles and is based upon commercially available technologies. Using the given mixture of technologies it is theoretically possible to reclaim the four different material types: leather, rubber, foam and textiles and for each material the estimated yield and purity can be seen in figure 5. In the process three basic steps are undertaken, these are: metal detection and removal, granulation and separation. The process may appear to be overly complex for such a relatively low value product. However, the cost modelling has shown that a relatively small proportion of the costs come from the purchasing and running of the recycling machining. The majority of the costs come from the sorting, transportation, and manual disassembly, required to recycle the shoes. Having a more complex yet less labour intensive recycling process therefore makes good economic sense.

It is still important however that this initial process plan is made more economical. This can be achieved by modifications to the existing technologies or by developing new technologies. In other words now that the proposed

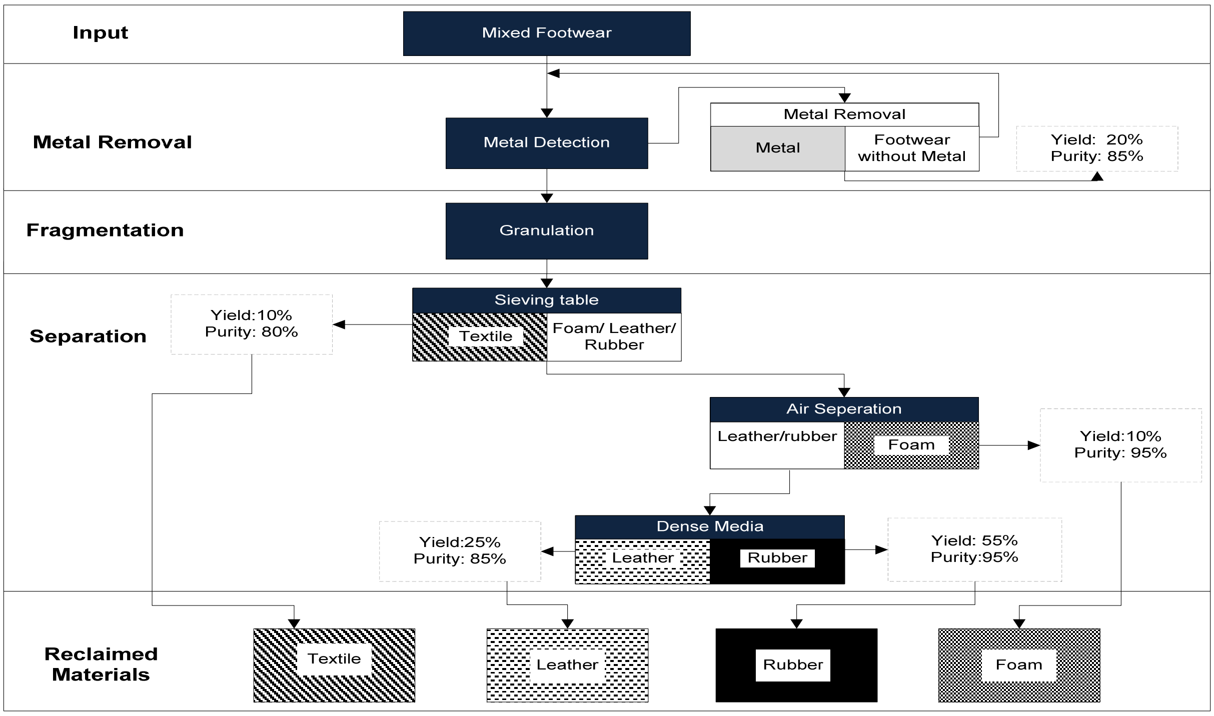

Figure 5: recycling process plan for footwear based upon medium grade recycling scenario.

recycling process is deemed sustainable from the market perspective, the technology push should now be given to improve the process plan and develop better recycling technologies.

3.4.1 Metal Detection and Removal

There are numerous metallic components present in footwear products; these include the visible metallic parts such as the metal eyelets, buckles and decorative components. In addition there are a number of metallic components that are often embedded in the footwear, for structural purposes, such as steel shanks, steel toe caps and metal heal supports.

The removal of these metal parts presents a challenge for the material recycling of footwear - the metals present in footwear are likely to constitute less than 10% by weight for the average shoe and are generally highly entangled with other components and materials. For these reasons, it is yet to be concluded what is the best method of removing the metallic content in footwear. The issues of material entanglement in particular means that it may not be technically feasible to remove metals with common metallic recycling technologies such as eddy current and magnetic separators. Furthermore, to appropriate deal with metallic content an addition shredding process would be needed prior to metal separation, adding further cost and complexity to the process plan. Shedding is necessary because granulators are unable to process metals without incurring economically unsustainable wear and damage. For these reasons it is proposed that the metal removal stage will involve a limited amount of manual sorting and disassembly. In the proposed process plan the following would occur: firstly, shoes will first pass through a metal detector and if metal is present they will be removed from the line for inspection. If there is visible metal, such as metal eyelets or buckles this will be removed. Experiments have been conducted and in most case visible metals can be removed in approximately 30 seconds per shoe. After removal of visible metals, the shoes will then go back through the metal detector and if metal is still present then the shoe must contain embedded metals. To remove these metals the shoe must be partial disassembled which experiments have shown will generally take longer than 2 minutes. Depending upon the labour costs this may not be an economical sustainable activity so an alternative recycling route may have to be sought for these shoes with deeply embedded metal.

3.4. Granulation

In order for the material separation stages to take place, the footwear must be fragmented into suitably sized particles. The fastest and most economical means of doing this is to use a granulator. Granulators are also highly flexible as there are readily available in a range of sizes, with different throughputs.

3.4.3. Separation Stage 1- Screening

The first stage of the separation process is to remove the majority of the textile fluff from the granulated mixture. For this a vibrating screening table is suggested. The granulated material is placed at the top of the inclined table and the vibration action of the table moves the material mix down the table, whilst at the same time causing the heaver particles to sink to the bottom and fall though the screen. The lighter textile fluff will move up to the top of the mixture, across the top of the screen, exiting the end of the table.

3.4.4. Separation Stage 2- Air Separation

Upon examination of the density chart in figure 3, it is clear that there is insufficient density difference between certain materials to enable successful separation using air based density separation. Air based separators generally require a density difference of 0.45 kg/m between materials [7]. Therefore, looking at the material densities it is theoretically possible to use an air based separator to liberate the PU and EVA based foams from the remaining mixture of leather rubber and foam granulates.

One such air based technology is an air table. With this technique the granulated material is placed in the middle of an inclined table and is subjected to an air steam that lifts the material (fluidises it) and as the table is vibrated back and forth the heaver materials (rubber and leather) rise up the table as the lighter materials (foams) move down the table.

3.5.5. Separation Stage 3 - Dense Medium

After the separation of the foam a leather and rubber mixture is left. However, because there is only a small density difference between leather and rubber, air based separation is deemed infeasible. Thus for the separation of the leather and rubber, a dense medium separator is suggested as it is able to provide the greater accuracy of separation needed between the materials. Most of the rubber materials used in footwear materials have a higher density than water and most footwear leather has a density lower than water. Furthermore, these materials have different hydrophobic properties, thus, when the mixture is placed in the water based separation bath the rubber will sink and the leather will float.

4.0 EXPERIMENTAL STUDIES

Initial experiments with the outlined recycling technologies have confirmed that it is possible to separate out the four primary material types (leather, rubber, foam and textiles) from the granulated mixture. A number of material samples, derived from leather based shoes, can be seen in figure 7. However, the reclaimed materials have a purity that is below the estimated levels. In particular there are problems with textile fibres contaminating the liberated materials. Work is underway to improve the process by further research and development of the technologies and by the identification of optimal process parameters. For each separation technology outlined in the proposed recycling process plan there are in fact a number of process parameters that need to be defined though experimental work. Correct definition of the process parameters is essential to ensure that efficient and consistent material separation occurs at the different stages of the recycling process. If the material purely is not sufficiently high or the consistency is poor then the materials may end up being limited to lower grade applications, thus adversely affecting the material value chain. It is also expected that the processing of different types of shoes will also have a direct effect on the materials yields and purities. Again, further experimentation will need to be done to fully understand these effects.

4. CONCLUSIONS

In order to make footwear recycling an economically feasible approach to other end-of-life options, a cost effective recycling process must first be developed. This paper has presented a four step methodology that can be followed to create a market pull based recycling approach, not just for footwear, but for other consumer based products. A key aspect of the methodology is that the markets and the materials applications are examined first and the finical implications are analysed. Only when a financially sustainable recycling scenario has been defined is the process plan and suitable recycling technology developed. An initial process plan has been proposed for post-consumer footwear recycling based upon these market pull principles, although further work must now be done to define the optimal process parameters and improve the process design.

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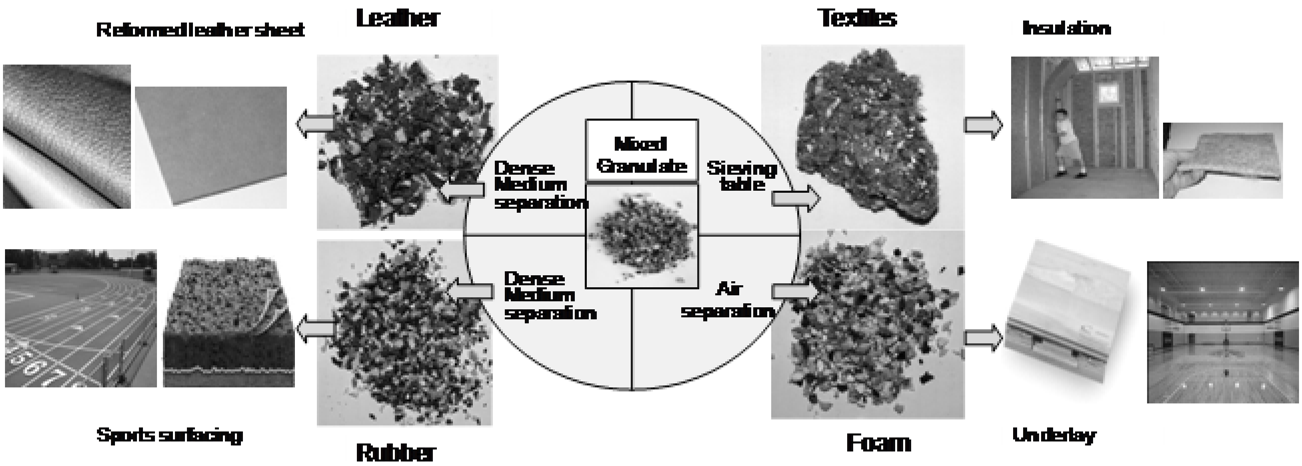

Figure 7 Sample materials and applications after separation processes.