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An air-based automated material recycling system for postconsumer footwear products

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ABSTRACT

The worldwide consumption of footwear is estimated to be in excess of 20 billion pairs of shoes per year. To date very little work has been done to develop material recycling solutions for mixed footwear products. In fact less than 5% of end-of-life shoes are being recycled, with most being disposed of in landfill sites around the globe. One of the primary reasons is that most modern footwear products contain a complex mixture of leather, rubber, textile, polymers and metallic materials, that makes it difficult to perform complete separation and reclamation of material streams in an economically sustainable manner. This paper discusses the development of an economically feasible automated material recycling process for mixed postconsumer footwear waste. Central to this process are bespoke air-based separation technologies that separate granulated shoe particles based upon the difference in size and weight. Experimental studies with three different types of postconsumer footwear products show that it is possible to reclaim four usable material streams; leathers, textiles, foams and rubbers. For each of the reclaimed materials there are a variety of applications such as surfacing materials, insulation boards and underlay products.

1. Introduction

The increased availability of cheap mass produced goods, coupled with rapidly changing consumer fashion trends has resulted in a sharp increase in the consumption of products in many industrial sectors. The worldwide per capita consumption of footwear has increased considerably, from 1 pair of shoes per year for every person in the world in 1950 to almost 2.6 pairs of shoes in 2005. In the EU, it is estimated that the amount of waste arising from postconsumer shoes could reach 1.2 million tonnes per year. The vision of 'Zero Waste to Landfill' thus remains as one of the major challenges of 21st century for the footwear sector. This target is very ambitious as currently less than 5% of the 20 billion pairs of shoes produced worldwide every year are recycled or reused (World Footwear, 2005; SATRA, 2003). However, increased raw material costs, producer-responsibility issues and forthcoming environmental legislations are expected to challenge the way the footwear industry deals with its end-of-life (EoL) products.

It is argued that in many situations, material recycling is seen as the most suitable means of dealing with discarded shoes (Staikos and Rahimifard, 2007b). However, for long-term sustainability of such footwear recovery activities an economically viable material recycling system must be established. In the automotive and electrical/electronic industries, where European Producer Responsibility directives, such as the End-of-life Vehicles (ELV) directive (European Commission, 2000) and the Waste Electrical and Electronic Equipment (WEEE) directive (European Commission, 2003) 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 easily recoverable metallic materials to facilitate an economically sustainable value chain (Coates and Rahimifard, 2007; Barba-Gutierrez et al., 2008; Abu Bakar and Rahimifard, 2008; Kahhat et al., 2008). However, footwear products typically contain a large mixture of materials, such as rubbers, polymers, leather and textiles that have relatively low recycled value.

Therefore understanding and developing methods for footwear recycling is of major concern to the footwear sector and this paper will discuss the development of an automated material recycling system for mixed postconsumer footwear waste. The first part of the paper begins by introducing the various EoL options for footwear and outlines the challenges of EoL footwear recycling. The paper then describes the recycling approach that has been developed, provides a simple economic analysis and outlines some potential applications for recovered materials. The later part of the paper then presents the results of experimental studies with three common types of footwear

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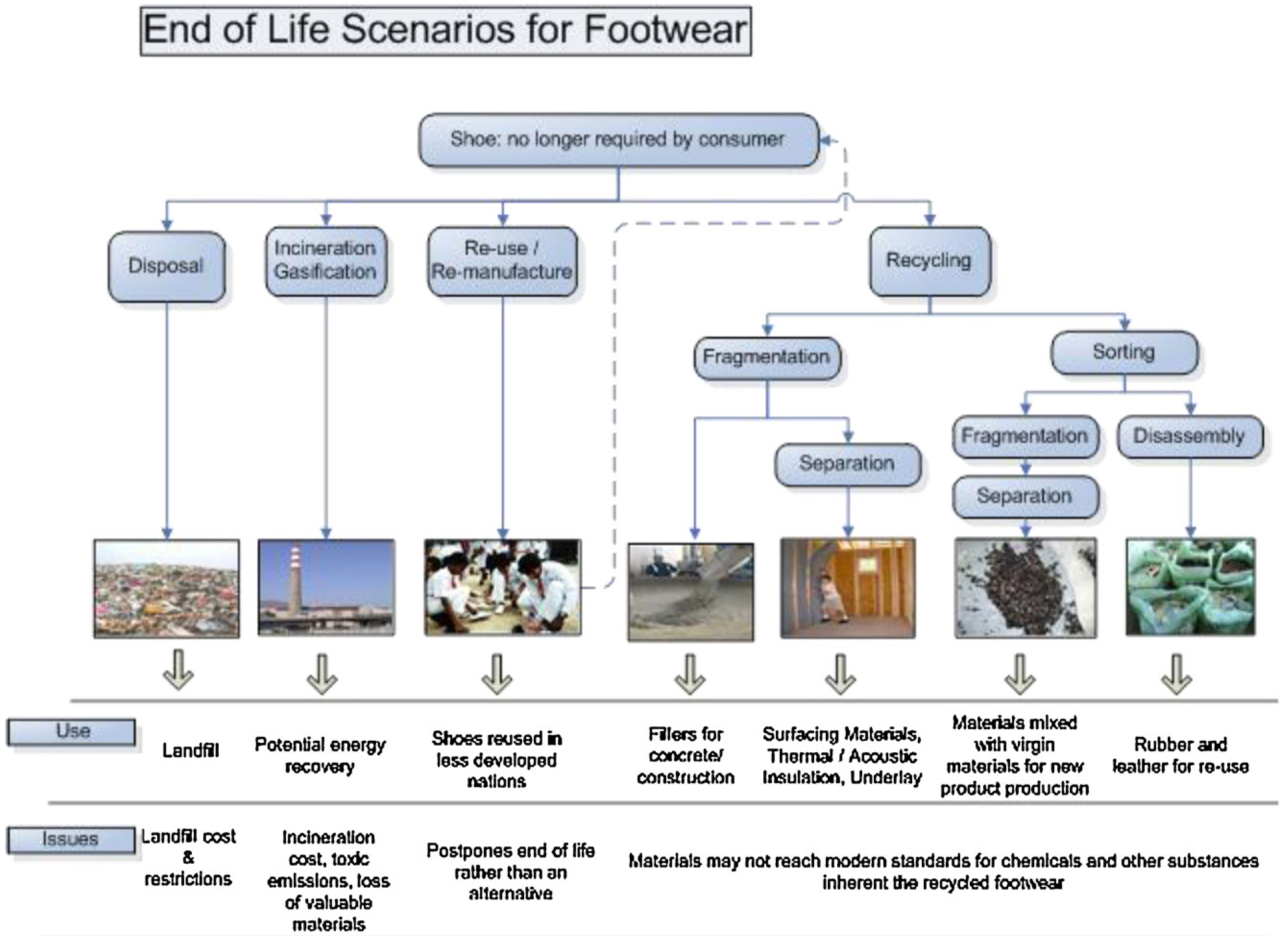


Fig. 1. End of life scenarios for postconsumer footwear products.

products. Finally further work is discussed and conclusions are drawn.

2. Background

As discussed by Staikos and Rahimifard (2007a) there are four main EoL options that can be considered for postconsumer footwear products, as illustrated in Fig. 1, these are: landfill, incineration/gasification, reuse and recycling. For each of the EoL options there are various environmental impacts, economic benefits and technical requirements that must be considered.

Land-filling is considered the most undesirable option, 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. Reuse involves the collection of worn or unwanted shoes for distribution mainly within developing countries. Charitable organisations such as the Salvation Army Trading Company Ltd. (SATCOL) and Oxfam, together with local authorities and municipalities are the main supporters of reuse schemes in the UK. However, it is argued that as the economic power of developing nations grows the demand for second hand shoes may begin to fall. Furthermore, not all shoes that are collected can be reused, due to their poor conditions, and in such situations material recycling is seen as the most suitable option.

Nike is currently the only footwear manufacturer which is engaged in postconsumer 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 (NIKE, 2012). 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 USA 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 25 million pairs of shoes to date (NIKE, 2012). However, the scheme is not designed to deal with the recycling of other non-athletic types of postconsumer footwear waste. Therefore, a more generic recycling approach as outlined in this paper is required to deal with various types and styles of footwear products.

2.1. Challenges related to material recycling of mixed footwear products

Postconsumer footwear products are a largely untapped commodity with a significant potential for recycling. This highlights the economic and environmental benefit that can be obtained from establishing a sustainable shoe recycling chain (Staikos and Rahimifard, 2007c). However, current material recycling facilities and operators are either incapable of dealing with the specific material mix in footwear products or do not provide the best method of recovering maximum value from postconsumer shoes waste. One

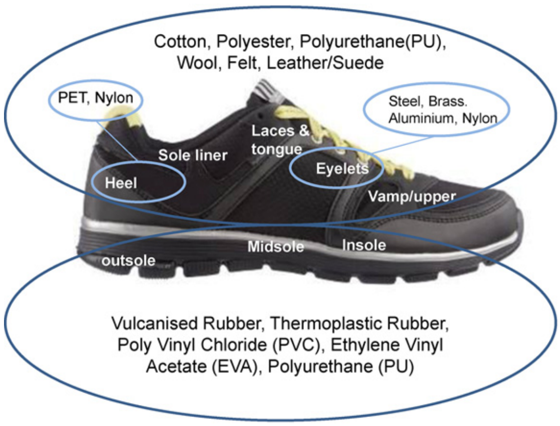


Fig. 2. A typical sports shoe with main parts and their commonly used materials.

of the major requirements for establishing sustainable recycling practices within the footwear sector is to investigate suitable recycling processes to successfully separate postconsumer shoes into well-defined mono-fraction material streams. The analysis of various postconsumer shoe waste has however shown that the material recycling of mixed footwear products is an extremely challenging problem. There are two particular problems that present a significant challenge to material recycling of shoes, namely the diverse range of shoe types with various construction techniques and the significant number of different materials used.

2.1.1. Materials

The footwear industry employs a wide variety of materials to make a diverse range of different types and styles of shoes. Fig. 2 represents some of the commonly used materials and components in a typical training shoe. According to Weib (1999) there are around 40 different materials used in the manufacturing of a shoe. Leather, rubber, foam, textile and plastics are amongst the basic materials most commonly used in shoe manufacture, with each material possessing its own specific characteristics. There are also numerous metallic components present in footwear products. These include visible metallic parts, such as metal eyelets, buckles and decorative components and other metallic components that are often embedded in the footwear for structural purposes, such as steel shanks, steel toe caps and metal heel supports. The removal of these metal parts presents a significant challenge for the material recycling of footwear – the metals are often present as a small percentage of the total shoe by weight and are generally highly entangled with other components and materials.

2.1.2. Construction

At their most simple, shoes are comprised of as few as two components per pair, for example flip-flops, with foam sole and rubber strap, or can be complex constructions with 60 or more components per pair, such as in many modern sports shoes. However, most can be described as having a subset of parts and components that are generally common to all types of shoe. These include; upper parts, lower parts (insole, midsole and sole) and grindery items (including metal shanks, eyelets, toe puffs, laces, etc.). A typical footwear product will be assembled from a number of components using a variety of joining technologies, such as gluing, stitching and moulding. Previous analysis (Staikos and Rahimifard, 2007c) has shown that due to the complexity of shoe design and construction it is technically difficult and time consuming to manually disassemble and separate footwear products into usable recycled material streams. It is argued that due to the relatively low material values manual processing in this manner would not be an economically sustainable activity for large scale footwear recycling. In addition to full manual disassembly, the authors have also explored the semi-automated separation of footwear components based upon slicing or pulling/tearing. However, due to the huge range of footwear styles and sizes these approaches have had only limited success with certain sub-categories of shoes. Thus these technologies are not considered suitable for the large scale processing of the many tonnes of mixed footwear waste currently sent to landfill.

3. Development of a material recycling system for footwear products

The complex material mixture of modern shoes and the wide variety of construction techniques used necessitates the use of an automated recycling process, based upon technologically feasible and commercially viable recycling technologies. Such highly mechanised recycling systems are currently employed by other industries (automotive, electronics) as the primary means of recycling end-of-life products in an economically sustainable manner (Coates and Rahimifard, 2007; Barba-Gutierrez et al., 2008; Abu Bakar and Rahimifard, 2008; Ramzy et al., 2008). Recycling products in this manner generally involves shredding or granulation, such that the product is split into different components and/or material types. After fragmentation subsequent separation machines exploit the differences in material properties (such as material size and density) to provide automated separation into different material streams. Generally speaking these technologies are effective for separating materials such as plastic and metal which have distinctly different properties. However, problems often arise when trying to separate materials with similar properties, such as the different types of polymers and rubbers that are commonly found in footwear products. (Gent et al., 2011; Dodbiba et al., 2005; Lee and Rahimifard, 2010).

Recycling technologies considered to be technically and economically feasible for footwear products include: shredding and granulation technologies; air-based separation devices; liquid-based density separation; and, for recovery of the metallic materials, magnetic and eddy current separation and simple sensor based ‘detect and eject’ chutes. Other commercially available recycling technologies such as electrostatic separation devices and advanced sensor based sorters (Dodbiba et al., 2005; Tilmatine et al., 2009; Tsuchida et al., 2009) have also been considered for footwear recycling. However, there needs to be further research into the technical and economic feasibility of such recycling technologies for mixed footwear products. At present material separation based upon particle size and weight is probably the most cost-effective, high-capacity process that could be used to automate the separation of footwear waste on an industrial scale. A recycling system based upon fragmentation and air-based separation technologies has thus been developed for the material recovery of footwear products. The process is outlined in Fig. 3 and has been designed to process the vast majority of footwear types and styles i.e. sports shoes and leather based shoes with rubber soles. In the process there are three main steps, these are: (i) sorting, (ii) metal removal and (iii) material separation. Experimental studies (Section 4) have derived the typical mass balance and purity of the main recoverable material fractions (as depicted in Fig. 3).

3.1. Sorting

It is envisaged that a commercial footwear recycling system will include a sorting stage to separate shoes into different categories

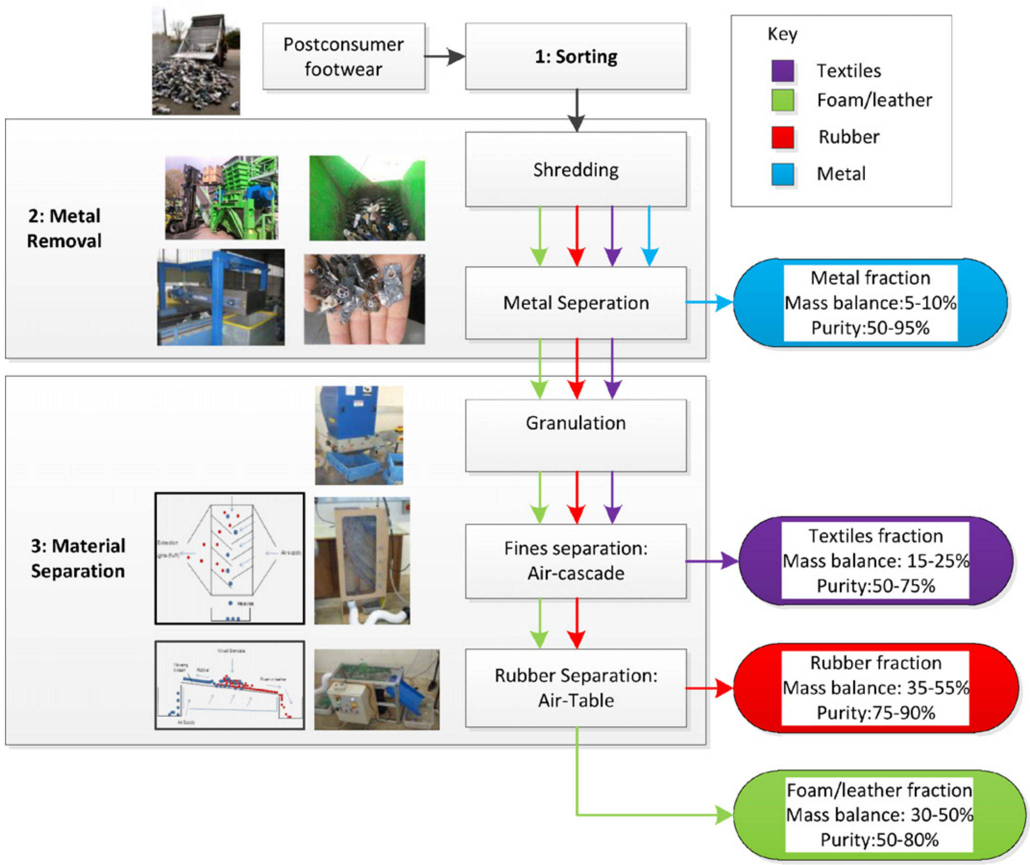


Fig. 3. Recommended footwear recycling process flow.

that will then be processed in batches. In this way the yield and purity of the target material types (leather, foam, rubber, textile and metal) can be improved. For example, to reclaim foam materials (EVA and PU) in the appropriate manner shoes that have high foam content, such as sports shoes, should be recycled separately from leather based shoes. This is because the separation of low density foams from leathers is present a significant challenge with the proposed air-based technologies.

3.2. Metal removal

There are several options that are currently being considered for the removal of the metallic parts in postconsumer footwear waste. The first involves the removal of metal using a manual removal process. For example, shoes could be pre-shredded to expose the embedded metal parts, which would then be sent to a picking line for manual sorting and removal of metallic items. However, initial experimentation has shown that depending upon the labour cost this manual intervention may not be an economical sustainable activity.

The second option is mechanical separation using specialist metallic separation equipment i.e. shredding followed by magnetic, eddy current and induction sensor based ‘detect and ejects’ chutes. When processing metal parts, shedding is generally necessary because granulators are often unable to process metals without incurring economically unsustainable wear and damage. The shredding process does of course add further cost and complexity to the footwear recycling process plan.

Initial experiments have been conducted with an over-band magnetic separator during shredding trials with commercially available equipment. Although no detailed analysis of the separation was conducted, initial visual inspection of the waste streams showed good recovery of the ferrous metals when shoes were shredded to 20–30 mm. As shoes contain both ferrous and non-ferrous metals (e.g. aluminium and brass) there will be a certain percentage of non-ferrous metals still present after magnetic separation. A subsequent separation stage is therefore needed to remove these non-magnetic metal particles. This could be done with an eddy current separator – however, it is argued that these separators do not provide the most technically or economically feasible means to remove the small percentages of non-ferrous metals present in the waste stream. An inexpensive means to separate the remaining metals after magnetic separation is to use a sensor based ‘detect and eject’ chute such as those employed to protect plastic process equipment from foreign metals parts. However, with this technology, a certain amount of additional (non-metallic) material will be ejected along with the metal parts, which may reduce the overall yield of recycled materials.

Apart from specialised metallic separation processes there are other technologies that could be used to remove the metallic parts from shredded footwear waste. Initial experiments using a simple sink-float liquid[1] based density separation process have proven that it is possible to successfully separate metals from rubber/foam/leather and highlight the potential of using a commercial dense media separator such as a hydrocyclone (Gent et al., 2011) to remove the metallic content present in shredded footwear waste.

[1] Magnetite powder dissolved in water to create liquid medium density of 2.00 g/m. Metals have density > 2.00 g/m and will therefore sink. All other footwear materials have density < 2.00 g/m and will thus float.

However, there are still concerns over the technical feasibility of completely removing all metallic content with the above mentioned technologies. As metal contamination can significantly reduce the value of the other recycled materials (e.g. rubber), it is argued that there is a need for the reduction or even elimination of metallic components at the footwear design stage.

3.3. Material separation

Once metal parts have been removed from the shredded waste stream, additional fragmentation must be done in order to further liberate materials and generate the required yield and purity from the developed air separation stages. Experiments have shown that optimal yield and purity occurs when the footwear waste stream is fragmented into the 3–6 mm size range. At this size range fewer particles will remain interconnected (e.g. particles consisting of both leather and rubber), enabling higher purity material to be recovered.

For fragmentation of footwear materials to this size range a granulator provides the most economically feasible approach. Granulators are available in a range of specifications, with different throughput rates, enabling the system to be easily scaled up for commercial implementation.

A key aspect of this research has been the development of low-cost air-based separation technologies to separate the granulated footwear materials into district fraction. Air-based separation technologies rely predominately on the exploitation of the terminal velocity difference between dissimilar material particles. The terminal velocity of a particle is in turn dependent upon both its size and weight. Both of these parameters have therefore been exploited for the separation of footwear materials. Firstly, different footwear materials tend to fragment in different ways. For example textiles tend to fragment into a fine dust that has a low terminal velocity and can then be separated from larger rubber and foam particles which have higher terminal velocity. Secondly, a difference in material density exists between certain footwear material types providing different terminal velocities of particles e.g. rubber particles are heavier than foam particles and can be effectively separated. Based upon these principles, experiments with air-based separation technology (zigzag columns, air-cascades, aspirators and vibrating air-tables) have proven that it technically possible to reclaim four of the most widely used footwear material types: leather, rubber, foam and textiles. At present, it is argued that the most economically viable means to provide this level of separation is a two stage process: an air-cascade separator to first remove the lighter textile fines and other fine leather and foam residues, followed by a vibrating air-table to provide final separation of rubber from foam or leather. However, alternative, novel air separation processes are currently under development, to provide higher purity and yields of certain material sub-sets, e.g. thermoplastic rubber from leather.

3.3.1. Stage 1: textile fines separation

For the textile fines separation a custom air-cascade process has been developed. As depicted in Fig. 4a this works in the following way: the granulated footwear material enters the top of the separator and falls down past a number of shelves. At each shelf air is blown into the mixture, creating mini air vortexes in which the textile fines are blown free of the larger particles. By the time the granulated mixture has passed all shelves and leaves the bottom of the separator, the vast majority of all textile fines have been removed leaving a predominately leather/foam and rubber mix.

3.3.2. Stage 2: rubber separation

The second stage of separation aims to liberate rubber granulates from the PU and EVA based foams from sports shoes, or for leather based shoes the rubber from leather. A suitable means to provide this separation is a vibrating air-table. As depicted in Fig. 4b, the air-table uses air and vibration to separate the heavier rubber that moves up the table from the lighter material that stratifies on top and slides down the table. Separation efficiency is highly dependent upon optimisation of various process parameters, which include: the angle of the vibrating deck; the vibration frequency; the air speed; and the surface characteristics of the deck (i.e. ridges and riffles). To ensure maximum separation efficiency the authors have developed a customised air-table that has been specifically designed and optimised for the separation of the granulated rubber from foam and leather materials in footwear products.

3.4. Overview of costs

A number of specific factors must be considered before the commercial implementation of a footwear recycling system, including factors such as market conditions, material revenues, local and geographical influences (e.g. cost of labour, transport, landfill taxes, etc.). A detailed discussion of these factors is considered out of

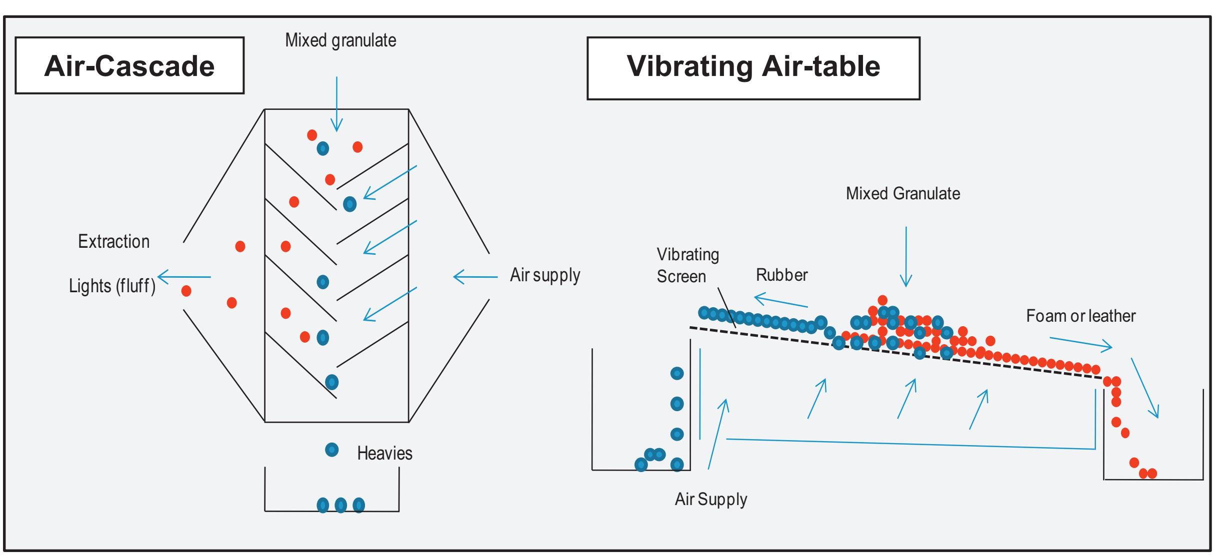


Fig. 4. Air separation technologies (a) air-cascade separator and (b) vibrating air-table separator.

Table 1
Summary of approximate costs of proposed footwear recycling system.

Equipment	Energy consumption (kw/h)	Capital cost-approximate (£)	Running cost[a] (£/tonnes)
Fragmentation			
Shredder (four shaft)	20	42,000	2
Granulator	20	25,000	2
Separation			
Magnetic separator	3	15,000	0.3
Detect and eject chute (2×)	1	16,000	0.1
Air-cascade	4	20,000	0.4
Air-table	4	24,000	0.4
Conveying			
Conveyor belts	3	6000	0.3
Screw feeders (2×)	3	15,000	0.3
Totals	58	163,000	5.8

[a] Running cost = (energy consumption × energy cost)/throughput), where energy cost is £0.05/kw and throughput is 0.5 tonnes/h).

the scope of this paper. However, in the context of the UK, a brief overview of the direct processing costs will be discussed. The cost of individual recycling equipment required to provide the proposed recycling system can be seen in Table 1. For a small scale system processing 0.5 tonnes/h, the total equipment investment costs are likely to be in the region of £160,000. For this throughput the running costs for energy will be approximately £5.8/tonnes and labour (based upon 3 people on minimum wage of £6.08 for sorting and loading and material packing) will be £36.48/tonnes. There are, of course, other indirect costs associated with the operation of such a system, such as maintenance costs, management costs and building lease. These would have to be considered for implementation of a commercial footwear recycling plant. At present, due to the lack of established value streams for recycled footwear material, there are also uncertainties regarding the revenue streams that could be generated from sale of reclaimed footwear materials. To subsidise these uncertain revenues it is argued that a gate fee could be charged to the end users whom deliver shoes (that would otherwise be send to landfill and incur fees) to the recycling plant e.g. textile/shoe reuse companies or local waste authorities that have. Charging a gate fee is common practice in the UK recycling industry. According to a recent study by WRAP (2011), for mechanical and biological treatment facilities this fee varies between £57 and £100, with £84 being the average. Thus for footwear recycling it is justified that a minimum gate fee of £57 (currently below the UK landfill tax + gate fee) should be charged. This income would then, at the very least, offset the direct energy and labour costs associated with the footwear recycling activities, leaving a potential profit to be made from the recycled material sales.

3.5. Recycled material applications

Using the developed recycling process it is possible to liberate four different and commonly used footwear material types, namely leather, rubber, foam and textiles. For widespread adoption of footwear recycling activities it is of vital importance that these reclaimed footwear materials have viable applications to support a sustainable recovery value chain approach. Thus for this research a preliminary study has been carried out to look for potential applications for recycled footwear materials. For leather, the recovered leather fibres may be reformed to produce leather sheets. E-leather (2011) is currently producing similar products with pre-tannery scrap leather; however the process may also be feasible for post-consumer leathers. Leather granules can also be treated to remove chromium and then used as fertilizer (Mu et al., 2003). The acoustic and thermal insulation properties of leather also make it a suitable insulation material (Lakrafli et al., 2012; Simeonova and Dalev, 1996). Reclaimed rubber also has a variety of uses such as surfacing product, matting and decking, and as an underlay material. In fact, recycled footwear rubber is already being used by NIKE (2012) for the surfacing of athletic tracks, football and baseball pitches and the commercially available Play-top material (Playtop, 2012) uses footwear rubber grind for the surfacing of playgrounds. Initial studies have also indicated that for some types of footwear rubbers it may also be feasible to finely grind the rubber into a remouldable material that can be used in the manufacture of new products. For recycled foams, applications can be found in underlay material for laminate floors and carpets and for sports pitch. The mixed textile (lighter fluff) reclaimed from footwear can be used for a variety of applications, such as filler (mixed with cement) for construction work, insulation materials for buildings and again sound-proofing materials (Chang et al., 1999). Toyota is using recycled foams/textiles, from automotive shredder residue (i.e. similar to footwear waste) to produce recycled sound proofing products such as dash board underlay panels (Toyota, 2011). Although the majority of these material applications for footwear waste are considered down-cycling there is clearly still considerable environmental benefit when compared with disposal to landfill (Staikos and Rahimifard, 2007c). In addition, due to the variety of potential applications there is real potential for economic value to be gained from each of the four reclaimed material streams, clearly highlighting that further development of a material recycling system for shoes shows promise.

4. Experimental studies

The primary objective of the experimental studies has been to assess the purity and yield of the rubber, foam, leather and textile materials recovered with the developed footwear recycling

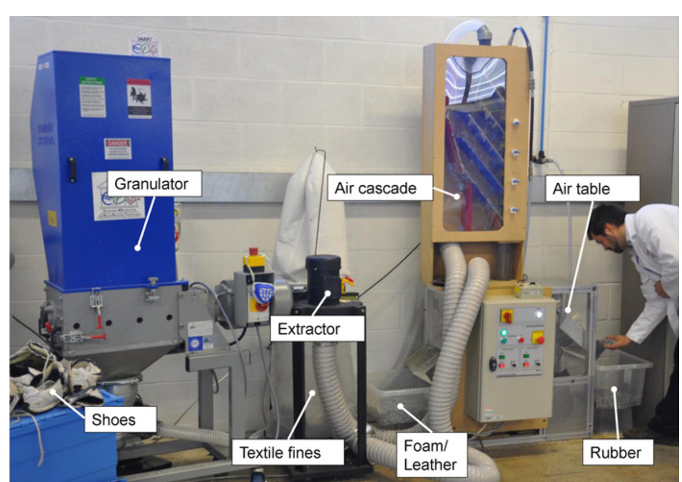


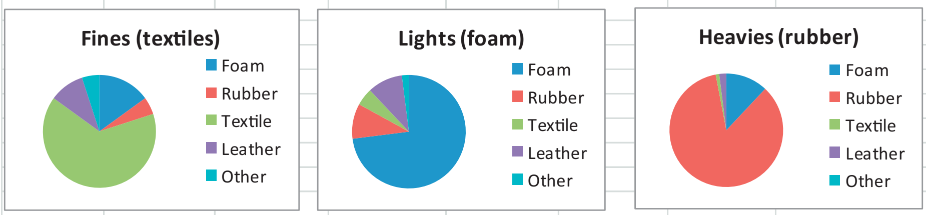
Fig. 5. Lab-scale footwear recycling rig for experimental studies.

Table 2
Target materials for experimental studies with three different shoe types.

Shoe type	Heavies fraction	Density (g/cm^3)	Lights fraction	Density (g/cm^3)	Fines fraction	Density (g/cm^3)
Sports shoe	Rubber (compact)	0.9–1.4	PU/EVA foam	0.4–0.6	Cotton/polyester	1.2–1.4
Leather: compact rubber sole	Rubber (compact)	1.0–1.2	Leather	0.7–0.9	Cotton/polyester	1.2–1.4
Leather: foamed rubber sole	Rubber (foamed)	0.5–0.9	Leather	0.7–0.9	Cotton/polyester	1.2–1.4

Table 3
Sports shoe material separation.

Materials	Fines (textiles)		Lights (foam)		Heavies (rubber)		
	Yield	86%	Yield	77%	Yield	88%	
	Purity	65%	Purity	73%	Purity	85%	Total % of waste
	% of fraction	% of waste	% of fraction	% of waste	% of fraction	% of waste	
Foam	15	3	**73**	27	12	5	35
Rubber	5	1	10	4	**85**	35	40
Textile	**65**	14	5	2	1	0	17
Leather	10	2	10	4	2	1	7
Other	5	1	2	1	0	0	2
Totals	100	22	100	37	100	41	100



system. This has been done though recovery trials with a lab-scale prototype system; as illustrated in Fig. 5. As outlined in Table 2, for these trials three different shoe types have been used: sports shoes, men's leather shoes with compact rubber soles and men's leather shoes with foamed rubber soles. For each of these trials there are three output fractions heavies lights and fines; each with associated target materials.

In the lab prototype system seen in Fig. 5, the material is pneumatically removed from the bottom of a granulator and taken into the first separation process (air-cascade) which removes the majority of the textile fluffs from the granulated mixture. The remaining rubber foam/leather then falls into the middle of the air-table where it is separated into different factions. An important consideration for the specification the footwear recycling system design has been scalability. The developed technology can be easily scaled up to reach the higher throughputs needed for a commercialised recycling system, simply by using a larger granulator and multiple air separation units in a modular fashion. In should be noted that this lab system does not include the metallic separation process for shoes with metal components.

4.1. Results

Previous experimental studies have concluded that a 3–4 mm average particle size (5 mm granulator screen) is the optimal size for liberation of footwear materials. Larger particle sizes were found to include a significant proportion of mixed material (interconnected material particles), while producing smaller particle sizes significantly reduced the process throughput.

To measure material separation efficiency, sample sizes of 10 kg of shoes for each of the three categories were prepared. For the purpose of these case studies the removal of metals was carried out manually before granulation and separation. Purity has been calculated as the percentage of the target material by weight in the corresponding processed waste stream, and yield has been calculated as the amount of target material collected as a percentage of the overall weight of the waste stream. Visual inspection has been used for measurement of purity and yield, i.e. 10 samples of 50 g each (collected at random from fractions after separation) were visually inspected and sorted to into their respective material type to calculate process efficiencies. Feed rate was kept constant for all trials at approximately 30 kg/h. The results from these experiments are summarised in Tables 3–5. Each of these tables shows the separation of different shoe types into three different material factions: fines, lights and heavies with target material in brackets. For each of these fractions a material breakdown and associated pie chart representation can be seen. Photos of sample materials from the lab trials can be seen, for sports shoes (Fig. 6) and for leather shoes with compact rubber soles (Fig. 7).

It should be noted that results were recorded after a phase of parameter fine tuning for each process step. For the air-cascade separation process, this included optimisation of the inlet and outlet air speeds. For the vibrating air-table this included optimisation of airflow speed, angle of deck and vibration frequency. During the

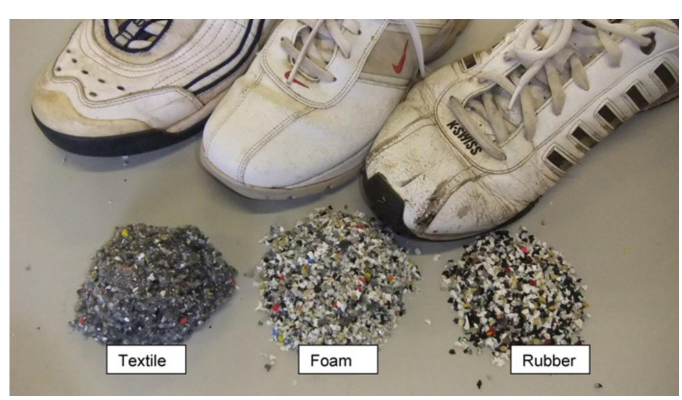
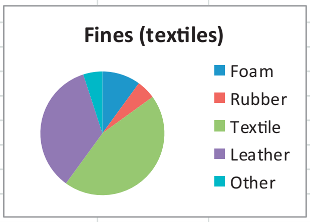
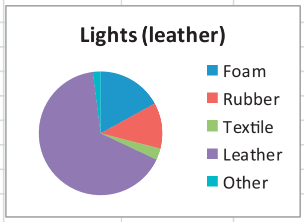


Fig. 6. Sports shoes separation into foam, textile and rubber at 3–4 mm average particle size.

Table 4
Leather shoe (high density rubber) material separation.

Materials	Fines (textiles)		Lights (leather)		Heavies (rubber)		
	Yield	86%	Yield	59%	Yield	89%	
	Purity	45%	Purity	66%	Purity	82%	Total % of waste
	% of fraction	% of waste	% of fraction	% of waste	% of fraction	% of waste	
Foam	10	2	17	5	2	1	8
Rubber	5	1	12	4	**82**	40	45
Textile	**45**	9	3	1	1	0	10
Leather	35	7	**66**	20	15	7	35
Other	5	1	2	1	0	0	2
Totals	100	20	100	31	100	49	100





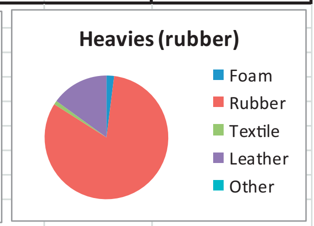
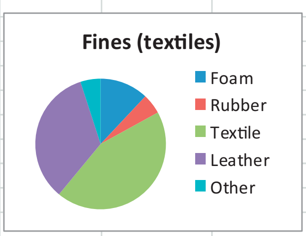
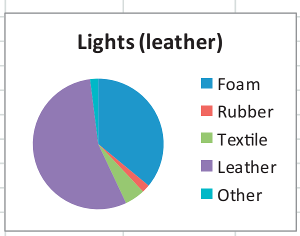


Table 5
Leather shoe (foamed rubber) material separation.

Materials	Fines (textiles)		Lights (leather)		Heavies (foam)		
	Yield	78%	Yield	48%	Yield	60%	
	Purity	44%	Purity	55%	Purity	58%	Total % of waste
	% of fraction	% of waste	% of fraction	% of waste	% of fraction	% of waste	
Foam	12	2	36	14	**58**	24	41
Rubber	5	1	2	1	**2**	1	3
Textile	**44**	8	5	2	1	0	11
Leather	34	6	**55**	21	39	16	44
Other	5	1	2	1	0	0	2
Totals	100	19	100	39	100	42	100





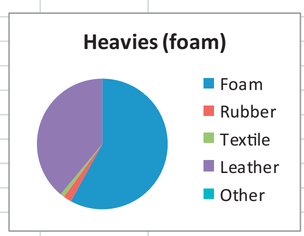


Fig. 7. Leather based shoes (with high density rubber soles) separation into foam, textile and rubber at 3–4 mm average particle size.

lab trials there was an issue in obtaining a balance between yield and purity. For example, it was possible to improve the purity of the rubber stream, but only with a reduced yield, since more of the smaller particles of rubber were found to report to the foam waste stream. This yield-purity balance in a commercial recycling operation would most likely be directed by the configurations of material value chains and the specific requirements of the final applications for the recovered materials.

4.2. Discussion of results

Results from experimental studies show that with the proposed air-based recycling system it is possible to successfully separate certain sub-sets of postconsumer footwear products into distinct material categories. For both sports shoes and leather based footwear with compact rubber soles, separation of rubber with over 80% purity and yield is possible. However, for the other separated material fractions from these shoes, the target materials (the textiles, leather and foams) separation purity and yield is considerably lower that 80%. Furthermore, for shoes with foamed rubber soles, there is clearly a poor level of separation using the developed system. In particular the separation of foamed rubber from leather shows only a 58% purity and 60% yield. The foamed rubber and leather have different shape characteristics when granulated (leather is flatter and more fibrous), which could be exploited for separation. However, the density of the leather is too similar to the foam materials and effective separation is not feasible with the vibrating air-table based technology. It is therefore recommended that further investigation will be needed with alternative technologies or with different process configurations (for example, it may be possible to use a finer granulator screen size to fiberize the leather materials which could then be separated from foamed rubber particles) for these types of shoes.

In spite of the varying degree of separation purity and yield it is argued that for down-cycled applications such as surfacing and underlay product the material purity obtained for each material stream during these trials would be sufficient. For example, the purity of textiles for insulation materials is not so important, more the physical characteristics of the materials i.e. light and fluffy. Furthermore, it is argued that at present rubber has the greatest potential to be reused into higher values applications such as manufacture of new shoe soles. For reclaim of rubber (which in most shoes is the largest percentage material) the developed system performed well in terms of yield and purity, clearly demonstrating the potential of the proposed footwear recycling system.

5. Conclusions and future work

The increasing scarcity of virgin material, the existing and forthcoming European producer responsibility directives and ever-increasing landfill charges necessitates that the appropriate end-of-life management and recycling of products are implemented in every manufacturing sector. In some product sectors, such as waste electrical and electronics and end-of-life vehicles, there has been a rapid growth in recycling activities driven largely by the economic values of materials. However, for consumer products, such as footwear, with limited valuable material content there are significant challenges for establishing an economically sustainable recovery and recycling process.

Until legislation arrives the establishment of a sustainable footwear recycling system is at present very much dependent upon the economical viability of the operation. To this end an automated recycling process, based upon low cost air separation technologies has been presented. The initial investigation and experimentation has focused on the separation of postconsumer shoe materials into four primary recycled material streams: rubber, leather, foam and textile fines. For each of these materials a number of potential applications exist, such as surfacing, insulation and underlay product. It must be noted that this can be defined as a down-cycling approach and may not provide the greatest environmental benefit, highlighting the requirement for further investigation into higher grade recycling scenarios to support long term recycling activities in this sector.

However, for high value applications, such as the manufacturing of new products, it is widely acknowledged that the reclaimed material stream should have purity in excess of 95%. Clearly it may not be possible to achieve this level of purity with the proposed system. Further work therefore needs to be done to investigate the technical feasibility as well as the economic and environmental impacts of alternative recycling approaches (e.g. sensor based sorting or electrostatic separation) for postconsumer footwear products. Improved material recovery can also be achieved through proactive approaches, such as better footwear design to support recycling, improved reverse logistics and collection and creation of novel recycled materials applications. In particular footwear design is seen as a key factor to enable significant improvements to material reclaim yield and purity. Thus the authors are currently working with producers to investigate the implementation of 'design for recycling' within the footwear sector. It is argued that such proactive apaches will give early adopters a significant competitive advantage when environmental legislation reaches the footwear sector.

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