Waste Management 29 (2009) 44–53

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Modelling of post-fragmentation waste stream processing within UK shredder facilities

Gareth Coates *, Shahin Rahimifard

The centre for Sustainable Manufacturing and Reuse/Recycling Technologies (SMART), Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, UK

ARTICLE INFO

Article history:
Accepted 12 March 2008
Available online 8 May 2008

ABSTRACT

With the introduction of producer responsibility legislation within the UK (i.e., waste electrical and electronic equipment directive and end-of-life vehicles directive), specific recycling and recovery targets have been imposed to improve the sustainability of end-of-life products. With the introduction of these targets, and the increased investment in post-fragmentation facilities, automated material separation technologies are playing an integral role within the UK's end-of-life waste management strategy. Post-fragmentation facilities utilise a range of purification technologies that target certain material attributes (e.g., density, magnetism, volume) to isolate materials from the shredded waste stream. High ferrous prices have historically meant that UK facilities have been primarily interested in recovering iron and steel, establishing processing routes that are very effective at removing these material types, but as a consequence are extremely rigid and inflexible. With the proliferation of more exotic materials within end-of-life products, combined with more stringent recycling targets, there is therefore a need to optimise the current waste reclamation processes to better realise effort-to-value returns. This paper provides a background as to the current post-fragmentation processing adopted within the UK, and describes the development of a post-fragmentation modelling approach, capable of simulating the value-added processing that a piece of automated separation equipment can have on a fragmented waste stream. These include the modelling of the inefficiencies of the technology, the effects of material entanglement on separation, determination of typical material sizing and an appreciation for compositional value. The implementation of this approach within a software decision-support system is described, before the limitations, calibration and further validation of the approach are discussed.

1. Introduction

The current investment in post-fragmentation technologies by many major UK end-of-life material processors is a testament to the ever increasing demand for end-of-life resources. Currently, only high value metals are being extracted from the waste before the remaining residue is either sold as aggregate or placed in to landfill. It is envisaged that ultimately this residue will also be recovered, either due to legislative targets, increased landfill taxation or economic value. To reach these goals it is necessary to understand the value-added processing that current post-fragmentation facilities are achieving, and to move away from rigid facility layouts, targeted at only high value waste stream materials. Future shredding facilities will be required to be dynamic enough to be altered based on the type of product or composition of waste they process. At these facilities end-of-life products are de-polluted and materials mined (extracted/purified) to the point of optimum value based on local, national and global material markets. Therefore, the development of a post-fragmentation modelling approach, capable of capturing the value-added processing that separation technologies can achieve, will be key in developing optimised post-fragmentation facilities.

2. Background to shredding and separation technologies

There are 37 shredder sites within the UK, of which 28 are located in England, 5 in Scotland, 3 in Wales, and 1 in Northern Ireland (Kollamthodi et al., 2003). The shredder acts as a central hub at which vehicle hulks, industrial materials and white goods waste streams are all mixed together (Ambrose et al., 2000). Here the waste is commutated into fist-sized fragments using a rotary hammer-mill, before the liberated materials, known as shredder residue (SR), pass through a range of automated separation technologies to extract and purify various materials. Shredding sites operate well-established fragmentation technologies that have

Abbreviations: DMS, dense media separators; ELV, end-of-life vehicles; EPR, extended producer responsibility; SR, shredder residue; WEEE, waste electrical and electronic equipment.

* Corresponding author. Tel.: +44 1509 227683; fax: +44 1509 227648.
E-mail address: G.Coates@lboro.ac.uk (G. Coates).

0956-053X/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.wasman.2008.03.006

high levels of throughput and automation (for example, a typical throughput rate of the hammer-mill is 150 tonnes/h). Although well distributed in geographical location throughout the UK, many shredder sites are united, either via organisation or opportunity, into shredder groups. Of the 37 shredding sites in the UK, one-half are operated by two main organisations, namely European Metals Recycling and Sims Metal, which have been estimated to process in the region of 70% of all end-of-life vehicles arising (DTI, 2004), with the remaining capacity provided by independent operators. Fig. 1 is taken from Manouchehri (2006) and demonstrates the typical process route of a fragmented waste stream; for an additional review of post-fragmentation separation equipment see Rousseau and Melin (1989).

Mechanical separation technologies (screens, dense media separators, over-band magnets, eddy current separators) are currently the preferred method of mass material recycling, and traditionally have been adopted for the upstream minerals refinement industry. The ability of mechanical separation technology to segregate the SR is highly dependent on the ability of the process to distinguish between the different material properties. Each process uniquely targets a material property within the waste stream that is susceptible to its influence. Wilson et al. (1994) refer to the more traditionally targeted properties such as magnetic susceptibility and density used within many well-established technologies, while others target more unusual differences such as particle resilience and surface friction.

Problems that complicate automated mechanical separation are the interparticle interactions that occur between materials in the waste stream. These interactions can be as a result of a number of factors: incomplete material liberation at the fragmentation stage, the frictional forces between components, moisture induced bonding or even electro-static attraction forces between materials (Oberteuffer, 1974). Therefore, the ability of a recycling technology to separate a material is highly dependent on the composition and interactions of the waste stream that is placed through it (Ferrão et al., 2006; Wilson et al., 1994). Different inter-particular interactions will occur depending on which materials are concurrently processed together, and only the dissimilarity of the targeted material property will determine whether the materials are ultimately segregated. The following sub-sections provide an overview of the main literature surrounding many of the main separation technologies used within the minerals refinement and recycling industry, and the selection of waste stream properties that form the basis of their mechanical separation.

2.1. Non-ferrous separation (Eddy current separation)

Eddy current separation technology is primarily focused on the non-ferrous part of the waste stream. The separation is brought about by inducing eddy currents inside the conductive particles of the stream. These currents lend a magnetic moment to the particles which are then propelled by the gradient field of the magnets. Opposite polarity magnets are laid end-to-end around the circumference of the drum; as the belt moves over the drum the magnetic field produces an electrodynamic force within conductive materials that accelerates them. Conventional separators (mainly utilised within the materials recovery industry) are typically known as horizontal drum separators. The selection of appropriate material properties with which to identify potential separable materials is described within much of the literature as the separation factor. This value is created by dividing the conductivity of a material (σ) by its density (ρ). Lungu and Rem (2002) specifically refer to this factor as being an integral parameter in determining the resulting trajectory of the material, a sentiment echoed from the early theoretical and practical papers of Schlomann (1975)in which he stated that a material will be deflected a characteristic distance (proportional to σ/ρ) substantially independent of the particle's size.

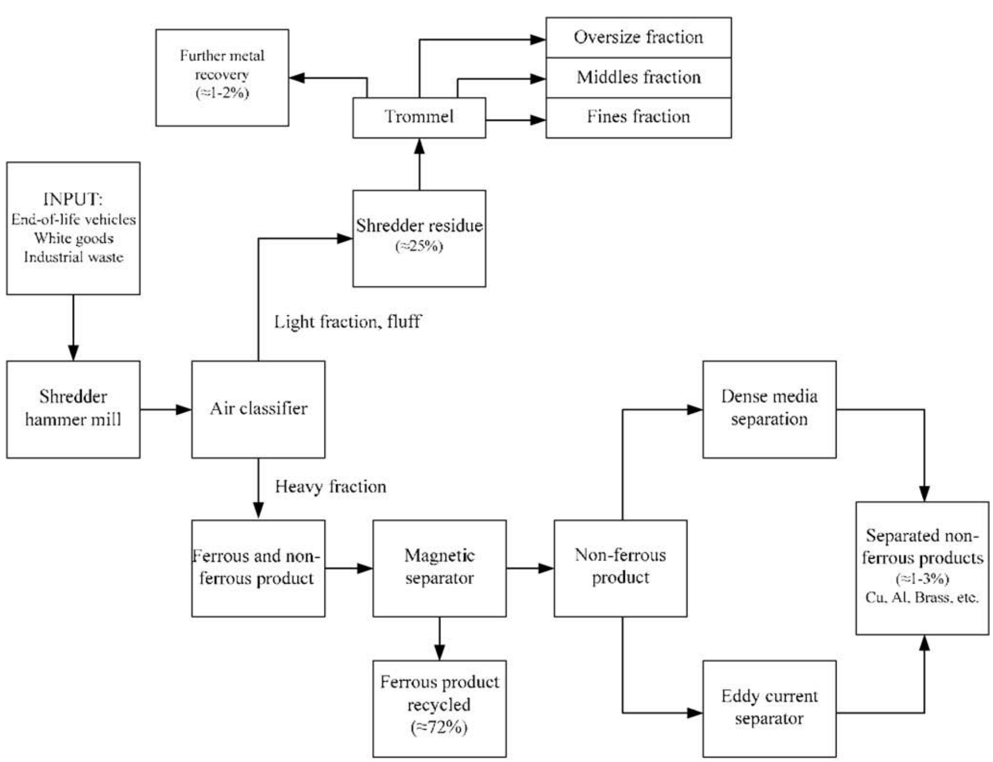

Fig. 1. Typical shredder site configuration, taken from Manouchehri (2006).

2.2. Air classification

Within air classifiers the input waste is introduced under pressure via the tangential inlet valve and starts swirling within the separation chamber. This creates a vortex, the centre of which generates a low pressure air column to the atmospheric pressure of the overflow pipe. Particles entering the vortex therefore have two competing forces acting on them, the centrifugal force due to its radial rotation around the chamber, and an opposing drag force created by the pressure difference. The cyclone separation process has been used extensively within the minerals refinement industry, and a great body of literature exists on the predictive modelling of the separation efficiencies of the process for both wet and dry cyclones (Avci and Karagoz, 2003; Plitt, 1976), qualitative testing of process design parameters (Molerus and Glückler, 1996), and the development of computational optimisation software (Conway, 1985). Specific papers that have directly referred to material properties that effect separation efficiency can be seen in the book by Boubel et al. (1984) in which the particle's mass is identified via its contribution to centrifugal force. Additional papers by Zhang et al. (1988) and Benzer et al. (2001) also suggest that a particle's physical size (maximum diameter) can be used as a separation metric.

2.3. Screening (trommels)

The screening of particles acts as a form of size classification to prepare the waste streams for the further downstream processes. Screening is therefore a way of sorting the waste stream according to particle size once it has been fragmented. It uses consistently defined aperture sizes to filter the waste stream; particles with sizes smaller than the aperture will be segregated from larger, bulkier particles. A detailed review of screening technologies can be found in the work of Suttill (1990). Although a great range of screening equipment exists that vibrate and agitate the waste stream in various directions, one of the most widely adopted techniques is that of the *trommel*. This uses a number of circularly aligned meshes of varying aperture sizes that slowly rotate as the waste is fed in. Each section of the trommel has progressively larger apertures to further segregate the courser particle sizes. A number of mathematical models have been developed to consider the various design attributes of various screen types on separation effectiveness (Soldinger, 2000; Subashinghe et al., 1989a,b). Research aimed at determining a simplified separation metric to describe the separation capability of a screen is presented by Mohanty et al. (2003) and utilises particle diameter and aperture size as a means of determining screening efficiency.

2.4. Dense media separation (DMS)

Dense media separators typically utilise heavy liquids such as Magnetite and Ferro-silicate solutions having specific densities of 1.5 and 3.5, respectively. The media is traditionally agitated to reduce the viscous effect of the separation liquids, and is known as "jigging". Given the fundamental operating principle of a dense media separator is density, this material property has been widely used within research literature to describe its separation performance. Weiss (1985) and de Jong and Dalmijn (1996) proposed the development of a normalized separation metric using material densities known as the *settling ratio*, that identified which materials would be most effectively separated if concurrently processed together. Further research that has considered various performance metrics and waste stream effects include: the influence of particle shape on separation effectiveness (Ferrara et al., 2000), the mathematical modelling of gravity separator performance (Napier-Munn, 1991), the size and density of particles on performance (Venkoba et al., 2003) and the mathematical modelling of centrifugal separator performance (Hu et al., 2001).

2.5. Magnetic separation

Magnetic separation is one of the oldest forms of material separation and has existed in the mineral processing industry since the early 1900s. High gradient magnetic separators have made the transition from the mineral refining industry to the end-of-life waste management sector, and are now an integral value-added process. The ability of these devices to effectively separate a material is dependent on the superiority of three competing forces: the magnetic forces from the device, the resistive forces when lifting the target substance from the waste stream and the positive and negative inter-particular forces between adjacent materials (Oberteuffer, 1974). Magnetic susceptibility (χ) describes the level of internal magnetisation of a material when subjected to a magnetic field. High magnetic susceptibility values describe the distinctive traits of ferromagnetic materials such as steel and iron that are traditionally easily separated via magnetic separation devices. Many material databases document an additional parameter to describe the ease with which materials can be magnetised known as the *relative permeability* (K_m); Eq. (1) describes its relationship to the magnetic susceptibility of a material

$$\text{Magnetic susceptibility}: \chi_m = K_m - 1 \tag{1}$$

Paramagnetic and diamagnetic materials have *relative permeability* and *magnetic susceptibility* values close to 1 and 0, respectively, while for ferromagnetic materials these values can be considerably larger (Nave and Nave, 1985).

3. Modelling post-fragmentation separation processes

Fig. 2 describes the overall post-fragmentation modelling approach adopted, and how the targeted parameters are used to benchmark the inefficiencies of the various separation technologies so that its value-added processing can be ascertained. The modelling approach considers each material from the input composition individually in turn. A fragmented material has both physical and material characteristics, some of which are used by the various separation technologies to make distinctions between other materials within the waste stream. By utilising these targeted parameters, combined with an appreciation for the separation inefficiencies due to the equipment and imperfect liberation, it is possible to predict in which processes a particular material is most likely to be separated.

The initial stage is to gain an understanding of the input composition of the product being processed. This not only allows an understanding of the various quantities of each material to be considered, but also provides an indication as to the different contamination ratios, which are important in determining the input waste streams value. The benefits of using compositional data as an input into the post-fragmentation model is that this data can be readily obtained from upstream design sources, but can be equally sourced using onsite shredder sampling. Certain European post-fragmentation sites already undertake this type of sampling, and provide a post-fragmentation sampling service to end-of-life waste producers. Rigorously testing the composition of each input waste entering their facility to ensure suitable recompense is given to the waste provider. Although systematic and extensive shredder sampling is not currently undertaken within UK facilities, it is envisaged that such compositional sampling will become commonplace in the future as legislative conformance monitoring becomes more widespread and the markets for different end-of-life materials become more established.

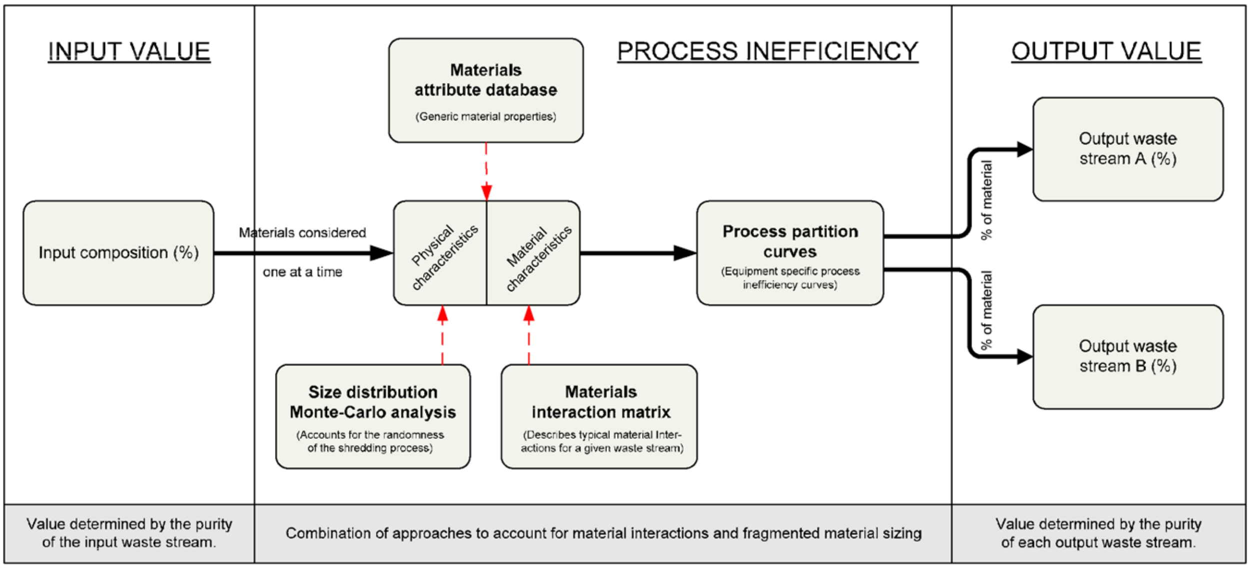

Fig. 2. Post-fragmentation separation modelling approach.

The following sub-sections uniquely focus on the capturing of process inefficiencies using recognised and bespoke modelling approaches, and highlight the considerations that are required to be made, based on the application of minerals processing research to end-of-life recovery and the need to determine physical as well as material characteristics.

3.1. Linking waste stream characteristics to separation technologies

For each technology discussed within the literature review, a parameter was identified that is used by each process to distinguish a target material from the rest of the waste stream (e.g., density for media separation tanks, shredded particle size for screening, etc.). These parameters target either the physical characteristics (morphology) of a shredded waste stream (shape, size, etc.) or its material characteristics (density, conductivity, etc.). Table 1 provides a summary of these targeted parameters for a range of the most common separation technologies.

3.2. Cataloguing physical and material characteristics

All data pertaining to the physical or material characteristics are stored within a *materials attribute database*, which is continually interrogated for each new material. Within this database there are a range of typical materials found within end-of-life products (plastics, metals, ceramics) and approximate values for each of the targeted parameters identified within Table 1 (density, size, conductivity, etc.). The different material types have every parameter listed, as this would allow for the possibility of each material to pass through every separation process, regardless of the process having any substantial effect or not.

3.3. Determining physical particle sizes of fragmented materials

Processes that base their separation on physical characteristics (e.g., screening) require each material to have some consideration as to the range of typical particle sizes created during shredding. This means that aside from not only knowing the material characteristics of a particular material within a waste stream, the approach also requires an understanding of a materials typical geometry (i.e., steel particles fragment into size ranges of between 0 and 100 mm, rubber particles range between 0 and 50 mm, etc.). Material characteristics can be readily sourced from a materials database, whereas the fragmentation effects of the shredding process are not consistent, producing particles of all sizes depending on the random effects of the liberation process. One way of overcoming this is to try and link the material characteristics of a waste stream constituent (e.g., density, izod impact strength) to a resultant particle size. Mathematical modelling of particle impacts indicative of those found within a shredder-mill is an extensive and complex research field, and is considered beyond the scope of this research. Another approach is to try and build particle size uncertainty into the model, capturing the random sizing effects of the shredding process based on the analysis of the output. This has been incorporated within the modelling approach by considering the fragmentation process as a number of random liberation events. Using Monte-Carlo

Table 1
Summary of targeted material parameters for a range of common separation technologies

Technology name	Description	Targeted parameter(s)	Physical or material
Screening	Used within Trommel and vibrating tables. Screen aperture size determines separation results	Particle size	Physical
Magnetic separation	Used to segregate the ferrous fraction from the waste stream	Magnetic susceptibility	Material
Non-ferrous Separation	A rotating magnet induces eddy currents within a conductive material and propels material	Separation factor (conductivity ÷ density)	Material
Air classification	A rotating air or liquid column creates a vortex and displaces materials according to their weights	Mass (density × volume)	Physical/material
Dense media separation	The liquid separation media's density floats and sinks waste stream materials	Density	Material

simulation in combination with size distribution data taken from existing fragmentation studies for a range of different material types (Harder, 2002), it is possible to account for the randomness of the shredding process.

Beta-PERT curves were selected to be overlaid on the industrial data to provide generalised input distributions for the main material types. These were then sampled using Monte-Carlo simulation to produce a random size distribution profile for each material, see Fig. 3. The benefit of adopting this approach is that Beta-PERT curves can be readily described using three input parameters; maximum, minimum and most likely, which can be easily catalogued within the *materials attribute database* along with more widely available material properties. The limitation of only using Beta-PERT curves to describe typical shredder output is routed in the lack of available industrial data with which to select more accurate and suitable distributions.

3.4. Modelling separation technology inefficiencies via process partition curves

Tromp/partition curves have long been used within the minerals refinement industry to describe the effectiveness of various separation processes (Wills, 1997), but have never been applied to end-of-life waste stream reclamation. The process partition curve is made up of three main parameters: the cut-point (x_{50}), the probable error of separation (E_p), and the cut-point off-set (present in some curves but not others). The process partition curve models the *partition co-efficient*, which is the percentage of the feed material incorrectly separated at the specific material parameter value identified (see Fig. 4). Hence, the cut-point (x_{50}) represents the material property value at which 50% of the feed will report to one output stream and 50% to the other.

The E_p is described as the density at which 75% of the waste will go to the wrong place (A), minus the density at which 25% will go to the wrong place (B), divided by 2 (see Eq. (2)).

$$E_p = (A - B)/2 \quad (2)$$

Using these three parameters and standard measurement procedures, it is possible to describe the separation efficiency for a particular process setup. The majority of separation technologies exhibit a process partition curve similar to that described by an inverse exponential function (sigmoid function). These curves can be generated to describe process inefficiency relative to a selected separation parameter, as described in Section 3.1.

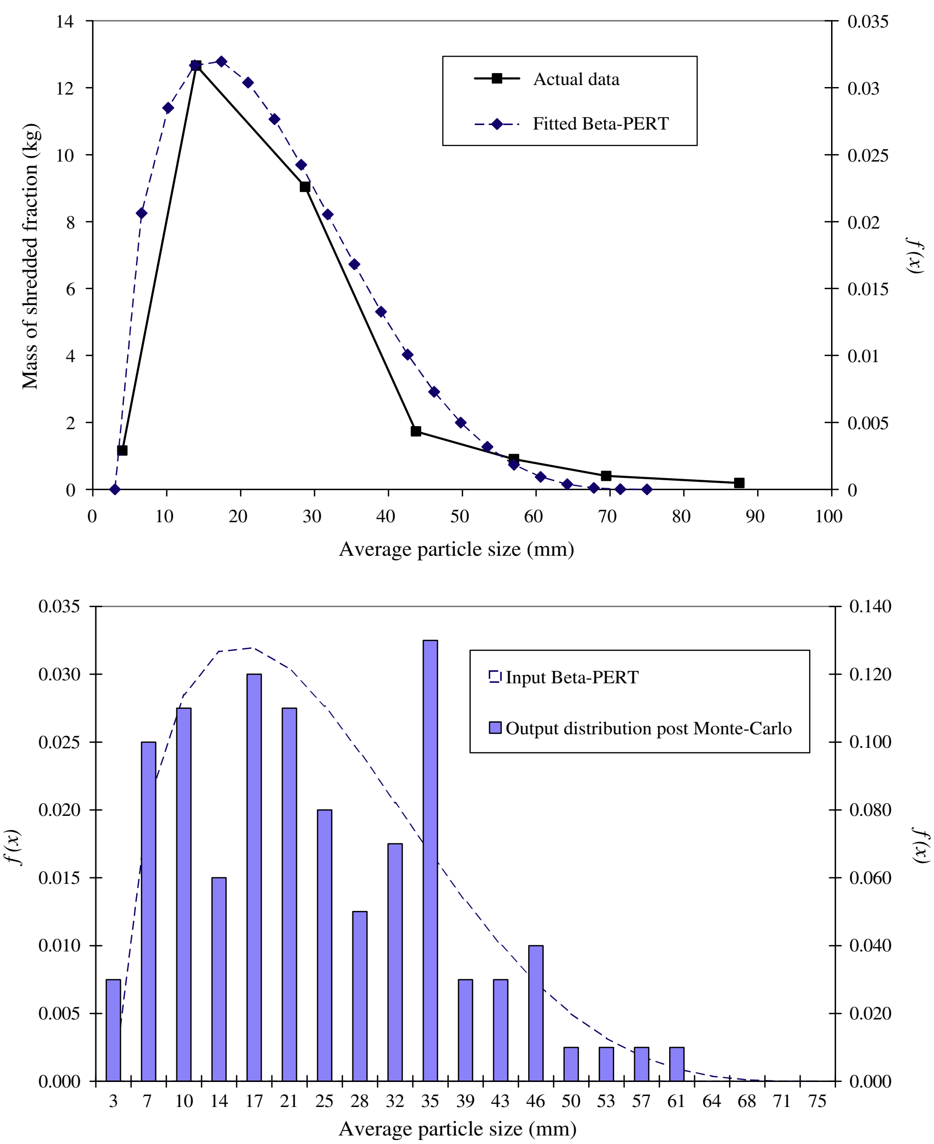

Fig. 3. The creation of material size distribution profiles using Monte-Carlo simulation.

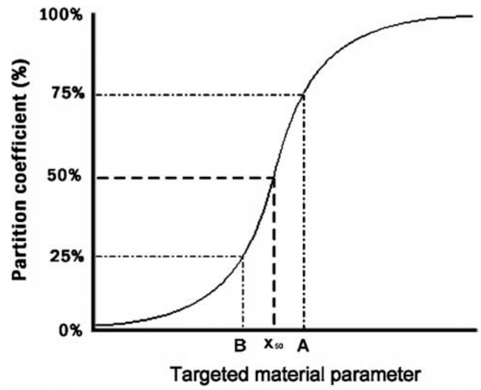

Fig. 4. Typical process partition curves using an inverse exponential function.

The curves are designed to model the inefficiencies of a particular process and vary depending on the machines design parameters (e.g., a smaller air-gap between the feed and magnet within an magnetic separator may pick up more ferrous metal, or a stronger vortex within a cyclone separator may lift heavier materials). Therefore, depending on how a process is set up and the machine parameters for that process, the shape of these curves can vary quite substantially from facility to facility. By specifying three variables within the model (x_{50}, E_p and off-set), the variations between equipment and operating parameters can be accounted for; it is simply a case of benchmarking the equipment at the facility in question. These process partition curves can then be used to model separation technology inefficiencies.

4. Modelling limitations

The limitations of using inefficiency modelling techniques taken from the minerals refinement industry and applying them to the end-of-life recycling sector, are the additional problems associated with material entanglement and incomplete liberation. The following sub-sections discuss these limitations and present suitable approaches to allow traditional process benchmarking techniques to be applied to end-of-life recovery technologies.

4.1. Modelling limitations due to material entanglement

If process partition curves are used in isolation to describe the separation effectiveness of typical end-of-life processes, a huge assumption is needed to make the model valid. This assumption is that every waste stream constituent is perfectly isolated from the rest of the feed during the fragmentation process, with zero inter-particular interactions between materials. An approximate analogy would be to consider a shredded waste stream as thousands of perfectly spherical balls, each an individual material and unable to interact and entangle with any other part of the waste. Each product would have been perfectly liberated into its individual materials, with geometry that would not tangle or bind with any other waste stream constituent. Each of these individual balls can then have their targeted material parameter tested by the technologies process partition curve to determine their predicted separation. In reality this is not the case. Unlike comminution within the minerals refining industry, the end-of-life shredding process produces materials that are rarely of singular composition, and are often attached to other materials either due to incomplete liberation or post-fragmentation entanglement. Therefore, determining a value for the targeted material parameter to be used within a processes partition curve is not as straight-forward, due to the need to consider the material properties of a combination of materials as opposed to one in isolation. The following sub-sections describe the limitations of developing a post-fragmentation separation model based solely on process partition curves, and the inadequacies of not including the inefficiencies due to inter-particular interactions within the model.

4.2. The inadequacies of using process partition curves in isolation

The inadequacies of generating a post-fragmentation costing approach using only process partition curves become apparent when considering examples such as the separation of a metallic shredded fraction using a water elutriation tank. Within this process, materials are separated using water as the separation media; dense materials will sink and lighter materials float. If a separation model only utilises process partition curves to model the separation, the situation within Fig. 5 is created, in which any material with a density suitably far from that of the separation media's density (1000 kg m^{-3}) generates a partition co-efficient approximately equal to 100%. This means that each of these waste materials will sink, and be perfectly separated from other waste stream constituents (such as glass, rubbers and plastics). In practise this is not the case, as a small percentage of un-liberated metallics will result in the incorrect output stream.

This is due to the materials that are processed by the water elutriation tank having the material properties of those chemically or mechanically joined to it, the apportionment of which depends on the contamination quantities. The predicted recovery values for other separation technologies, based on different targeted material parameters also exhibit a similar lack of correlation to real world values. This would suggest that the effects of inter-particular interactions and cross-material contamination greatly affect the efficiency of post-fragmentation separation technologies, and cannot be ignored when modelling the post-fragmentation process.

4.3. Modelling material entanglement via a materials interaction matrix

To account for the inefficiencies in separation due to material interactions, it is necessary to develop a method that is capable of describing the compositional contamination between various material types. Given that materials interact differently depending on the composition of the waste stream they are processed within (e.g., shredded electronics will interact differently than a shredded automobile), this contamination description must be changeable depending on the products that the shredder is processing.

The most logical place to catalogue these material interactions is at the shredding stage, before any separation technology has altered the waste stream. At this point it is possible to sample the shredder output to determine which materials have been un-liberated and cross-contaminated, and in what percentages. This sampling would be a rather laborious task, but once achieved it

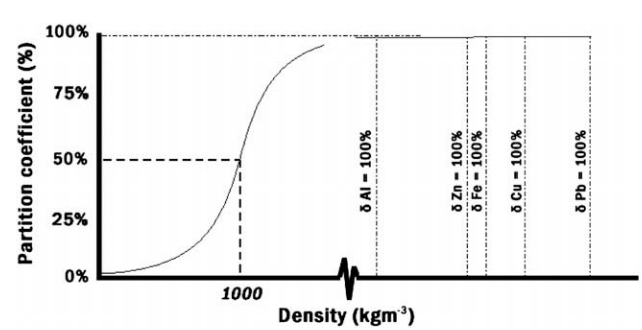

Fig. 5. Typical process partition curves using an inverse exponential function.

would provide an accurate snapshot of the typical waste stream entanglements and interactions for a range of waste stream types (electronics, automotive, industrial scrap, etc.). Shredder sampling would determine a percentage fraction of a particular material that is un-liberated during the shredding process. This un-liberated material must be given a new material property based on the types and quantities of material it is most likely to interact with.

Within the modelling approach the percentage un-liberated fractions from each material can be used as weighting factors based on the assumption that there is a linear relationship between contamination and the target material parameters considered. Fig. 6 shows an example assumption using polypropylene joined with copper.

Assuming that at minimal contamination levels the mix material will have material properties approximating polypropylene, while at the other extreme, heavy contamination will have the material properties of copper. If it is assumed a linear relationship between the two (highlighting this as the main assumption of the model), it is possible to use the percentage quantities of the un-liberated input feed (u_n) as a weighting factor. Eq. (3) gives an example of how these weighting factors are used for a dense media separator, and shows the combined material density for a group of materials cross-contaminated

$$\delta_{\text{Combined}} = \frac{\delta_1 u_1 + \delta_2 u_2 + \cdots + \delta_n u_n}{u_1 + u_2 + \cdots + u_n} \tag{3}$$

where u_n = % un-liberated fraction of input material mass and δ_n = density of un-liberated material fraction.

The limitation of using Eq. (3) in isolation is the assumption that each un-liberated material only takes part in one interaction (e.g., all un-liberated metals and all un-liberated plastics interact and produce one new material with the combined properties of all of them). However, within a multi-material system, each un-liberated material can potentially interact with any other in varying quantities or simply not at all. Therefore, another level of apportionment is required. To model the interaction between multiple materials this requires not only the percentage of un-liberated material to be specified, but of that percentage what amount interacts with each other material.

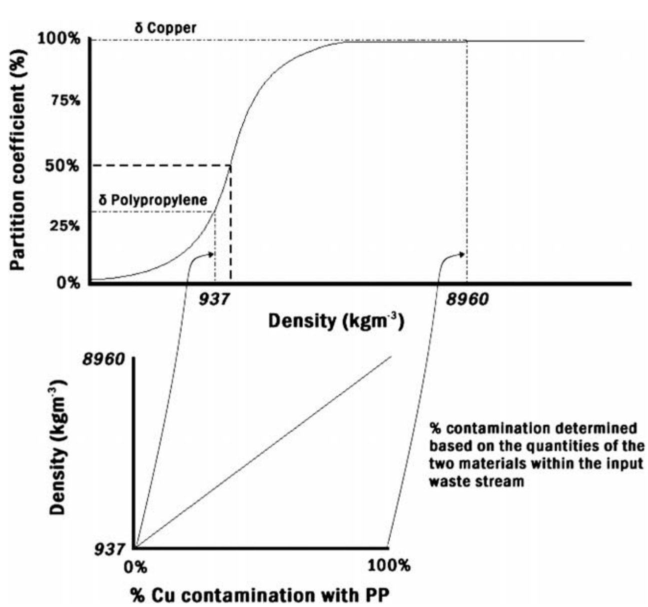

Fig. 6. Highlighting the assumed linear relationship between the two components interacting.

	Copper	Iron	Rubber	Glass	PVC	PU
Copper		100%			50%	
Iron	40%					
Rubber					50%	
Glass						
PVC	60%		100%			
PU						
Total	100%	100%	100%		100%	

Fig. 7. A 2D example of the materials interaction matrix.

The most effective way of describing this multiple materials interaction within the post-fragmentation model is to use a matrix, as depicted in Fig. 7.

By locating the materials within the waste stream, along the top and down the side a *materials interaction matrix* can be developed that describes the percentage entanglement of an un-liberated material to the rest of the waste stream. The vertical columns identify the targeted material considered; entries within this column highlight the materials that typically interact with it. In this approach the diagonal within the matrix is always set to zero, as materials cannot interact with themselves. Every column must equate to 100% to fully attribute the un-liberated fraction, and every entry must have a transposed entry about the diagonal (e.g., if copper interacts with PP, PP must interact with copper). Fig. 7 provides an example matrix of a waste stream composed of six different materials. Within this example, the un-liberated percentage of copper interacts with iron and PVC, at 40% and 60%, respectively. Conversely, 100% of the un-liberated iron interacts with copper, and 50% of the un-liberated PVC mixes with copper, and finally, the other 50% of the un-liberated PVC interacts with all the un-liberated rubber.

4.4. Limitations of the material interaction matrix modelling approach

The materials interaction matrix has been developed by this research in response to the realisation that process partition curves are not capable of modelling the separation capabilities of UK separation facilities in isolation. The inclusion of the materials interaction approach therefore provides an additional means by which process inefficiency can be further described. Within the above examples this is limited to a 2D matrix, and provides only a basic demonstration of multiple material entanglements. Incorporating additional complexity into this modelling approach, beyond that outlined above, cannot be justified due to the lack of data available in existing shredding facilities. It is therefore considered beyond the scope of this paper to account for complex multi-material interactions, but the author recognises the need to expand this approach in the future when the acquisition of more detailed processing data becomes a more widely adopted practice.

5. Determining waste stream value

The composition of a fragmented waste stream varies depending on the type of product being shredded. Shredding facilities within the UK process a number of white goods and industrial waste streams as well as end-of-life vehicles; which result in a large variety of different material types and compositional grades. Due to the lack of established specifications for each liberated material, the secondary markets for these materials are limited. Materials are often collectively grouped based on the requirements of the material re-processor, e.g., all grades of aluminium are generically classified as one, all grades of steel and iron classified as another. Within these material groupings, market value is clearly a function of material contamination (grade). Therefore, to work out the economic value of a material stream, a clear understanding is required as to the purification capabilities of the post-fragmentation separation processes, and their effects on a material grade. Currently, there are no formalised specifications available for the majority of the shredded materials produced during post-fragmentation processing. This research has therefore developed a method to estimate the level of achievable value based on its final purity.

This method is based on an exponentially decaying value curve. This type of curve has been adopted due to its close correlation with the typical material recycling scenario found within industry. It is often the case that the purification of material streams can only raise the market value so far. It is the reduction of the contaminants to zero over the last few percent that significantly boost its market value. In terms of available market prices that can be used to generate these material value curves, certain assumption needs to be made. These include

- At zero percent contamination, the material market value for virgin material can be adopted (V_{Max}).
- Inert wastes streams that cannot be successfully purified to the levels required for recycling can be sold for a positive value as industrial aggregate (V_{Min}).
- Certain waste streams will require minimum contamination or they will have to be disposed of via a negative landfill charge (see dashed line in Fig. 8).
- The rate of end-of-life value improvement can be controlled via the curve decay rate (k).

A suitable equation that incorporates these three control parameters (V_{Max}, V_{Min} and k) that generates the £/tonne value of a material with x percentage contamination, is given in Eq. (4) and is plotted in Fig. 8

$$\text{Value}(\text{£/tonne}) = (V_{Max}e^{-kx} + V_{Min}) - (V_{Min}e^{-kx}) \quad (4)$$

Once V_{Max}, V_{Min} and k have been developed for a range of end-of-life materials, the value curve can be applied as a conversion tool, translating the predicted output grades (%) produced by the post-fragmentation model into a realistic assessment of market value.

6. Software implementation and model calibration

The post-fragmentation modelling approach has been implemented using Microsoft Office Excel® and Microsoft Visual Basic® for Applications (VBA). The following sub-sections discuss the calibration of the software implementation of the post-fragmentation modelling approach.

6.1. Data availability for modelling

The archaic nature of the ELV recovery sector is exemplified by the lack of an abundant amount of end-of-life processing data. The detailed analysis and data collection that are undertaken by many vehicle suppliers is currently not reciprocated by end-of-life operators. Only recently has the first ELV shredder trials been held within the UK, to determine which materials are recovered and in what quantities (Weatherhead and Hulse, 2005). Comprehensive equipment benchmarking exercises are not standard practise within UK shredding facilities, and therefore present a difficult challenge when trying to validate the post-fragmentation model approach. The recent governmental study can be used to calibrate the approach and show the ability of the technique to replicate real world data, but the author recognises the need to further validate the model by producing a facility specific example.

6.2. Facility layout and vehicle composition

The shredder trial data used to calibrate the post-fragmentation model was originally collated using natural ELVs that had a registration date around 1990. Ideally, the input composition into the model should be from a vehicle produced around this same period. Numerous sources of literature exist regarding the changing composition of ELVs over the last two decades (ACORD, 2001; Hooper et al., 2001; Montedison, 1992; Staudinger and Keoleian, 2001). For the purposes of model calibration, compositional data from the Association of Plastic Manufacturers in Europe (APME, 1999) describing a 1995 vehicle will be adopted. All the vehicles used within the shredding trial were systematically de-polluted to remove the rubber types and fluids; hence for consistency the composition used within the calibration was adjusted to simulate the removal of these materials.

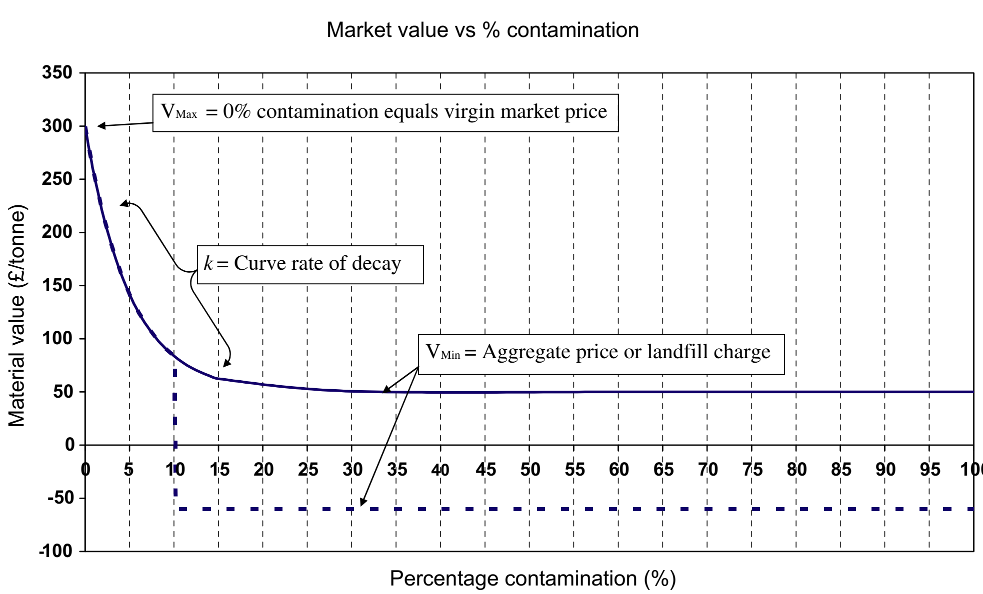

Fig. 8. The generated exponentially decaying value curve used to determine end-of-life market value for a range of materials without specifications.

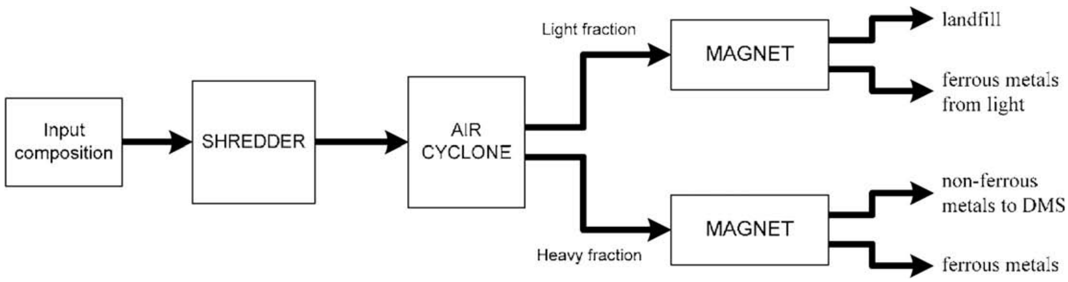

Fig. 9. An overview of the shredder site setup and the four main output waste streams used within the UK Governmental benchmarking study (Weatherhead and Hulse, 2005).

Table 2
The demonstrating the ability of the modelling approach to be calibrated using facility benchmarking data

Adjusted 1995 vehicle composition, main material groups	% grade input	% to scrap metal waste stream	% to density media separator waste stream	% to scrap metal waste stream from light fraction	% to landfill waste stream
Ferrous metals	70.84	68.98	1.27	0.51	0.04
Non-ferrous metals	10.82	0.31	9.59	0.05	0.83
Rubber	1.98	–	0.92	–	1.06
Glass	3.14	–	1.02	–	2.12
Other	3.15	–	1.24	–	1.90
Plastics	10.07	–	7.20	–	2.86
Predicted	100.00	69.30	21.25	0.56	8.80
Actual		69.72	20.88	0.43	8.97

For the purposes of demonstrating the post-fragmentation modelling approach, the waste stream processing route shown in Fig. 9 was adopted.

6.3. Demonstrating the ability of the model to replicate real world data

Based on the processing scenario described in Fig. 9 and the input composition adopted, the models process partition curves, materials interaction matrix and size distribution profiles were adjusted to replicate the output seen within the shredder trial data. Table 2 shows the main material groups used within the input composition and the predicted distribution of the materials amongst the four main output streams at the shredding facility. This effectively demonstrates the post-fragmentation model's ability to replicate the separation capabilities seen within industry.

The modelling of current separation processes can provide a foundation for facility optimisation, where waste streams are assessed for their value and recoverability before a bespoke processing route is generated based on either environmental or economic drivers. A fully validated facility model would not only allow the optimum configured setup to be determined, but also support additional technology investment decisions.

7. Conclusion

Given the important role that mechanical separation is currently playing within the UK's waste recycling strategy, the understanding of value-added processing achieved by this technology will be vital in ensuring its continued role in end-of-life materials recycling. The movement of these facilities away from a continuous material flow within a rigid processing route, to one that can consider batch waste stream processing based on a configurable facility layout, should be the sector's focus in the long-term. To achieve this, rigorous data collection is required so waste stream routing is based on optimum value and recycling potential.

This paper has described the development of a post-fragmentation separation model, capable of simulating the value-added processing that a piece of automated separation equipment can have on a fragmented waste stream. The model takes the input composition of a waste stream and determines the most likely route of each material through post-fragmentation separation technologies, and based on its material attributes and component interactions, generates a material value as a function of its post-separation contamination. The research has identified a range of challenges in modelling the costs of a post-fragmentation process. These included the modelling of inefficiencies within the technology, the effects of material entanglement on separation, the determination of typical material sizing and an appreciation for compositional value. A number of mathematical/statistical techniques, including process partition curves, Monte-Carlo analysis, material interaction matrices and material value curves, have been used to aid the modelling of the direct costs of post-fragmentation processing.

The aim of the research has been to develop a theoretical modelling approach to consider the material separation processes during post-fragmentation activities. Given the lack of extensive post-fragmentation data currently collected from UK facilities, the model has been calibrated using data generated through a governmental benchmarking study. However, the bespoke level of data required to model facility specific machines must come from industrial validation. The author therefore recognises the need to embark on an extensive program of facility specific industrial validation exercises, due to the distinct lack of post-fragmentation reclamation data currently available. Once validated for a particular facility, this model would generate valuable knowledge as to the best method of utilising separation technologies to effectively mine the waste streams processed.

Acknowledgements

This work has been carried out as part of a collaborative research programme at Loughborough University, funded by the Engineering and Physical Science Research Council (EPSRC), entitled "Cost-oriented Approach to Design and Recovery of Vehicles to meet the requirements for the End-of-Life Vehicles Directive". The authors would like to acknowledge the support of Mr. D. Wilkins of European Metal Recycling Ltd.

References

ACORD, 2001. 4th Annual Report [online]. <http://www.wasteonline.org.uk/resources/InformationSheets/vehicle.htm#6> (accessed 02.04.06.).

Ambrose, C.A., Singh, M.M., Harder, M.K., 2000. The material composition of shedder waste in the UK. IWM Scientific and Technical Review (November), 27–35.

APME, 1999. Plastics: The Material of Choice for the Automotive Industry [online]. XXXX/GB/09. <http://www.plasticseurope.org> (accessed 24.04.07.).

Avci, A., Karagoz, I., 2003. Effects of flow and geometrical parameters on the collection efficiency in cyclone separators. Aerosol Science 34, 937–955.

Benzer, H., Ergun, L., Lynch, A.J., Oner, M., Gunlu, A., Celik, I.B., Aydogan, N., 2001. Modelling cement grinding circuits. Minerals Engineering 14 (11), 1469–1482.

Boubel, R., Fox, D., Turner, B., Stern, A., 1984. The Fundamentals of Air Pollution. Academic Press Inc., Oval road, London.

Conway, T.M., 1985. A computer program for the prediction of hydrocyclone performance, parameters, and product-size distributions, Software No.: M233, Mintek.

de Jong, T.P.R., Dalmijn, W.L., 1996. Improving jigging results of non-ferrous car scrap by application of an intermediate layer. International Journal of Mineral Processing 49, 59–72.

DTI, 2004. Consultation on the Transposition of Articles 5 and 7 of the End-of-Life Vehicles Directive (200/53/EC): The End-of-Life Vehicles (Producer Responsibility) Regulations 2004 [online]. URN 04/542. <http://www.dti.gov.uk/files/file30649.pdf> (accessed 04.04.07.).

Ferrão, P., Nazareth, P., Amaral, J., 2006. Strategies for Meeting EU end-of-life vehicle reuse/recovery targets. Journal of Industrial Ecology 10 (4), 77–93.

Ferrara, G., Belvilacqua, P., Lorenzi, L.D., Zanin, M., 2000. The influence of particle shape on the dynamic dense medium separation of plastics. International Journal of Mineral Processing 59, 225–235.

Harder, M.K., 2002. Polymer Processing B: Towards Processing Polymers from ASR [online]. Waste and Energy Research Group, University of Brighton. <http://www.brighton.ac.uk/werg/pdf/Reports/polymerprocessingb2002.pdf> (accessed 02.04.06.).

Hooper, R., Potter, A.K., Singh, M.M., 2001. Diversion from landfill: mechanical recycling of plastic from materials recovery facilities and from shredder residue. Green Chemistry 3, 57–60.

Hu, S., Firth, B., Vince, A., Lees, G., 2001. Prediction of dense medium cyclone performance form large size density tracer test. Minerals Engineering 14 (7), 741–751.

Kollamthodi, S., Hird, A.B., Elghali, L., Johnstone, K., Wayman, M., McColl, V., 2003. Data required to monitor compliance with the End of Life Vehicles Directive [online]. Project report PR SE/483/02 prepared for DEFRA by TRL Ltd, UK. <http://www.defra.gov.uk/environment/waste/topics/elvehicles/trlstudy-one.pdf> (accessed 15.03.05.).

Lungu, M., Rem, P., 2002. Separation of small nonferrous particles using an inclined drum eddy-current separator with permanent magnets. IEEE Transactions on Magnetics 38 (3), 1534–1538.

Manouchehri, H.R., 2006. Mapping and development of shredding product stream(s): Four shredding plants in Sweden (What should be done for better performance of the plants?) [online]. JK 88011, Northland Oretech Consulting Co. <http://www.jernkontoret.se/informationsbanken/vara_publikationer/pdf_forskning/d817.pdf> (accessed 03.09.06.).

Mohanty, M.K., Palit, A., Khanna, N., 2003. Models for predicting the performance of a linear screen. Coal Preparation 23, 215–237.

Molerus, O., Glückler, M., 1996. Development of a cyclone separator with new design. Powder Technology 86 (1), 37–40.

Montedison, 1992, Nuovi materiali e chimica: il caso del settore automobilistico, No. 3/1992, Innovazione e Materie Prime, Milan.

Napier-Munn, T.J., 1991. Modelling and simulating dense medium separation processes – a progress report. Minerals Engineering 4 (3/4), 329–346.

Nave, C.R., Nave, B.C., 1985. Physics for the Health Sciences. Sauders Elsevier Publishing, Philadelphia, PA.

Oberteuffer, J.A., 1974. Magnetic separation: a review of principles, devices and applications. IEEE Transactions on Magnetics MAG-10 (2), 223–237.

Plitt, L.R., 1976. A mathematical model of the hydrocyclone classifier. CIM Bulletin 69 (December), 114.

Rousseau, M., Melin, A., 1989. The processing of non-magnetic fractions from shredded automobile scrap: a review. Resources, Conservation and Recycling 2, 139–159.

Schlomann, E., 1975. Separation of nonmagnetic metals from solid waste by permanent magnets i. Theory. Journal of Applied Physics 46 (11), 5012–5018.

Soldinger, M., 2000. Influence of particle size and bed thickness on the screening process. Minerals Engineering 13 (3), 297–312.

Staudinger, J., Keoleian, G.A., 2001. Management of ELVs in the US [online]. CSS01-01, Center for Sustainable Systems. <http://css.snre.umich.edu/css_doc/CSS01-01.pdf> (accessed 02.04.06).

Subashinghe, G.K.N.S., Schaap, W., Kelly, E.G., 1989a. Modelling the screening process – an empirical approach. Minerals Engineering 2 (2), 235–244.

Subashinghe, G.K.N.S., Schaap, W., Kelly, E.G., 1989b. Modelling the screening process: a probabilistic approach. Chemical and Materials Engineering 59, 37–44.

Suttill, K.R., 1990. Screens for all occasions: the choice has never been wider. Engineering and Minerals Journal 191 (2), 18.

Venkoba, R., Kapur, P.C., Konnur, R., 2003. Modeling the size–density partition surface of dense-medium separators. International Journal of Mineral Processing 72, 443–453.

Weatherhead, T., Hulse, D., 2005. A study to determine the metallic fraction recovered from end-of-life vehicles in the UK [online]. A report produced for the DTI by JEMA Associates Ltd, UK. <http://www.dti.gov.uk/files/file30654.pdf> (accessed 20.05.07).

Weiss, N.L., 1985. SME Mineral Processing Handbook. Met. and Pet. Eng. Inc., New York.

Wills, B.A., 1997. Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery. Butterworth-Heinemann, Oxford.

Wilson, R.J., Veassey, T.J., Squires, D.M., 1994. The application of mineral processing techniques for the recovery of metal from post-consumer wastes. Minerals Engineering 7 (8), 975–984.

Zhang, Y.M., Napier-Munn, T.J., Kavetsky, A., 1988. Application of comminution and classification modelling to grinding of cement clinker. Transactions of the Institution of Mining and Metallurgy: Section C 97, 207–213.