Journal of Hazardous Materials B139 (2007) 575–583

Journal of Hazardous Materials

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# A novel assessment tool for reusability of wastes

Sangdae Park [1], Alastair Martin [*,2]

*School of Chemical Engineering and Analytical Science, The University of Manchester, PO Box 88, Sackville Street, Manchester M60 1QD, UK*

Available online 15 May 2006

**Abstract**

This paper presents a new assessment method, which is able to determine the practicality of opportunities to reuse wastes. In this study, the term—*reuse* has much wider concepts than simply recycling to a process. In other words, *reuse* in this case can include recycling, utilisation as a raw material for other processes, and particularly transformation of the waste to low or preferably high value added products. Preliminary opportunities for the reuse of a waste can be generated by various methods such as brainstorming, desk research, consultation with industrial and academic contacts, and the like. In this work, each preliminary solution is then assessed according to three different categories—technical, economic, and environmental and regulatory, in order to determine the viability for reuse. The responses of nine collaborating companies to questionnaires pertaining to the three categories were used to set up feasible boundaries of each category in terms of the reuse of their wastes. Based on the replies, lower bounds for each category were determined, and then the preliminary solutions generated were ranked. The approach was applied to several industrial examples. The ranking of the high-dimensional information was aided by visual representation on a parallel coordinate graphic plot. Although the selection or rejection of an opportunity was highly dependent on the boundaries obtained, the approach proposed could provide a useful guideline to decision-makers for selection/rejection of the reuse opportunities available.


*Keywords:* Assessment tool; Waste reusability; Parallel coordinates

## 1. Introduction

Although the definition of waste can vary depending on countries, places and time, it is true that its definition has been getting close among countries, for instance, Kyoto Protocol in 1997 and the EU Regulation on Ozone Depleting Substances in 2002. In general, a waste is defined as any solid, liquid, or contained gaseous substance arising from the application of any process. The waste can be a by-product of a laboratory operation, a process, a commercial reagent, or even a product that is no longer wanted or needed.

For the last century, there has been a great deal of research and development and applications for wastes such as waste minimisation and treatment [1–3], the environmental assessment of wastes [4,5], minimisation of environmental impact [6,7], life cycle assessment [8,9,10,11], etc. The reason for such huge efforts is that the generation of wastes has been one of the major environmental problems of production companies. Moreover, swiftly changing regulations have put further pressure on manufacturing companies. In 1999, for instance, the UK Government released ‘a way with waste’, a draft waste strategy for England and Wales. The national waste strategy for Scotland was also launched, with specific goals for reducing special and industrial waste arisings. In the 1999 budget, the landfill tax was placed on a ‘landfill escalator’ of £1 per year until 2004. The 2003 budget subsequently raised the landfill tax escalator to £3 per year from 2005. As seen in this example, the cost related to wastes becomes one of the major considerations for the revenue evaluation of production companies.

Until now, there has been increasing pressure for methods of recycling and reusing wastes to mirror rapid changes in the environmental policies. As an application, municipal solid waste (MSW) can be used as a fuel in MSW power plants, called waste-to-energy incinerators [12–16]. The US Environmental Protec-

*Abbreviations:* CPQ, company priority questionnaire; EPA, environmental protection agency; ICP, inductively coupled plasma; MCSS, multi-criteria scoring system; MFS, most favourable solution; MSW, municipal solid waste; TOC, total organic carbon

* Corresponding author. Tel.: +44 161 306 4395; fax: +44 161 306 4399.
*E-mail addresses:* s.park@manchester.ac.uk (S. Park), alastair.martin@manchester.ac.uk (A. Martin).
[1] Tel.: +44 161 306 4345; fax: +44 161 306 4399.
[2] Present address: The Environment and Sustainable Technology, School of Chemical Engineering and Analytical Science, University of Manchester, Manchester M60 1QD, UK.

0304-3894/$ – see front matter 
doi:10.1016/j.jhazmat.2006.02.068

**Nomenclature**

*Subscripts*

| | |
|---|---|
| $i$ | a criterion |
| $j$ | a question in the company priority questionnaire |

*Superscripts*

| | |
|---|---|
| $k$ | a preliminary opportunity |

*Sets*

| | |
|---|---|
| $I$ | three criteria, $I=\{$technical, economic, environ&regulatory$\}$ |
| $K$ | a list of preliminary opportunities generated |
| $Q_i$ | The questions related to a criterion $i$ in the questionnaire |
| $S_j$ | the score marked for a question $j$ in the questionnaire |

*Parameters*

| | |
|---|---|
| $\mathrm{LB}_i$ | the lower bound for a criterion $i$ |
| $\lvert Q_i \rvert$ | the number of questions related to a criterion $i$ in the questionnaire |
| $\mathrm{TS}^k$ | the total score for a preliminary opportunity $k$ |
| $w_i^k$ | The variability factor estimated to a preliminary opportunity $k$ for a criterion $i$ |
| $\gamma_i^k$ | the new score recalculated from $\delta_i^k$ and $w_i^k$ |
| $\delta_i^k$ | the score given to a preliminary opportunity $k$ for a criterion $i$ |

tion Agency (EPA) reported that 33.1 million tonnes (14.0%) of the nation's MSW was burned and generated electricity [17]. As another branch, several studies reported their results for the reuse of vegetable residues. Rodriguez-Kabana et al. [18] addressed the reusability of olive pomace as a nematodes controlling agent for tomatoes. Citrus waste streams can be utilised in horticulture [19]. The limonoid compounds in citrus peel and seeds can be used as an insect feeding-deterrent for agricultural crops [20].

All of these studies show that many of the wastes which are currently disposed of have potential to become saleable product after converting into other materials or even as they stand. In this study, we concentrate on a different viewpoint from the above studies in terms of reusability of wastes. The studies addressed above have put specific effort into investigating a destination of the designated waste stream, which they already knew or wanted. In other words, they investigated the feasibility of a single method rather than searched for other reuse opportunities of the designated waste. Taking a municipal solid waste (MSW) as an example, MSW can be used as a fuel. Consequently, much of the research has focused on improving incineration and raising the fuel specification of the material. There are, however, alternative uses; the waste may also be utilised as a soil conditioner after composting or other treatments.

In this sense, wastes currently being disposed of need to be investigated more systematically in order not to lose or miss a good opportunity, which is technically feasible and economically beneficial. Of course, the valuation of the waste stream is not a simple task. However, it is worth considering the potential value of wastes prior to disposing of them. The objective of this work is thus to develop an assessment approach which can provide good guidelines for selecting the most favourable opportunities. Once this has been done, in-depth analysis and full-implementation must be performed for the selected opportunities.

## 2. Assessment for reusability of wastes

As a result of the previous efforts for waste minimisation as well as the increasing pressure to recognise environmental and human concerns, many manufacturing companies have already documented their wastes. For this reason, it is assumed in this study that a waste stream has been designated as suitable for consideration. If this is not the case, of course, an investigation of a site to classify what is an appropriate waste should be considered prior to an assessment of reusability. In this study, the methodology is intended primarily for use on unavoidable waste streams, which will be high-priority waste streams from the viewpoint of the company. When the waste streams have been identified as suitable for consideration the data gathering in terms of characterisation can begin.

### *2.1. Characterisation of waste*

Each designated waste stream will be thoroughly but efficiently characterised in order to provide vital information concerning the material to be used during the ideas generation stage. This involved work to be conducted on-site and with representative samples of the waste material, as well as work conducted off-site, including gathering information from a variety of sources to build a portfolio of relevant worldwide best practice in the field of waste utilization. The following works were carried out with the collaborating company: (i) Investigation for process history of the waste and the overall operation of the site. It included a relatively simple block process flow diagram just showing the main plant items, the flow of materials and the origin of the waste where in the process it arose. (ii) Time spent on a site visit to observe the operation. This time was also spent obtaining samples to be taken away for testing as necessary. Of course, samples should be taken according to established protocols. It could be worthwhile sampling waste streams as close to the point of origin as possible, particularly where individual waste streams are later mixed to produce a single composite stream for disposal. In summary, the information obtained from on-site work was the quantity of waste being produced, the current destination of the waste streams, the true cost of disposing of the waste, regulations covering the treatment or use of the waste streams, and any other facts that the company already examined in terms of the waste streams. On the other hand, a significant part of the off-site work involved building up knowledge of the physical characteristics of the waste material and that could involve time-consuming work in the laboratory. It is up to the data gatherer to decide what physical characteristics of the waste material are important at this stage of the investigation. As a guideline, the data gathering here is intended to eventually provide information that is valuable during ideas generation stage. It is important not to spend too much time in the laboratory obtaining information that does not add significantly to the data gathered from the site visits and communication with the company. However, if the waste material from a company is relatively unknown some work will be inevitable since some basic information concerning the waste such as the appearance, composition, etc. needs to be known prior to ideas generation stage. The other major part of off-site work involved investigating work that has been performed world-wide concerning the possibility of further uses for the waste stream, for example, works carried out on any material that shares characteristics similar to those of the waste material. Subsequently, the salient information gathered from on- and off-site works were assembled into a concise briefing document suitable to be circulated amongst any parties involved in the project. As well as the hard facts this document provides a history of the waste material enabling rapid appreciation of the material and its origins from a point of zero knowledge.

### 2.2. Generation of ideas

At this stage information gathered from a diverse range of sources will be combined to form an encompassing base of knowledge comprising a multitude of preliminary opportunities for utilising the waste material. A preliminary opportunity is one whose advantages and disadvantages have not been established in detail, but is identified as worthy of investigation. All the preliminary opportunities will be gathered from a number of sources including brainstorming sessions, desk research, consultation with industrial and academic contacts, or conferences and workshops.

The objective of brainstorming sessions is to generate as many utilisation ideas for the designated waste streams as possible, not to define the ultimate or ideal solutions. Prior to the brainstorming, some period referred brainstorming planning is required to run the actual session more efficiently. The activities being performed during this period are to prepare an information pack as a result of characterisation, to set objectives for the session, to select participants chosen according to the waste streams, to select an appropriate venue and to set an agenda for the session. The findings of the session are summarised and are fed back to the participants. Any later ideas after the brainstorming sessions can also be included in the list of findings. From our experience, the outcome of brainstorming is affected by the timing and length of session, selection of participants, the number of participants, venue, the quality and quantity of information pack and the role of facilitator. In particular, the experiences learnt from seven different brainstorming sessions show that (i) participants from marketing department in the company had wider information for waste utilisation than people being in charge of purchasing, (ii) the venue should be away from the usual business location of the participants and (iii) the length of sessions was normally 3–4 h including the lunch break.

Desk research is most useful for locating scientific information concerning the subject of best practise waste utilisation around the world. This scientific information supplies valuable technical data on cutting edge technology. When it comes to locating information concerning more practical implementations of technology, desk research proves more useful as a tool for obtaining a brief overview of the process and contact details, since commercial operations are subject to far more stringent restrictions on reporting. Press releases were a particularly good source of the latter information. Textbooks and journals provided more detailed and impartial information on well-established technology.

In this work, industrial and academic contacts had a number of major advantages over desk research. They were privy to more recent developments than have yet been publicised, and were much more versatile than a one way transfer of knowledge from an inflexible body. They were also privy to information that was too sensitive to publish, though it should by no means be taken for granted that they divulged this information. On the other hand, these contacts had limited time available; therefore time spent with industrial and academic contacts needed to be used efficiently, possibly after using desk research to establish that a discussion was worthwhile. More than anything else, workshops and conferences provide an ideal opportunity for networking. A large number of people attend and their time is at a premium, since the event contains a lot of scheduled activities. In this respect, the actual information gleaned from a workshop can be secondary to the opportunities gained for subsequent gathering of information by the other methods, though it should not be discounted. Most conferences involve a series of talks that can contain interesting knowledge. During this project, three different workshops were easily arranged by industry organisations and consultancies, and they were encouraged to be attended using advertisement on magazine, brochures and direct contacts.

As a result of ideas generation addressed above, various preliminary opportunities could be generated and these ideas were taken forward to the next stage, i.e. assessment for the reusability. The desired result of ideas generation, and therefore the input to the assessment stage, is a substantial list of preliminary opportunities for the reusability of a waste stream. The ultimate suitability of each opportunity varies immensely.

### 2.3. Assessment for reusability

The objective of this stage is to select the most promising preliminary opportunities without expending undue resources. A large number of preliminary opportunities could be generated in the previous stage and it would be unwieldy and inefficient to consider all the ideas in detail. Each preliminary opportunity is analysed individually using a number of criteria, broadly divided into three categories; technical, economic and environmental and regulatory. In particular, scores of each preliminary opportunity according to the criteria are measured. In this study, all scores of the three criteria for each preliminary opportunity have been estimated as a result of consultation with industrial and academic contacts. In addition, variability factors for the criteria are also considered to reflect the possibilities of the changes in near future. All of these criteria are subjected to a brief analysis to give a first best estimate and the results combined in a process referred as a multi-criteria scoring system (MCSS). The MCSS provides a method to evaluate the overall merit of a solution on the basis of a number of potentially conflicting and diverse criteria constrained by lower bounds of acceptability by measuring the scores according to a set of criteria in standardised units and combining scores using simple mathematical techniques. This involves drawing up a unique profile for each preliminary opportunity illustrating its strengths and weaknesses.

### *2.3.1. Scores for three criteria*

Firstly, technical score for a preliminary opportunity $k$ ($\delta^k_{\text{technical}}$) reflects how well-established the technology required by the preliminary opportunity is, the amount of research that has been conducted into the preliminary opportunity and how much more will be needed, any reliance on seasonal demand for a product, whether the preliminary opportunity provides a safe final destination for the waste material for which no further attention is due, and whether the preliminary opportunity can provide a single destination for the entirety of the waste material.

Secondly, economic score for a preliminary opportunity $k$ ($\delta^k_{\text{economic}}$) is given after first estimates of capital cost, operating cost and profit margins. It may also reflect saleability or marketability for the opportunity. The capital cost required for the potential solution is often a determining factor into whether it gets the go-ahead. This normally provides a barrier despite the solution being financially viable overall. Similarly, high operating costs deter those companies who operate on tight margins. The overall financial benefit of the solution should be taken into account. However, it must be considered that at present companies pay a significant amount for the disposal of their waste and therefore this does not necessarily translate into the need for the solution to make a substantial profit.

Lastly, environmental and regulatory score for a preliminary opportunity $k$ ($\delta^k_{\text{environ\&regulatory}}$) is measured after considering the flexibility of the location of any new operations required by the realisation of the preliminary opportunity, the possibility of creating new job opportunities by expanding operations, judging whether public concern is likely to arise due to the preliminary opportunity being implemented, whether any discharges needing attention will result from the preliminary opportunity, whether the opportunity will require the construction of large structures, the permits required to implement the preliminary opportunity and the likelihood of future regulations impacting on the continuation of the opportunity.

### *2.3.2. Variability factors of preliminary opportunities for criteria*

Variability factors of each opportunity $k$ for a criterion $i$ ($w^k_i$) reflect the possibility of changes in the near future for the given scores. In other words, the variability factors used in this work can be considered as the similar concepts as time sensitivity factors. Suppose that the preliminary opportunity generated is manufacturing of bio-fuel from vegetable oils. It may receive lower scores for technical and economic criteria but a high score for environmental and regulatory. However, the score for technical criterion is likely to move into the area of high score soon, since currently research and development are ongoing and many practical demonstrations have been reported. In this case, a technical score with a variability factor will be more realistic and reasonable than one without a variability factor. As another reason, the scores obtained may need correction parameters to allow for uncertainty caused by the rapid estimation of the scores. All of the criteria have been analysed in a relatively imprecise and superficial way. Consequently, the original scores obtained are recalculated by the following equation:

$$\gamma^k_i = (1 + w^k_i)\delta^k_i, \quad \forall k \in K, \forall i \in I = \{\text{technical, economic, environ\&regulatory}\} \tag{1}$$

In Eq. (1), $\gamma^k_i$ means the newly obtained score of the opportunity $k$ for the criterion $i$, $w^k_i$ is the variability factor of the criterion $i$ for the preliminary opportunity $k$, and $\delta^k_i$ indicates the estimated score of the opportunity $k$ for the criterion $i$. In this study, variability factors are given between −1 and 1, i.e. $-1 \leq w^k_i \leq 1$. As a result, the preliminary opportunities will be differentiated depending on the variability factors given even though they have the similar reusability in the beginning. In the same way as determining the scores for the criteria, variability factors have been estimated by industrial and academic contacts.

### *2.3.3. Lower boundary of acceptability*

The lower bounds of acceptability of each criterion $i$ ($\text{LB}_i$) reflect the minimum levels of concern regarding the three criteria (technical, economic and environmental and regulatory) in the company. In this study, in particular, questionnaires called company priority questionnaire (CPQ) are circulated to the company in order to find out indirectly what level of concern for each criterion the company has. However, it is possible to do this directly by enquiring the company regarding to the minimum levels for the criteria. The CPQ circulated in this work is shown in Table 1. In the table, first six questions ($Q_1$–$Q_6$) are utilised to estimate the lower bound for technical criterion of the company, next three questions ($Q_7$–$Q_9$) are used for measuring the lower bound of economic criterion, the lower bound for environmental and regulatory one is obtained by using the remaining questions ($Q_{10}$–$Q_{15}$). It is worth noting that the number of questions needs to be extended in order to observe the company's concern more accurately. The mean values of the scores obtained from questionnaire are simply used as lower bounds of acceptability. In other words, the lower bound for each criterion ($\text{LB}_i$) can be written as follows:

$$\text{LB}_i = \frac{\sum_{j \in Q_i} S_j}{|Q_i|}, \quad \forall i \in I = \{\text{technical, economic, environ\&regulatory}\} \tag{2}$$

In Eq. (2), $S_j$ denotes the score marked for the question $j$, and subset $Q_i$ indicates the questions related to the criterion $i$, whereas $|Q_i|$ means the number of questions included in the subset. Based on the questionnaire shown in Table 1, the subset $Q_{\text{technical}} = \{Q_1, Q_2, Q_3, Q_4, Q_5, Q_6\}$, $Q_{\text{economic}} = \{Q_7, Q_8, Q_9\}$ and $Q_{\text{environ\&regulatory}} = \{Q_{10}, Q_{11}, Q_{12}, Q_{13}, Q_{14}, Q_{15}\}$. Thus, the number of questions for three criteria is $|Q_{\text{technical}}| = 6$, $|Q_{\text{economic}}| = 3$, $|Q_{\text{environ\&regulatory}}| = 6$, respectively. As a result, the lower bounds of the criteria can be determined

Table 1
Company priority questionnaire (CPQ)

| Statements: please circle a number from 1 to 5 indicating how much you agree with the following statements (5 being to agree the most strongly) | Strongly disagree | | | | Strongly agree |
|---|---|---|---|---|---|
| Q01. We would prefer to find technology that has been well-established for a significant period | 1 | 2 | 3 | 4 | 5 |
| Q02. We would be interested in involving a continuous process rather than a batch process | 1 | 2 | 3 | 4 | 5 |
| Q03. We are willing to invest significant time and money researching an alternative destination for our waste | 1 | 2 | 3 | 4 | 5 |
| Q04. We would prefer to find a single destination for our waste | 1 | 2 | 3 | 4 | 5 |
| Q05. We would be interested in not generating another waste stream for our waste | 1 | 2 | 3 | 4 | 5 |
| Q06. We would prefer to take consistent amount of waste all year round | 1 | 2 | 3 | 4 | 5 |
| Q07. It is a priority for us to find an alternative destination for our waste that will not involve investing significant capital | 1 | 2 | 3 | 4 | 5 |
| Q08. It is a priority for us to find an alternative destination for our waste that will not involve high operating costs | 1 | 2 | 3 | 4 | 5 |
| Q09. It is a priority for us to find an alternative destination for our waste that gives a high financial return | 1 | 2 | 3 | 4 | 5 |
| Q10. We are interested in an alternative destination for our waste that creates a positive social impact in an area | 1 | 2 | 3 | 4 | 5 |
| Q11. We would take strenuous measures to ensure that few harmful emissions are resulted in | 1 | 2 | 3 | 4 | 5 |
| Q12. We are willing to find a location where our waste would not need to be accommodated on or very near to our existing premises | 1 | 2 | 3 | 4 | 5 |
| Q13. We want to avoid involving building facilities which could be an eyesore or a drain on nearby natural resources | 1 | 2 | 3 | 4 | 5 |
| Q14. We would be interested in an alternative that is not affected by new regulation in the future | 1 | 2 | 3 | 4 | 5 |
| Q15. We would prefer to find an alternative destination for our waste that will not involve having to apply for any permits | 1 | 2 | 3 | 4 | 5 |

by $\mathrm{LB}_{\mathrm{technical}} = (S_{Q_1} + S_{Q_2} + S_{Q_3} + S_{Q_4} + S_{Q_5} + S_{Q_6})/6$, $\mathrm{LB}_{\mathrm{economic}} = (S_{Q_7} + S_{Q_8} + S_{Q_9})/3$, and $\mathrm{LB}_{\mathrm{environ\&regulatory}} = (S_{Q_{10}} + S_{Q_{11}} + S_{Q_{12}} + S_{Q_{13}} + S_{Q_{14}} + S_{Q_{15}})/6$.

### 2.3.4. Multi-criteria scoring system (MCSS)

As the final stage, integration between individual scores and the corresponding variability factors is performed, as shown in Eq. (3). Each preliminary opportunity has one value as a total score and it is possible for all the preliminary opportunities to be compared and discriminated between

$$\mathrm{TS}^k = \sum_{i \in I} \gamma_i^k,$$
$$\forall k \in K,\ I = \{\text{technical, economic, environ\&regulatory}\} \quad (3)$$

In Eq. (3), $\mathrm{TS}^k$ means total score of the preliminary opportunity $k$ and $\gamma_{ik}$ indicates the newly obtained score of the opportunity $k$ for the criterion $i$. After estimation of total scores for all preliminary opportunities by using Eq. (3), it is possible to determine the most favourable solution (MFS) by Eq. (4)

$$\mathrm{MFS} = \max_k \{\mathrm{TS}^k\} \quad (4)$$

The profiles for all the preliminary opportunities are compared and the most favourable solution (MFS) selected as potential use. The remaining preliminary opportunities, however, will be retained as reserved use, for possible consideration in the future. Fig. 1 shows the overall procedure for the proposed assessment method. As seen in the figure, a list of preliminary opportunities are provided in the assessment method as input data, while MFS is selected for the potential uses and other preliminary opportunities are reserved for the future uses. Multi-criteria scoring system merges the scores and variability factors to produce a single total score for each preliminary opportunity, and lower bounds are utilised to discriminate the preliminary opportunities.

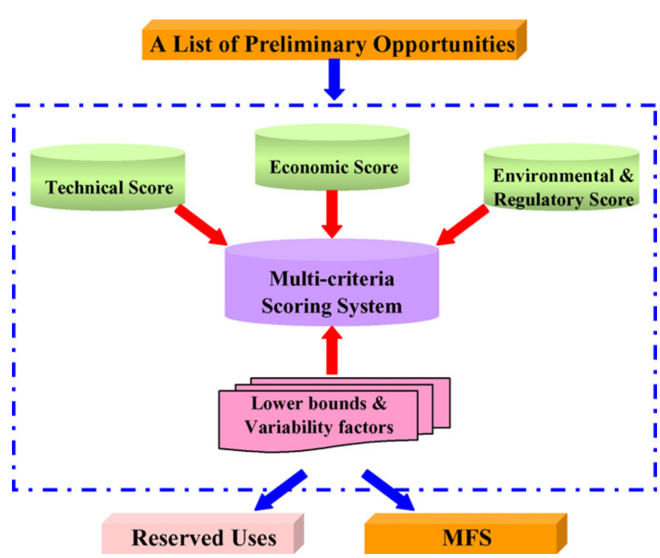


Fig. 1. A schematic diagram for multi-criteria scoring system.

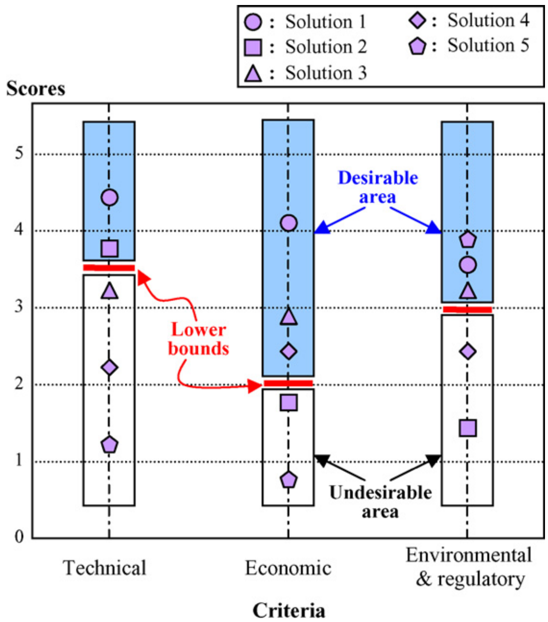


Fig. 2. An example of parallel coordinates approaches.

#### 2.3.5. *Graphical representation*

In this study, a parallel coordinate graph is introduced to illustrate the results of the assessment of reusability for a designated waste stream. In general, the aim of a parallel coordinate graph where a point in *m*-dimensional space is mapped onto a point in two-dimensional space is to represent complex data in a visual and more understandable style. For this reason, the parallel coordinate system is not affected by the increment of the number of criteria. Although three different criteria are taken into account in this study, the number of criteria is likely to be increased. For instance, the environmental and regulatory criterion may be separated as two different criteria. In addition, either social effect or public concern might be added as another criterion.

Fig. 2 shows an example of a parallel coordinate graph where five different preliminary opportunities obtained from ideas generation stage were mapped in two-dimensional space. In the figure, each preliminary opportunity is mapped depending on both a corresponding criterion and a given score. The lower bounds obtained from the CPQ are also shown in each criterion. It shows both desirable and undesirable areas, which are separated from the lower bounds of each criterion. Although the graphical representation has an advantage for making those results easier to understand, it is not straightforward to determine the prioritisation for the preliminary opportunities. This disadvantage can be overcome by obtaining a single total score for each preliminary opportunity addressed in the previous section.

## 3. Case study

### 3.1. *Industrial example 1*

This example describes the application of the method developed above to a waste stream produced by a manufacturer of fine chemicals. Fig. 3 shows the simplified process diagram for

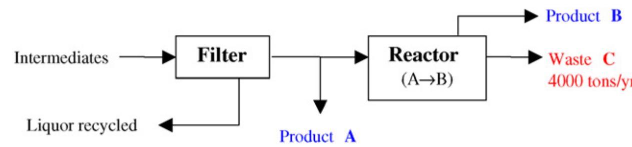


Fig. 3. A simplified process diagram for an industrial case study.

the production of products and waste. As seen in the figure, an intermediate processed from previous operations is filtered to produce product A, which is one of the major products of the company. The liquor from filtration is recycled to a previous operation. In the next unit operation, shown as reactor, product A is converted to product B, which is a second major product of the company, by heating to 160–180 °C. In this unit operation, about 4000 t of waste C are produced every year as a result physical processing rather than chemical processing. The company sends the waste to landfill at a cost of £80/t, resulting in a total disposal cost of £320,000 per year. The unit landfill cost (£80/t) includes the transport cost, landfill tax, labour cost and gate fee.

After analysis, it was identified that the waste consists of a combination of impurities (10.0 wt.%) together with product A (60.0 wt.%) and product B (30.0 wt.%). In this stage, the remaining relevant characteristics of the impurities were identified by laboratory analyses such as ICP for measuring metal components, TOC for quantity analysis of organic carbon. The data was compiled into a concise information pack which was used to support the generation of ideas for possible reuses of the waste.

An extensive survey of literature, consultation with experts and a brainstorming session involving the main parties generated a list of 8 preliminary opportunities that could be applied. The occurrence of preliminary opportunities is shown in Fig. 4 as a flowchart composed after the brainstorming session. Unlike a conventional flowchart, this flowchart must accommodate uncertainty as answers to specific questions may themselves be ‘maybe’ or ‘not sure’. Of course, these responses need to initiate after further investigations. All preliminary opportunities obtained from ideas generation were based on the production of product A, product B or product D. All three products can be produced from the waste by manipulating the major operating parameters like temperature, pressure, and the amounts of the key reactants. Four out of the eight preliminary opportunities related to the destinations of product A, while another three opportunities were for product B. The remaining opportunity was associated with the production of product D, which can be produced by combining the waste with water. Table 2 shows the applicability of the preliminary opportunities with respect to the production of products A, B and D.

The assessment for the eight preliminary opportunities was carried out according to the method addressed in the previous sections in order to identify the most suitable potential use for the waste. The questionnaire (CPQ) shown in Table 1 was used to develop an understanding of the companies priorities with respect to the three categories (technical, economic and environmental and regulatory). From the reply, the lower bounds for technical, economic, and environmental and regulatory criteria were estimated on the basis of Eq. (2) as 4.14, 3.33 and 3.92,

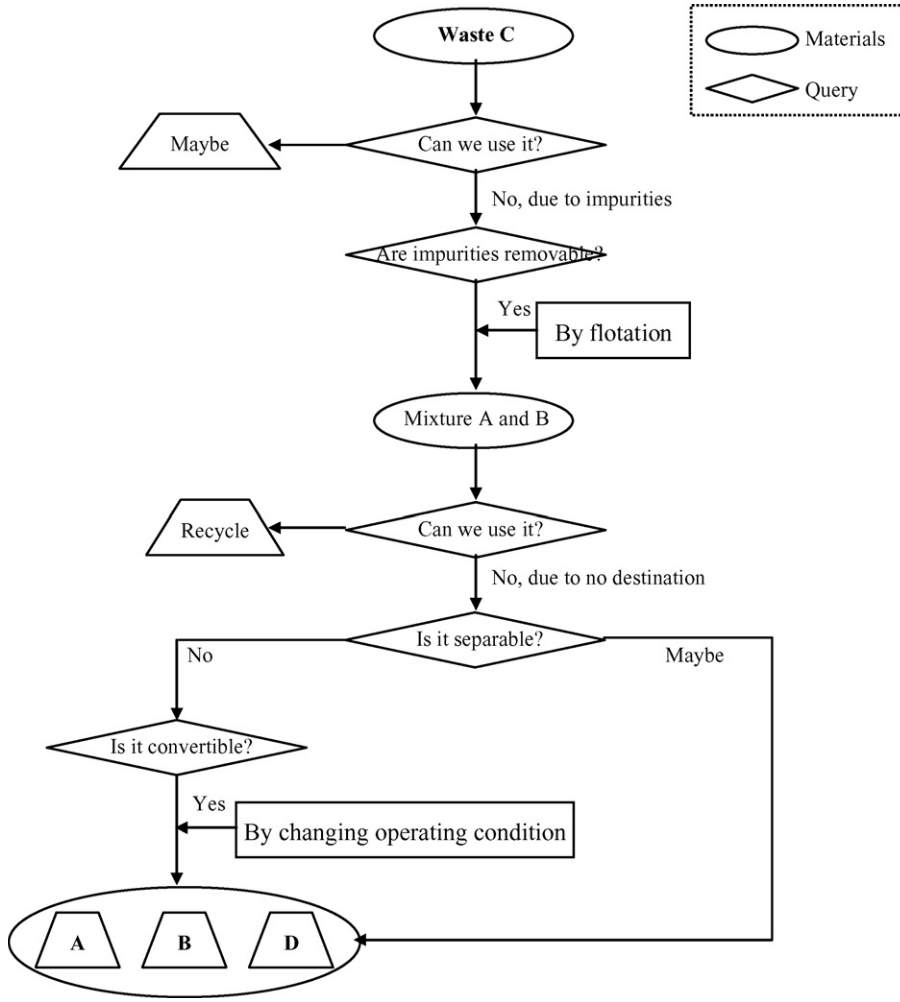


Fig. 4. Summary for the result of preliminary opportunities.

respectively. During this period, scores and variability factors of all preliminary opportunities for the three criteria were estimated by a panel of academic and industrial representatives. Table 3 shows the scores and variability factors for the eight preliminary opportunities. Although the scores after considering variability factors ($\gamma_i^k$) are not shown in Table 3, it can be readily calculated by Eq. (1).

All preliminary opportunities were mapped in a parallel coordinate graph shown in Fig. 5. In the graph, both scores with and

Table 2
Applicability of the preliminary opportunities

| Preliminary opportunities (*k*) | Aimed product | Application |
|---|---|---|
| 1 | Product A | Low grade general purpose |
| 2 | | Environmental treatment |
| 3 | | Use in metallurgical industry |
| 4 | | Use in mineral industry |
| 5 | Product B | Low grade general purpose |
| 6 | | Waste treatment |
| 7 | | High grade product |
| 8 | Product D | Animal feed |

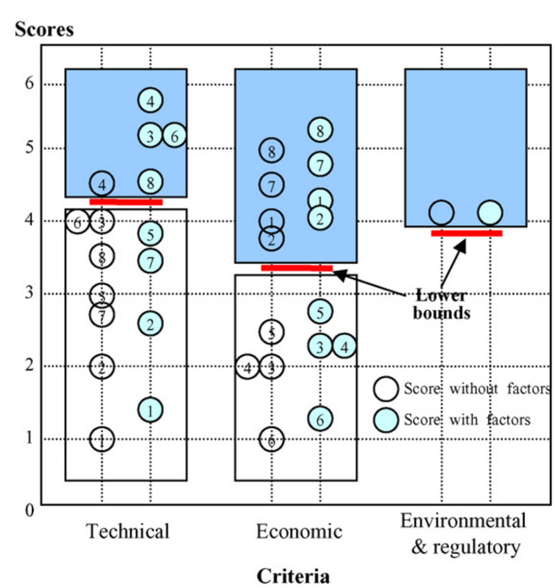


Fig. 5. Graphical analysis by the parallel coordinate graph.

Table 3
Scores and variability factors for the preliminary opportunities estimated

| Preliminary opportunities ($k$) | Technical criterion | | Economic criterion | | Environmental and regulatory criterion | | $TS^k$ |
|---|---|---|---|---|---|---|---|
| | $\delta^k$ | $w^k$ | $\delta^k$ | $w^k$ | $\delta^k$ | $w^k$ | |
| 1 | 1.0 | 0.3 | 4.0 | 0.1 | 4.0 | 0.0 | 9.70 |
| 2 | 2.0 | 0.3 | 3.9 | 0.1 | 4.0 | 0.0 | 10.89 |
| 3 | 4.0 | 0.3 | 2.0 | 0.1 | 4.0 | 0.0 | 11.40 |
| 4 | 4.5 | 0.3 | 2.0 | 0.1 | 4.0 | 0.0 | 12.05 |
| 5 | 3.0 | 0.3 | 2.5 | 0.1 | 4.0 | 0.0 | 10.65 |
| 6 | 4.0 | 0.3 | 1.0 | 0.1 | 4.0 | 0.0 | 10.30 |
| 7 | 2.8 | 0.3 | 4.5 | 0.1 | 4.0 | 0.0 | 12.59 |
| 8 | 3.5 | 0.3 | 5.0 | 0.1 | 4.0 | 0.0 | 14.05 |

Table 4
Scores, variability factors and lower bounds for example 2

| Preliminary opportunities ($k$) | Technical criterion | | Economic criterion | | Environmental and regulatory criterion | | $TS^k$ |
|---|---|---|---|---|---|---|---|
| | $\delta^k$ | $w^k$ | $\delta^k$ | $w^k$ | $\delta^k$ | $w^k$ | |
| 1 | 5.0 | 0.0 | 1.0 | 0.0 | 4.5 | 0.0 | 10.50 |
| 2 | 5.0 | 0.3 | 1.0 | 0.3 | 3.8 | 0.0 | 11.60 |
| 3 | 4.0 | 0.0 | 2.0 | 0.2 | 4.4 | 0.0 | 10.80 |
| 4 | 3.5 | 0.0 | 2.5 | 0.2 | 4.3 | 0.0 | 10.80 |
| 5 | 4.0 | 0.0 | 1.5 | 0.0 | 4.3 | 0.0 | 9.80 |
| 6 | 4.5 | 0.3 | 3.5 | 0.3 | 4.1 | 0.0 | 14.50 |
| 7 | 3.0 | 0.3 | 1.5 | 0.3 | 4.3 | 0.0 | 10.15 |
| 8 | 4.5 | 0.3 | 3.5 | 0.3 | 4.1 | 0.0 | 14.50 |
| 9 | 1.5 | 0.3 | 4.5 | 0.3 | 4.3 | 0.0 | 12.10 |
| 10 | 1.0 | 0.3 | 4.0 | 0.3 | 4.0 | 0.0 | 10.50 |
| Lower bounds | 3.14 | | 3.33 | | 3.67 | | |

without variability factors are illustrated. The highlighted circles with numbers are the scores with variability factors. As a result of the assessment, the 8th preliminary opportunity that is an idea for the production of product D from the waste was chosen on the basis of Eq. (4) as the potential use (i.e., MFS), while the remaining opportunities were held in reserve for future investigation.

### 3.2. Industrial example 2

The designated waste stream considered in this example is produced from a company, which manufactures cellophane films. The majority of this film is in the form of edge trim and is currently disposed of to landfill. The company expects that the cost of disposal to landfill is to increase significantly in the near future due to new restrictions. The cost of landfill is £40/t including transport fee, landfill tax and tipping charge. The total amount of waste produced is approximately 2700 t per year. Hence, total disposal cost of film waste is over £100,000 per year.

The proposed characterisation and ideas search procedure include a brainstorming session involving 12 academic and industrial representatives. As results of ideas generation, 10 different reuse opportunities, i.e. preliminary opportunities were identified. Table 4 shows the results of estimation for scores and variability factors according to the criteria, and it also shows total scores obtained from Eq. (3) and lower bounds of the criteria calculated from the CPQ responses. Consequently, the 6th and 8th preliminary opportunities were selected as the most favourable opportunities since both ideas had the same total score. The 6th preliminary opportunity is related to the conversion from complex carbon chains like cellulose to short chains of carbon, while the 8$^{th}$ opportunity is for biodegradation like composting.

## 4. Conclusions and discussion

In this study, a relatively simple and systematic approach to assess the reusability for wastes was proposed. As described in the earlier sections, various preliminary opportunities for the reuse of a waste could be obtained through ideas generation tools such as brainstorming, desk research and workshops or conferences. For the preliminary opportunities generated, three criteria, i.e. technical, economic, environmental and regulatory criteria were considered in order to identify advantages and disadvantages of each preliminary opportunity more efficiently. On the basis of each criterion, individual score and the corresponding variability factor for a preliminary opportunity were estimated by representatives from industry and academia. As a result, the total score for each preliminary opportunity was evaluated, and the preliminary opportunities could be differentiated between to determine the most favourable solution and reserved uses. The parallel coordinate graphic method was utilised to visualise the high-dimensional results. As shown in the case study, the proposed approach could readily handle the industrial examples, and the most favourable solution and the reserved uses could be obtained. As additional progresses, the host companies could find other disposal route for their wastes as results of their efforts to reduce the cost and the amount.

Consequently, the benefits of the proposed approach will be (i) improvement of profitability by transforming costly wastes into valuable products, (ii) enhancement of the company's environmental profile, and (iii) protection against current and/or future regulations. Nevertheless, it should be noted that a much more in-depth analysis and a full-scale feasibility study for the advantages of the most favourable solution selected should be carried out before the opportunity is implemented in full.

## Acknowledgements

The authors acknowledge the financial support of Northwest Regional Development Agency (NWDA) for Transformation of Waste to Products ($TW_2P$) project. The authors also acknowledge support provided by Environlink Northwest and Enviros Consulting Limited.

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