A review of the pre-assessment and assessment techniques used in waste minimisation audits

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Abstract

Waste minimisation is a useful tool for reducing raw material and utility consumption and consequently the generation of waste. A specific area, in which it has been successfully applied by industry with significant financial and environmental savings, is water minimisation. Recent years have seen the development of a large number of pre-assessment and assessment techniques for respectively identifying waste minimisation focus areas (opportunities) or options (solutions) during a waste minimisation audit. This paper critically reviews these techniques and assesses their relative merits. The pre-assessment techniques are analysed in terms of their ease and speed of implementation, whilst the usefulness and applications of the available general assessment techniques are considered.

Keywords: waste minimisation, wastewater, focus areas, opportunities, solutions

Introduction

What is waste minimisation?

Waste minimisation has been defined as the 'prevention and/or reduction in the generation of waste; the improvement in the quality of waste generated, including reduction of hazard; and the encouragement of reuse, recycling and recovery' (IWM, 1996). In South Africa and the UK, however, a more narrow definition is often used: waste minimisation refers to the reduction or elimination of the generation of waste at source (IWM, 1996; Barclay and Buckley, 2000). Waste minimisation thus considers raw materials, water and energy consumption; and the resultant solid, liquid and gaseous wastes produced (March Consulting Group, 1999). Hence waste minimisation is at the top of the waste management hierarchy (Fig. 1).

The overall aims of a waste minimisation programme are the maximisation of business efficiency and the reduction of the company's impact on the environment (March Consulting Group, 1999). Benefits to the companies include cost savings, environmental improvement, increased throughput, and risk and liability reduction. Cost savings are incurred through the reduction of effluent treatment and waste disposal costs, the improvement of product yield as well as the reduced requirement for raw materials and utilities (Envirowise, 1996a; Petek and Glavic, 1996; Barclay and Buckley, 2000; Barclay and Buckley, 2002). Environmental improvement is observed as a result of the reduction in the consumption of materials and natural resources. Hence improved compliance with environmental regulations and legislation result (March Consulting Group, 1999; Barclay and Buckley, 2000). Increased throughput in a company is due to **process intensification**, which leads to decreased capital expenditure (Envirowise, 1996a). Due to the minimisation of the waste from a process, the

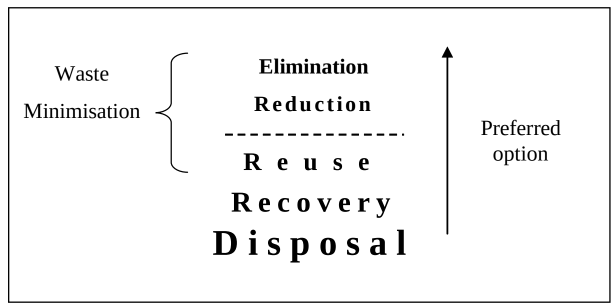

Figure 1
Waste management hierarchy (Phillips et al., 2002)

associated environmental risks and liabilities in the workplace and the natural environment are simultaneously reduced. There is thus a better understanding, control and management of present risks and future liabilities within a company (Envirowise, 1996a).

Why is waste minimisation important with regard to water?

A variety of drivers towards water and wastewater minimisation in industry have been identified. These include the following (Goldblatt et al., 1993; Rosain, 1993; Wang and Smith, 1993; Envirowise, 1996b; 1997):

- Reduced availability and increasing cost of fresh water
- Requirement for more stringent compliance with water discharge limits
- Increasing discharge costs
- 'Good neighbour' policy
- Avoidance of bottlenecks in industry where an increased volume of water is required and is not always available from the water company's piped distribution system.

In recent years, the responsibility of South Africa's companies to monitor waste continually and reduce the impact on their employ-

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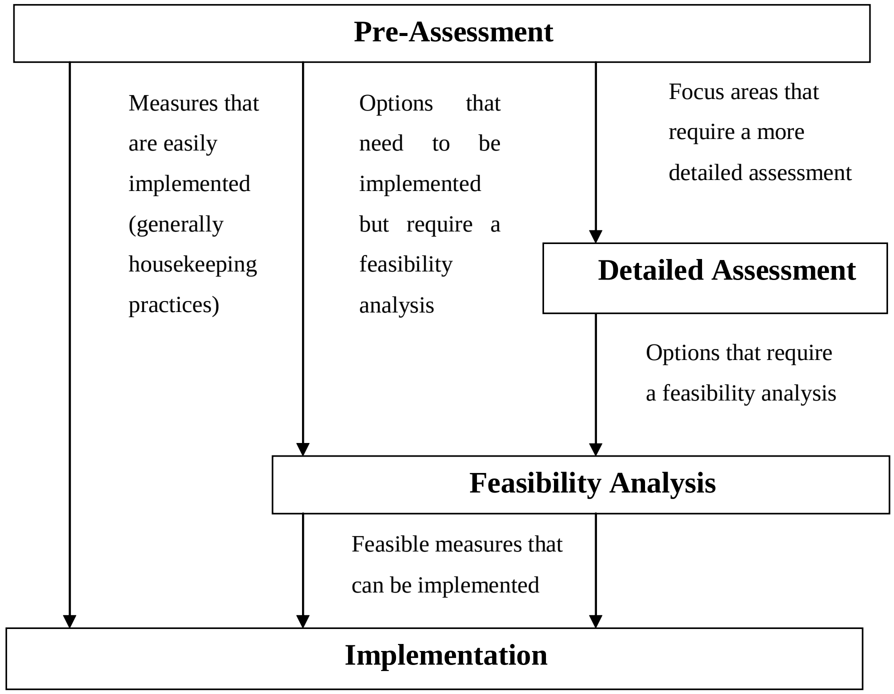

Figure 2
Schematic diagram for the determination of which waste minimisation options are suitable for implementation (Van Berkel and Kothuis (1993))

ees, neighbours and the environment has been emphasised through the constitution and national legislation (The National Water Act, 1998; The National Environmental Management Act, 1998). Specific limits on the quality of discharged wastewater are enforced through local bylaws (e.g. Msunduzi Municipality Industrial Effluent Bylaws, 1998). However, the stringency of compliance with bylaws limits appears to vary between municipalities in South Africa (Msunduzi Municipality Industrial Effluent Bylaws, 1998, Ethekwini Municipality Industrial Effluent Bylaws, 2002). The true cost of water is often underestimated by companies (Envirowise, 1996b, 1997) since it includes both the cost of the raw water and the cost of its treatment and disposal. Since companies effectively pay twice for water used, the scope for saving on water usage could be large when compared to other utilities or raw materials (Envirowise, 1996b). This is especially the case in Europe, where the cost of water is relatively high (Envirowise, 1996b), and will become more significant in South Africa as population growth and/or drought makes water resources scarcer. The minimisation of water use and wastage in industry is thus a particularly important area of waste minimisation, where both environmental and economic savings could be achieved.

An outline of the strategy for waste minimisation

To place the techniques reviewed in this paper into context, the waste minimisation strategy is briefly described. Implementation of any waste minimisation programme in a company involves several defined steps (EPA, 1992; March Consulting Group, 1999; Envirowise, 1998):

- Commitment to action and organisation of a project team
- Pre-assessment of the process
- Detailed assessment
- A feasibility analysis of selected options
- Implementation and monitoring the measures.

The latter steps are illustrated in Fig. 2. Obtaining the commitment of senior management in a company is essential, in that management is responsible for the allocation of human resources; access to confidential information from departments (for waste minimisation audits); and for the allotment of financial resources where necessary (EPA, 1988; Barclay and Buckley, 2000). The project team should include personnel from all levels of employment so that ideas from the shop floor to top management could be used. The project team should be led by the project champion (EPA, 1988; March Consulting Group, 1999).

The pre-assessment stage is the initial stage in conducting a waste minimisation audit. The goals of this stage are to identify focus areas (opportunities), to assess the scope for waste minimisation, to identify the exact sources and causes of wastes and emissions, as well as to prioritise the waste streams for action (Envirowise, 1996a; Barclay and Buckley, 2000; Kothuis, 2002).

The assessment phase in a waste minimisation audit refers to detailed research into focus areas, highlighted in the pre-assessment stage, as having potential for waste minimisation. It involves the collection of further data and its subsequent analysis (EPA, 1988; Barclay and Buckley, 2000).

Through the pre-assessment and assessment stages, options (solutions) to waste minimisation opportunities are generated. These options can involve improved housekeeping practices, raw material changes, internal recycling, product changes and technological changes, including process changes (Barclay et al., 2000; Barclay and Buckley, 2000). Simple measures that do not require a large capital investment could be implemented immediately. These include material substitutions if there are no major impacts on production rate or product quality and if no equipment changes are required. Those options that are found to require a more substantial initial capital investment necessitate a feasibility analysis. The feasibility analysis has three components: technical, economic and environmental evaluations. An option needs to be deemed feasible in all three areas prior to implementation in a company (EPA, 1988; Barclay and Buckley, 2000). Once measures have been implemented in the company, control systems can be set up as a quality control measure to monitor performance (EPA, 1988).

The past decade has seen the development of numerous tech-

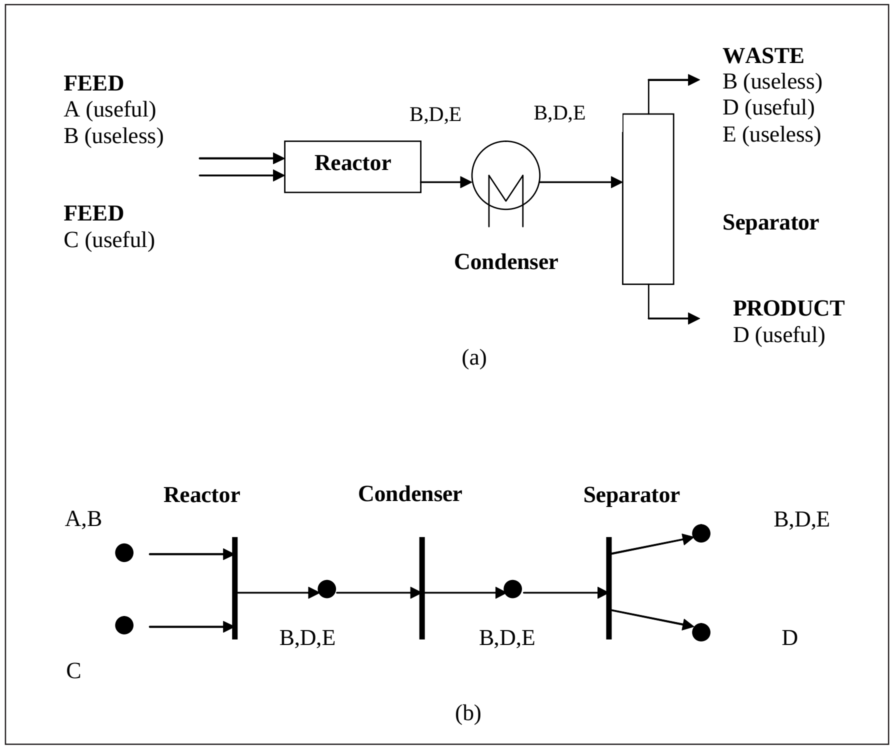

Figure 3
(a) A schematic drawing of a separation process.
(b) P-graph model for the process in (a) (Halim and Srinivasan, 2002a)

niques to identify waste minimisation opportunities in the pre-assessment and assessment stages of a waste minimisation audit (EPA, 1988; March Consulting Group, 1999; Barclay and Buckley, 2000). Knowledge of effective technique(s) is crucial to any waste minimisation audit. To date, no comparative study has been performed to evaluate the various techniques. This paper aims to review the available pre-assessment and assessment techniques and to critically assess their relative merits.

The pre-assessment stage

The pre-assessment techniques used in identifying waste minimisation opportunities can be classified further as qualitative or quantitative methods.

Qualitative methods

Qualitative methods prioritise the waste streams for waste minimisation without analysis of the relative flow rates or concentrations of the components in the waste stream. These methods can be used independently as a qualitative analysis tool, or as a pre-requisite for quantitative analysis.

P-graph method

The P-graph method of Halim and Srinivasan (2002a) focuses on process wastes. Each material constituent of a stream is classified as useful or useless by referencing it to its function in the overall process (Fig. 3 (a)). Raw materials, solvents and cooling agents are examples of useful components, whilst material impurities and waste by-products are classified as useless. A material should be considered useless only if it serves no function in the process.

The streams and units that contribute to the presence of useful and useless material in each waste stream are then represented using a process graph (P-graph) (Fig. 3(b)). In the P-graph, a material stream is represented by a circle, a unit operation by a bar and connections between the material streams and unit operations by directed arrows.

The P-graph facilitates the identification of opportunities for the separation of the useful material from the waste stream, as well as the reduction of useless materials at source. It is a simple method that does not require the composition of each stream to be known, merely its components.

Hierarchal decision procedure

Douglas (1992) proposed a hierarchical decision procedure for identifying potential pollution problems early in the development stage of a design. His method consists of eight levels. The first seven include analysis of the type of pollution prevention problem, the input-output structure of a flow sheet, the recycle structure of the flow sheet, specification of the separation system, energy integration, evaluation of alternative designs and the creation of a flow sheet at each level to identify the waste being produced. The last level is the economic analysis, which generally follows the development of various flow sheet designs. This level is included to terminate poor design projects early. Hence the hierarchal decision procedure includes aspects of a feasibility analysis and thus is not purely a pre-assessment technique. The expense of major alterations to an existing plant's design may preclude use of this method for existing plants, although it can be used on a smaller scale for additions to plants.

Mizsey and Fonyó (1995) combined the hierarchal decision procedure with an onion diagram approach to yield a systematic procedure for waste minimisation in process industries. The onion diagram consists of five levels, representative of successive unit operations in a plant (i.e. the reactor in the centre). Each level, which generates specific waste materials and emissions, is analysed prior to migration to the next level. The process continues until the outermost layer is reached. Through application of this method, all process wastes and their sources should be identified. Although this method facilitates identification and prioritisation of waste minimisation focus areas, it does not generate specific options for the waste minimisation problem. These will need to be established

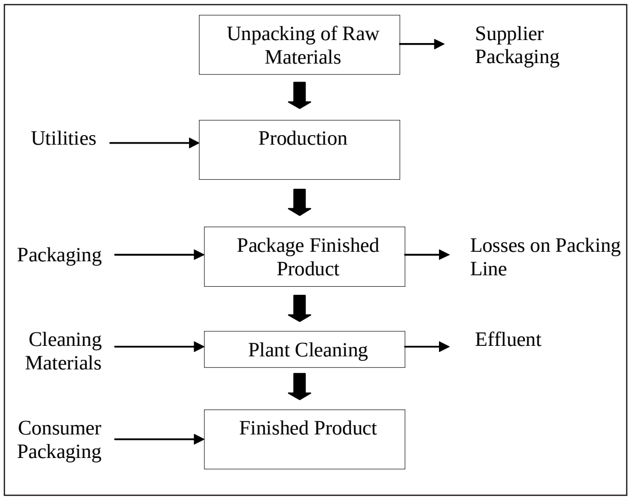

Figure 4
A site process flow diagram for a manufacturing company (Envirowise, 1996a)

through a more detailed assessment and/or collective brainstorming with personnel from all levels of employment within the company (Envirowise 1996a; March Consulting Group, 1999; Barclay and Buckley, 2000).

Quantitative methods

These pre-assessment techniques use quantitative analysis that serves to establish the relative amount of one or more species or flow rates in numerical terms. The methods below describe various approaches to identifying waste minimisation focus areas (opportunities).

Process flow diagrams

Process flow diagrams show, in pictorial form, how materials flow through a process operation (EPA, 1992; Envirowise, 1996a; March Consulting Group, 1999; Barclay and Buckley, 2000). Mapping of the process explains where raw materials, ancillary materials (materials which are integral to the process but do not form part of the final product), consumables and utilities (water and energy) are used, and where known wastes (gas/solid/liquid) are generated.

A process flow diagram is generally constructed for the site as a whole, and then for each process in turn. A general site process flow diagram for a manufacturing company is shown in Fig. 4. Flow rate, composition and cost data are then collected for each of the input and output streams (Envirowise, 1996a; March Consulting Group, 1999; Barclay, 2000) and added to the diagram. Once sources of reliable existing data have been established, the outstanding data can be determined through measurement (Envirowise, 1996a; Barclay, 2000).

Process flow diagrams are generally used in the initial stages of a waste minimisation audit as they form the basis of various other techniques, including scoping audits and calculation of the true cost of waste. The degree of accuracy with which waste minimisation opportunities can be identified in a company using this technique will depend upon the amount of detail and depth on the diagram. The diagrams can be used as a tool for the identification of broad focus areas for improvement such as whole processes or departments or alternatively for marking specific areas for optimisation, such as process streams or utility use (Envirowise, 1996a).

TABLE 1
Scope for savings (Environment Agency, 1988)

Utility	Scope for saving
Raw materials	1 to 5%
Packaging	10 to 90%
Ancillary materials	5 to 20%
Consumables	10 to 30%
Electricity	5 to 20%
Heat for process and space heating	10 to 30%
Water	20 to 80%
Effluent	20 to 80%
Solid waste	10 to 50%

Scoping audits

A scoping audit involves the collection of annual cost data and the quantity of material used for all input streams, including utilities, and all waste streams (Barclay and Buckley, 2000). The waste streams include solid, liquid (effluent), hazardous and general waste streams; any discharges to stormwater drains and gaseous emissions. General guidelines exist as to the savings that could be expected in all areas through the implementation of a waste minimisation programme (Table 1) (Environment Agency, 1988; Barclay and Buckley, 2000).

In each category in Table 1, savings are calculated through multiplication of the annual cost by the minimum and maximum scope for saving percentage. The respective values generated give the minimum and maximum savings expected for that area. From these values, areas for improvement can be identified and ranked according to the maximum scope to save. This gives an indication of potentially important focus areas for waste minimisation (Environment Agency, 1988; Barclay and Buckley, 2000). Although this method appears to rank streams according to their cost alone, it also accounts for the streams' toxicity, liability and environmental impact; since the greater these factors, the greater the stream cost.

It should be noted that the 'scope for saving' percentages in Table 1 are those calculated for a range of U.K. industries, based on the results of previous waste minimisation projects (Environment Agency, 1988). The applicability of these percentages to South African industries still needs to be ascertained.

DuPont's method

DuPont (Mulholland and Dyer, 1999) developed a waste minimisation methodology for the identification of new process improvement opportunities that reduce/minimise waste. Their methodology is based on the following principles:

- The volumetric flow of an air or gaseous waste stream and the volumetric flow and organic loading of a wastewater stream determine the required end-of-pipe treatment and operating cost.
- The same gaseous and water flows influence manufacturing plant investment and manufacturing costs.
- End-of-pipe treatment is required only because the streams contain components that have to be abated or removed.

Mulholland and Dyer (2001) used these principles to develop a two-pronged approach for process analysis and waste minimisation. The first phase in identifying waste minimisation opportunities is the waste stream analysis of a company, involving four steps:

- The 1st step is the listing of all components in the waste stream as well as its key parameters. For example, this could include water, inorganic compounds and the pH.
- The 2nd step involves the identification of the components triggering concern. For example, the concentration of the components present in the stream could be compared to those accepted by the local wastewater treatment plant. The sources of these components should then be determined and waste minimisation options generated for their removal or reduction.
- Step 3 is the identification of the highest volume materials (such as diluents, carrier gases or water). Their source in the plant should be determined and, again, waste minimisation options generated.
- Step 4 involves continuous assessment. If the components in Steps 2 and 3 have been successfully minimised, the next set of components of concern is considered and options generated for their elimination or reduction.

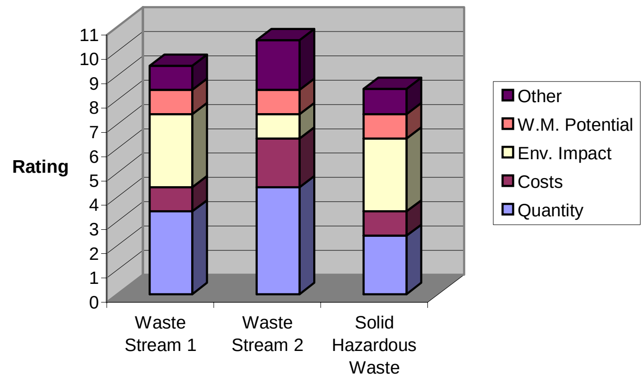

Figure 5
Bar graph showing the ranking of waste streams for waste minimisation using the waste index system of Kothuis (2002)

The second phase of Mulholland and Dyer's (2001) method involves process analysis. For a plant to operate at zero waste (i.e. all raw materials converted into products with no waste of utilities) either the raw materials, intermediates or products must serve the same function as those input streams which later become waste, or the process must be modified to eliminate the latter streams. The process analysis phase also consists of four steps:

- In the 1st step, all raw materials, including intermediates, are listed (List 1).
- Step 2 requires the listing of all other materials in the process that do not form saleable products (List 2). 'List 2' might include materials like by-products, solvents or water.
- The 3rd step involves finding ways of using the materials on List 1 instead of the compounds on List 2, or finding ways to modify the process so that the compounds on List 2 are made redundant.
- Step 4 entails looking exclusively at the formation of by-products and asking how the chemistry of the plant could be modified to minimise or eliminate the by-products.

The combined use of the waste stream and process analyses should result in a technology plan for driving the process towards minimum waste.

The waste index method

A number of workers used a waste index method to prioritise waste streams for a more detailed waste minimisation analysis. Each of these waste index methods uses a set of selection criteria for screening the waste streams.

Halim and Srinivasan (2002b) have suggested applying criteria such as the quantity and frequency of the waste stream, the cost of managing the existing waste stream, possible regulatory impacts in the future, safety and health risks to the employees and public, ease and cost with which waste minimisation alternatives could be implemented and the demonstrated effectiveness of the option. The last two criteria incorporate aspects of a feasibility analysis, thus combining pre-assessment of a process with economic and technical evaluations of any proposed options. It is, however, unlikely that waste minimisation options are known a priori when this method is used to identify important streams for waste minimisation.

Halim and Srinivasan (2002b) recommended that companies using this method assign each criterion a weight. Each criterion's index value for a particular waste stream is then calculated through multiplication of the rank (score) of the waste stream by the criterion's weight. The waste index value for each waste stream is calculated by the addition of all the criteria's index values. A criterion considered to be more important to a company would thus affect the index more than a lesser criterion. This waste index thus provides a general methodology, as it specifies neither the ranking nor weighting system to be used. It is designed to allow the important waste streams to be identified, based on their high index values, and hence to flag those streams that require further, more detailed analysis. To flag the important waste streams for a more detailed assessment, the weights of the feasibility criteria would need to be set to zero.

Kothuis (2002) suggested that the quantity, cost, environmental impact, waste minimisation potential and other aspects (e.g. risk, legal liability, occupational health, image) associated with the waste stream be used as criteria in prioritising waste streams for waste minimisation. He suggested ranking each of these criteria from 0 to 5 depending on the nature of the waste. This differs from the method of Halim and Srinivasan (2002b) in that specific criterion ranking values are given and then totalled for each waste stream. Kothuis (2002) recommended the plotting of a stacked bar graph to illustrate the results (Fig. 5). The stacked bar graph shows the contribution of each criterion to the overall waste stream value. A decision can then be made on what stream to prioritise for waste minimisation and which criterion of the stream should be addressed first.

Hawkey (1992) also developed a weighted index system to rank waste minimisation options. Suggested criteria include the amount, cost, toxicity, short-term liability, long-term liability, good management practice and emissions of the waste being considered. The amount (V) of waste is defined as the weight of the waste produced, whereas the cost (C) involves all the costs associated with the production and treatment of the waste. The toxicity factor (T) takes into account the type, number and concentration of the toxic constituents of the waste. The short-term liability (ST) looks at the potential risks associated with the transportation of the waste. On the basis of the chosen disposal procedure, the long-term liability (LT) attempts to quantify the life-long responsibility of the producer for the waste. The good management practice variable (GMP) assesses where the current waste treatment fits into the waste management hierarchy (Fig. 1). The emissions factor (E) takes into account the amount of material lost by evaporation as well as the cost required to replace the material. Since any emission is undesirable, association with its make-up value allows comparison between various waste streams.

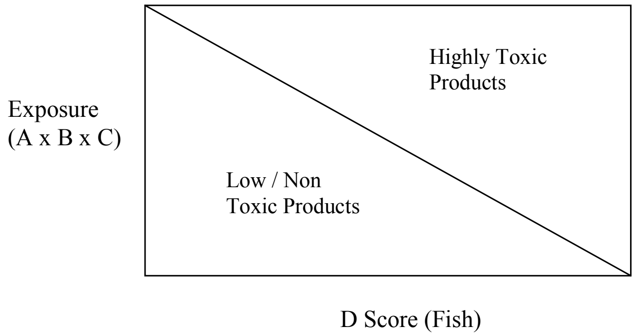

Figure 6
Corresponding co-ordinate system for a textile company in South Africa (Binda et al., 2002)

Waste stream data for each criterion are categorised into subgroups of the same order of magnitude. For example, if the cost of all waste streams per year ranges from R10 000 to R80 000, this variable can be divided into seven subgroups each of R10 000. Each subgroup can be assigned a whole number value from 1 to 7. The variables ST, LT and GMP are then combined into one total liability value (L); it is merely the sum of the integers that have been assigned to the waste for each of the three variables. Eq. (1) gives the appropriate weights to environmental, employee, business, regulatory and health concerns:

$$\text{Rank} = (L + E)[(CV) + T] \qquad (1)$$

Once calculated, the rank of a waste stream can be used to prioritise the waste streams for waste minimisation efforts. As with Kothuis's (2002) method, the importance and weight of each criterion in Hawkey's (1992) method is pre-determined (Eq. (1)).

The South African textile industry uses a score system (Binda et al., 2002) to monitor their pollution potential based on the characteristics of dyes and chemicals used. The environmental impact of all the chemicals and dyes are based on four criteria: the amount of chemical in excess (A), biodegradation (B), bioaccumulation (C) and toxicity (D). Each criterion is given a score of between one and four, with four indicating the most damaging chemical. Data required for this ranking is obtained from the material safety data sheet of the chemical or dye, the amount of chemical used, and the annual wastewater volume produced. An exposure score is calculated as the product of the scores of the criteria, A, B and C (A x B x C). The exposure score is plotted against the toxicity score (in fish) (D) for all the chemicals used by the company. On this graph, a diagonal line divides chemicals of high and low toxicity. A typical graph of this nature is shown in Fig. 6.

This system allows comparison between the chemicals and dyes used by a company and identifies the highly toxic chemicals or dyes that would form the focus areas of a waste minimisation programme. Although this score system was developed to identify environmentally harmful chemicals and dyes, a shortcoming is that it ignores a number of factors (waste minimisation potential, cost of the stream and liability) that are also important in identifying focus areas for waste minimisation. It is thus not a stand-alone system and should be used in conjunction with another pre-assessment method.

Calculation of the true cost of waste

Companies often underestimate the true cost of waste, since disposal cost only is considered. However, both the direct and indirect costs have to be taken into account when calculating the true cost of waste (Envirowise 1995; 1996a; March Consulting Group, 1999; Phillips et al., 2002). Indirect costs include unconverted raw materials in the waste stream, handling and processing costs (utility and transportation costs as well as employees' time), management and monitoring costs, lost revenue due to reduced capacity, potential liabilities and the cost of any required segregation of waste (Envirowise, 1996a; Barclay and Buckley, 2000; Phillips et al., 2002). It is estimated that the true cost of waste is 5 to 20 times that of the disposal cost (Phillips et al., 2002).

Calculation of the true cost of waste for each waste stream in a process allows the streams to be prioritised for a more detailed waste minimisation assessment. This method ranks the streams according to their cost; however, the quantity, environmental impact and liability of each stream are reflected in their true cost.

Benchmarking

Benchmarking involves the setting of a desirable consumption level for an operation, process or individual piece of equipment (Barclay and Buckley, 2000). A benchmark, also called a key performance indicator (KPI), is an indication of the efficiency of a process (March Consulting Group, 1999). Benchmarking further allows comparison of a company's performance with similar companies on a global scale. External benchmarking is often co-ordinated through industry associations.

The South African metal finishing industry uses a Cleaner Production Benchmarking Tool (CPBT) (Dahl, 2000; Telukdarie et al; 2002) to assist in identifying waste minimisation opportunities. The Cleaner Production Tool uses eight criteria to fully describe the cleaner production profile in a metal-plating facility. The criteria specified are occupational health and safety, the operational practice of the wastewater treatment plant, the chemical savings of the wastewater treatment plant, the waste minimisation potential of the process, the state of the rinsing system, the required water savings, the maintenance of the process baths and the consumption of process chemicals. The latter three criteria are scored by benchmarking them against built-in goal values representing best available technology (BAT). Hence the company can compare its performance in cleaner production to the best world-market performance. The remaining criteria are scored using a waste index scoring system. The resultant scores range between 1 and 100, with 0 to 20 considered unacceptable, 20 to 50 considered poor, 50 to 80 fair, and 80 to 100 good. The criteria in a metal finishing plant with the lowest overall scores would be identified as focus areas for waste minimisation programmes.

Sustainability auditing

Sustainability auditing involves an examination of the full life-cycle consequences of products and services on the natural environment as well as on regional, national and global economies, ecosystems and prospects. Sustainability auditing is thus an environmental management tool that considers life-cycle costs and seeks to assess alternative products and services (Nitkin and Brooks, 1998).

Sustainability auditing is developed on particular conceptual frameworks. These involve the identification of key issues within an organisation, the development of sustainable development targets and indicators, and the routine measurement of the progress to achieve the targets. A conceptual approach is the sustainable development records (SDR) approach (Daly, 1977; McCartney, 2003). The SDR model looks at the resource base of a company, its operation and the service it provides. The operational aspect of this model is gauged through calculation of what is termed a 'thrift indicator'. This indicator ties in closely with waste minimisation. It is calculated as follows:

$$\text{Thrift} = \frac{\text{a measure of the size of the operation}}{\text{a measure of the size of the input of resource}} \quad (2)$$

The size of the input of a given resource can be measured in terms of raw materials consumed, labour, and surface area for the operation or utilities and waste generated. The units of the ratio depend upon the aspects of the company being considered and can be unique for a particular company . The thrift ratio, once calculated, allows comparison of operating efficiency in the company (before and after the implementation of waste minimisation measures) and between companies in the same sector (benchmarking). Sustainability auditing is thus a broad subject of which only one aspect is directly applicable to waste minimisation.

The assessment stage

The detailed data collection and analysis performed during the assessment stage are often project-specific. For example, if it has been ascertained that a raw material change needs to be made, laboratory tests will need to be conducted on the suitability of specific alternative raw materials. However, three general techniques have been used to identify waste minimisation opportunities and options during the assessment stage: mass and energy balances, water pinch analysis, and monitoring and targeting graphs.

Mass and energy balances

Any material or energy entering a process as an input must come out of the process as an output, in one form or another (Envirowise, 1996a; Felder and Rosseau, 1999; Zbontar and Glavic, 2000). This is called the mass/energy balance. The general mass balance equation is represented below:

$$\text{Input} + \text{Generation} - \text{Output} - \text{Consumption} = \text{Accumulation} \quad (3)$$

This mass balance equation can be simplified in three situations: where the balance is for total mass, the generation and consumption terms become zero; where the balance is being used for non-reactive species, the generation and consumption terms become zero; and lastly, where the system is operating at steady-state conditions, the accumulation in material is zero (Felder and Rousseau, 1999).

A primary use of mass balance equations is that they allow parts of the process to be identified where raw materials are converted into waste (effluent, solid waste or emissions) and not into useful product (Barclay and Buckley, 2000). Losses from the site are categorised as either captured or uncaptured losses. Examples of uncaptured losses include emissions (to the atmosphere) or leaks and spills, whereas captured losses are quantifiable, such as solid waste (March Consulting Group, 1999). Identification of these losses allows waste minimisation opportunities to be identified. Mass balance calculations should account for stock gains and losses. Hence a period between two successive stock-takes is recommended for the calculation (Envirowise, 2001).

The mass balance generated is not a precise representation of the company's activities; it is merely a representation of the material balance (Barclay and Buckley, 2000). This lack of precision is due to several factors (EPA, 1992) since:

- Most processes have numerous process streams, many of which affect environmental media.
- The exact composition of many streams is unknown and cannot be easily analysed.
- Phase changes can occur within a process, thus requiring multimedia analysis and correlation.
- Plant operations or product mix change frequently so that material flows cannot be easily characterised by a single balance diagram.
- Many sites lack the historical data required to characterise all of the process streams.

Despite their limitations, material balances are essential to organise data, identify gaps, and estimate missing information, to help calculate concentrations of waste constituents where quantitative composition data are limited, and reveal data collection problems where 'mass in' fails to equal 'mass out' (EPA, 1992). Mass balance techniques thus provide a means of keeping a process in control; they serve to act as an indicator of the process's performance; and highlight streams that would benefit from waste minimisation analysis.

The energy balance is a further simplification of Eq. (3). Since energy can neither be created nor destroyed, the generation and consumption terms are eliminated yielding the energy balance equation (Felder and Rosseau, 1999):

$$\text{Accumulation} = \text{Input} - \text{Output} \quad (4)$$

Energy balances in industry are useful in that they allow calculation of the energy efficiencies of equipment such as boilers, compressors and refrigeration systems. The calculation of such efficiencies facilitates the prioritisation of unit operations for action. Barclay and Buckley (2000) have reviewed these energy efficiency calculations in detail.

Zbontar and Glavic (2000) have used the principles of mass and energy balances to minimise the quantity of wastewater and cooling water or condensate discharged, and consequently the freshwater consumption of a company. They propose that the wastewater quantity can be reduced by either reuse (used directly in other operations) or regeneration-reuse (the refining of the wastewater prior to use elsewhere in the operation or process). Baseline information on plant water usage and wastewater generation is obtained before constructing a water flow diagram with inflow and outflow rates, temperature, pH and pollutant concentration. The collected flow sheets are evaluated for possible connections of the outflows from a particular process for use in the same or other processes, taking into account the possibility of regenerating the wastewater (e.g. the reuse of cooling water after it has been allowed to return to the required temperature in a storage tank). The main factors taken into account at this stage are safety, temperature and pollutant concentration, distance between the individual processes or units and corrosiveness of the medium. Once possible connections have been determined between water outflows and water consumers, the investment required, savings for the changes, and eventual additional costs are estimated.

Water pinch analysis

Water pinch analysis is a derivative of pinch analysis, a method used to optimise heat exchanger networks and the subsequent provision of the minimum consumption of hot and cold utilities in a process. Pinch analysis utilises mass and energy balances for the analysis of the process temperature levels and calculates the

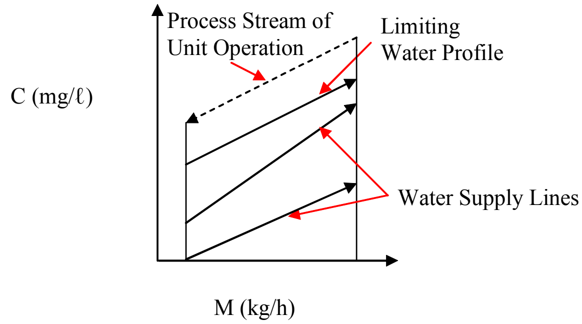

Figure 7
A water supply line graph of contaminant concentration (C) as a function of the mass of contaminant transferred (M) showing how any water supply line below the limiting water profile will satisfy the unit operations requirements (Wang and Smith, 1993).

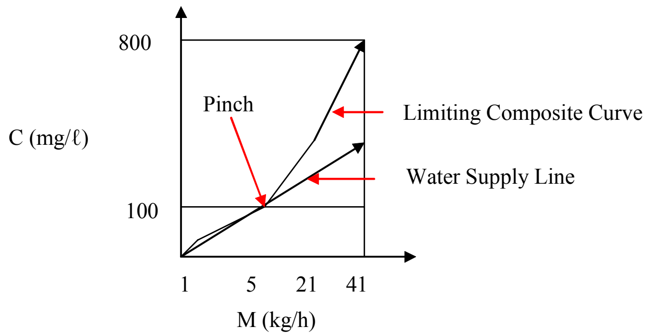

Figure 8
A water supply line graph showing the 'pinch' for the determination of the minimum water flow rate (Wang and Smith, 1993)

maximum exchange of heat flow within the process at minimum investment costs (Petek and Glavic, 1996). Wang and Smith (1993) have adapted the pinch analysis approach and applied it to wastewater minimisation. Water pinch analysis allows the targeting of minimum water flow rates in mass-transfer processes that use water (e.g. desalinisation, steam stripping, washing operations).

Wang and Smith's (1993) conceptual approach to water pinch analysis makes use of a graph of contaminant (species transferred) concentration (C in mg/ℓ) as a function of the mass of contaminant transferred (M in kg/h). For a given unit operation, the inlet and outlet contaminant concentrations and M can be plotted for the process stream (Fig. 7). Maximum possible inlet and outlet contaminant concentrations can then be determined for the water stream, which is contacted with the process stream. To avoid settling out of solid material these maximum concentrations are dependent on factors such as the minimum mass transfer driving forces, maximum solubility, the need to avoid precipitation of material from the aqueous solution, fouling of equipment, corrosion limitations and the minimum flow rate requirements (Wang and Smith, 1993). The line defined by these maximum concentrations is termed the limiting water profile (Fig. 7). Water supply lines can be plotted on the graph. Any water supply line below the limiting water profile on the graph will satisfy the operation's requirements (Fig. 7). For each unit operation in a process, the water flow rate is minimised through the use of freshwater (with a contaminant concentration of zero) and the specification of the maximum possible outlet concentration (Wang and Smith, 1993).

To minimise the water flow rate for the process as a whole, the water-using operations have to be analysed overall. For this, a limiting composite curve is constructed in which the inlet and outlet concentrations of the water streams in all the processes define concentration intervals. Within each interval, the rate of mass transfer is constant. The limiting composite curve for the overall process is obtained by combining operations within defined concentration intervals. Hence it represents how the total system would behave if it were a single water-using process. The minimum freshwater requirement is determined by constructing a water supply line tangent to this curve (Fig. 8). A pinch point occurs where the supply line touches the limiting composite curve. Here, the mass transfer driving force reaches a minimum. Wang and Smith (1993) have extended this method to consider multiple contaminants and the reuse and recycling of water with the regeneration of the water stream.

The analyses involved with water pinch analysis can be carried out using Water Software (WATER, 2000) (Thevendiraraj et al., 2003). This software developed a solution to the defined problem using mathematical programming based on the water pinch technology principles (Thevendiraraj et al., 2003).

Monitoring and targeting graphs

Monitoring and targeting involves the measurement of the consumption of raw materials and utilities (such as water and energy) as a function of a process variable and is a useful technique for determining waste minimisation opportunities where there is a variable target, such as energy consumption (March Consulting Group, 1999; Barclay and Buckley, 2000). Further steps involved in monitoring and targeting include determination of the performance levels of a company, setting obtainable targets or goals for the consumption of a particular resource, and ongoing monitoring and feedback of progress made (Phillips et al., 2002).

Monitoring and targeting analysis is usually achieved through the use of specialised monitoring and targeting software (Cheeseman and Phillips, 2001). A number of graphical representations have been developed for monitoring and targeting results (Envirowise, 1996a; March Consulting Group, 1999; Barclay and Buckley, 2000). Commonly used graphical representations include trend graphs, XY scatter plots, variance graphs and cusum plots.

Trend graphs

A trend graph (Fig. 9) shows the actual material consumption over a period of time. Comparison between time periods shows seasonal variations in the raw material and utility consumption (Envirowise, 1996a; March Consulting Group, 1999; Barclay and Buckley, 2000). A shortcoming of this plot, however, is that it shows no measure of performance; it does not take into account fluctuations in the consumption of resources due to variations in production levels (Barclay and Buckley, 2000).

Target consumption can also be included below the actual production on the trend graph. The target is the desired/expected consumption for a process (March Consulting Group, 1999). Waste minimisation opportunities are identified through the process of attaining this target.

XY scatter plots

These plots allow comparison of the raw material and utility consumption to a relevant production variable (i.e. performance). For example, the consumption of water can be plotted as a function of the mass of product manufactured over the same time period (Fig. 10) (Envirowise, 1996a; Barclay and Buckley, 2000).

A 'best fit' linear regression can be used to highlight several features of the process (Envirowise, 1996a; Barclay and Buckley, 2000):

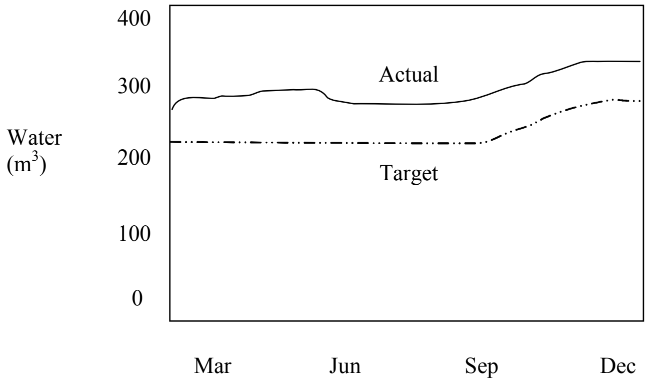

Figure 9
Trend graph showing variations in monthly water consumption (March Consulting Group, 1999)

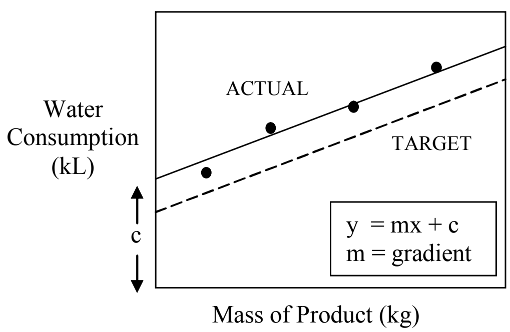

Figure 10
Scatter plot graph of consumption as a function of production (Envirowise, 1996a; March Consulting Group, 1999).

- The base load (the amount consumed at zero production) of the process is given by the y-intercept (c).
- The running efficiency of the plant is given by the slope (m) of the line.
- The spread of points indicates how tightly the process is controlled .

The values of c and m would ideally be minimised through the course of a waste minimisation programme (i.e. the base-load of a process would be reduced and the process efficiency would increase). Determining the reasons for the scatter of points and the large magnitude of the y-intercept and slope further leads to the identification of waste minimisation opportunities (Envirowise, 1996a).

A target can be set for future production to improve the efficiency of the process. This target is included in the XY scatter plot (Fig. 10) (Barclay and Buckley, 2002) and is representative of the desired consumption of the resource related to production. The practicality of this target should be verified through the use of a mass balance. Setting a consumption target allows monitoring and targeting to be used as a management-lead approach (March Consulting Group, 1999).

Variance graphs

In a variance graph, the variance is calculated as the difference between the actual consumption and the target consumption (March Consulting Group, 1999). This graph shows changes in performance (Fig. 11).

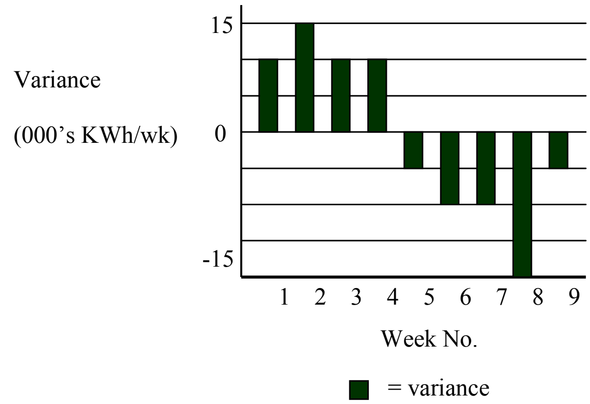

Figure 11
Variance graph showing variance as a function of time (March Consulting Group, 1999)

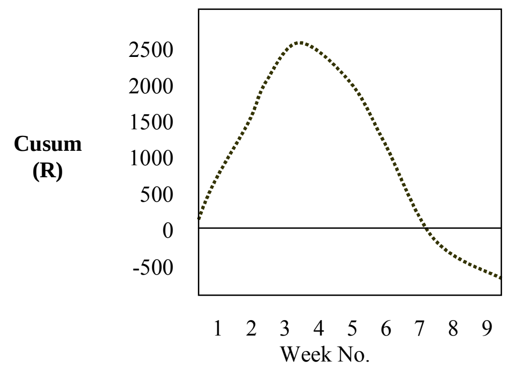

Figure 12
Cusum plot showing rand spent on a particular consumable over a production period (Barclay and Buckley, 2000; March Consulting Group, 1999)

The graphical representation thus illustrates when a unit operation in a plant exceeds the desired consumption (indicated by positive variance values on the graph), and serves to highlight the need for waste minimisation options for that unit operation.

Cusum Plots

Another way to show variance from a target is a cusum plot (Barclay and Buckley, 2000; March Consulting Group, 1999). The cumulative sum is calculated by adding variances over the time period analysed and has proven a useful method of plotting what is happening on a plant (Fig. 12).

This type of graph illustrates various performance measures:

- Positive and negative gradients of this graph respectively indicate if the unit operation is operating at above and below target consumption
- The x-intercept of this graph indicates the time required for the unit operation to obtain an average consumption corresponding to the target consumption of a resource
- The points below the x-axis show that the unit operation is averaging below target consumption for the entire time period being investigated.

This type of graph serves to highlight the unit operations that are out of control and the need for identifying waste minimisation options for these.

Comparison of available pre-assessment and assessment techniques

A diverse range of pre-assessment and assessment techniques is available to industry to identify waste minimisation opportunities and options. Two questions arise:

- Do the pre-assessment and assessment techniques yield similar waste minimisation opportunities and options?
- Which pre-assessment and assessment techniques are most suitable for a waste minimisation audit?

To date, no comparative, quantitative study has been published to address the above questions. However, several general comments are made below.

Pre-assessment techniques are designed to identify broad focus areas (opportunities) and/or options for waste minimisation without the need for performing a detailed study (Envirowise, 1996a; Barclay and Buckley, 2000). Techniques are required that are quick and relatively simple to apply. From this review, it would appear that scoping audits, the waste index method, calculation of the true cost of waste and benchmarking meet these requirements. Caution needs to be exercised when using the scoping audit since it was developed for the UK industry and may require modification for application to South African industry. Techniques developed for specific sectors in South African industry (e.g. Cleaner Production Bench-marking tool of the Metal Finishers (Dahl, 2000; Telukdarie et al., 2002)) are particularly suitable but lack general application to all industries.

It is difficult to draw conclusions regarding the relative suitability of the general assessment techniques since each of the techniques contributes a different facet to a waste minimisation initiative. Mass and energy balances enable identification of problematic streams (including waste streams) by considering process input and output streams, flow rates and compositions; water pinch analysis minimises wastewater and hence process water requirements in mass transfer processes through considering contaminant concentrations and their mass transfer; and monitoring and targeting minimises raw material and utility consumption by considering consumption as a function of time and production. All these assessment techniques as well as project-specific investigations performed during the assessment stage require detailed research and hence a greater time and financial commitment from the company.

Studies have shown that the amount of time invested by a company in a project correlates positively to the quality of the options produced (De Bruijn et al., 1995; De Bruijn and Hofman, 1998). Options using quick techniques, like the pre-assessment techniques, have been found to be mainly good-housekeeping measures (De Bruijn and Hofman, 2001). Assessment techniques tend to produce options that are better tailored to the company and that are more profound (e.g. fundamental changes to a production process) (De Bruijn and Hofman, 2001).

Conclusions

This paper has reviewed the currently available pre-assessment and assessment techniques used in waste minimisation audits. Each of these techniques has been critically assessed in terms of its usefulness and possible shortcomings. Simple pre-assessment techniques that quickly identify waste minimisation focus areas (opportunities) include scoping audits, the waste index method, calculation of the true cost of waste, and benchmarking. A comparative, quantitative study needs to be performed to establish whether these techniques identify similar focus areas for a given case study. The general assessment techniques cannot be easily compared since each technique adds a different dimension to a waste minimisation initiative. Options generated using assessment techniques are more profound than those generated using pre-assessment techniques alone.

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