Developing Life Cycle Inventories for Waste Management Report No. CWM 128A/97

Volume No. 2 of 2

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Developing Life Cycle Inventories for Waste Management

Volume No 2 of 2

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Overview of Waste Management 1

Non-Hazardous Waste Arisings

1.1 It is estimated that about 210 million tonnes of controlled waste are generated in the UK per annum (Figure A1.1, Table A1.1). The non-hazardous element of controlled waste is generated from a variety of sources, principally:

Household	Mixed household refuse placed in dustbins and plastic sacks for doorstep collection and larger items and garden waste taken by householders to Civic Amenity sites. Also separated materials, paper glass etc., taken to recycling banks;
Commercial	General refuse from offices, restaurants, shops etc. Mainly dominated by paper and card, but may contain a proportion of putrescible material;
Industrial	Waste from industrial processes. May involve very large quantities of single materials, for example, blast and steel furnace slags, food and processing wastes, etc.; and,
Demolition and Construction	A high proportion of concrete and brick, but also including soil, stones and asphalt and smaller amounts of wood, plastic, metals and insulation materials.

1.2 It should also be noted that the term 'Municipal Solid Waste' (MSW) is in common usage to describe collectively all the non-hazardous wastes collected by local authorities (or their contractors). This includes wastes collected from households and from some (but not all) commercial premises, together with wastes delivered to CA sites by householders. In practice it is MSW that is the *de facto* waste stream with which this project is primarily concerned.

The estimated composition of UK domestic waste, is shown in Table A1.2.

Figure A1.1: Annual UK Total Waste Arisings (Millions of Tonnes Per Annum)

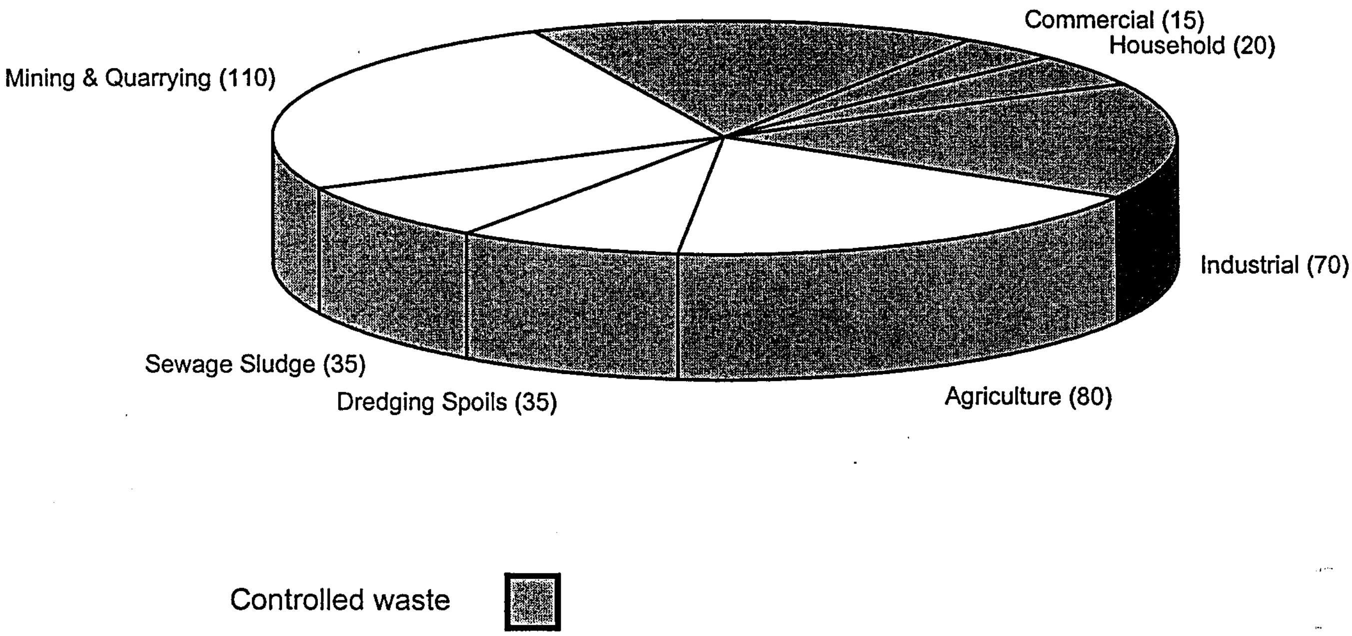

Table A1.1: Estimated Annual UK Controlled Waste Arisings

Category of Controlled Waste	Total Arisings (millions of tonnes per annum)	Percentage of Total Controlled Waste Arisings
Household	20	9
Commercial	15	8
Industrial	70	33
Construction & Demolition	70	33
Sewage sludge[1]	35	17
TOTAL	210	100

Source: Department of the Environment

1 Sewage sludge is only a controlled waste when landfilled or incinerated

Table A1.2: Calculated Composition and Ranges of UK Domestic Waste Arisings and Components

	Concentration Weight %:		
Category	**Minimum**	**Maximum**	**Typical**
Paper & Card	21.6	54.1	33.2
Plastic film	3.4	8.1	5.3
Dense Plastic	2.7	10.1	6.0
Textiles	1.1	3.4	2.1
Misc. Combustibles	1.4	13.6	8.1
Misc. Non Combustibles	0.4	4.2	1.8
Glass	2.7	16.9	9.3
Ferrous Metal	2.8	10.8	5.7
Non Ferrous Metal	0.3	3.9	1.6
Putrescibles	13.9	27.8	20.2
Fines (> 10mm)	3.5	12.4	6.7
TOTAL	-	-	**100.0**

Source: Kerbside Collection of Recyclables from Household Waste in the UK - A position study Atkinson, W., New, R., Warren Spring Laboratory Report LR 946, 1993.

The Waste Hierarchy

1.3 The environmental policies of the European Commission and the UK government emphasise the importance of developing a sustainable approach to waste management and recognise the resource potential that wastes possess, both in terms of their materials content and their energy content. There is a strong policy presumption that wherever possible these resources will be recovered.

1.4 One way in which these policy preferences have been expressed and summarised is through the hierarchy of waste management options (Department of the Environment, 1995).

HIERARCHY OF WASTE MANAGEMENT OPTIONS

- **REDUCTION** Reducing the production of waste to the minimum consistent with economic sustainability.
- **REUSE** Putting objects back into use, for example, reusing bottles.
- **RECOVERY** Finding beneficial uses for waste, including:
  - i) materials recycling - putting materials back into use, e.g. reusing the glass from bottles;
  - ii) composting - processing organic waste to produce a soil improver or growing medium; and,
  - iii) energy recovery - burning waste and recovering the energy, or collecting and using landfill gas.
- **DISPOSAL** Sending wastes to landfill is the least attractive option because no benefit is obtained from the materials. The emphasis here must be on ensuring that disposal is environmentally sound.

1.5 Waste management in the UK has been strongly weighted towards the bottom end of the waste hierarchy, with a particularly heavy reliance on landfill for the disposal of household and other wastes. Landfill is, however, increasingly being seen as the disposal method of last resort, to be restricted to intractable wastes and residues from other waste treatment processes that cannot be recovered.

1.6 The UK's dependency on landfill has been influenced by several factors. The geological structure of Britain and the pattern of minerals working has been one of the most important, creating a combined void space of which much has been suitable for infill and restoration using waste materials. However, land use planning considerations are now placing much tighter restrictions both on minerals development and landfill disposal. A second important factor has been the fact that gate prices for different waste management methods have not fully reflected their environmental costs.

1.7 There is a growing recognition of the environmental effects of different waste management options and the need to take these fully into account in choosing a waste management strategy. This study is one of a number of contributions to the development of appropriate tools for the evaluation of waste management policy options at national and local level.

1.8 The economics of waste management are also changing in response to these policy shifts. For example, energy recovery is being encouraged through the mechanism of the Non Fossil Fuel Obligation (NFFO), whereas landfill disposal is being discouraged through the new landfill tax.

The Hierarchy and the LCI System Boundary

1.9 It is a methodological principle of Life Cycle Assessment that the purpose of the study should be stated as transparently as possible, and, as part, of goal definition, it is important that the boundaries of the system under study should be defined. These principles are explained in greater detail in Annex 2.

1.10 The emphasis in this report is on the management of *household wastes*, although the methodology developed is equally applicable to other waste streams. In most cases the system boundary has therefore been taken to be the physical curtilage or boundary of the property. It is the point at which wastes generated by households leave the household. The waste may be collected in its entirety at this boundary by the local authority household waste collection service or the householder may take certain components of the waste to other waste reception facilities (for example, by foot to a local recycling facility, or by car to a CA site).

1.11 In choosing to define the system boundary in this way it might appear that the LCI fails to take into account possible waste avoidance/minimisation or waste re-use. This is not the case, however. The methodology which has been developed allows the effects of these important elements in any waste strategy to be included. This is achieved through modifying the specification (quantity and composition) of the assumed waste stream generated by households, and hence the materials flow across the system boundary.

The National Household Waste Analysis Project (NHWAP)

1.12 Table A1.2 shows the 'typical' composition of UK household wastes, and also demonstrates the wide variations which occur in the weight of the individual waste constituents. The data from which this summary table has been derived is a relatively large and growing dataset which has been generated through the work done in recent years under the Department of the Environment's (and subsequently the Environment Agency's) National Household Waste Analysis Project (NHWAP).

1.13 The aim of NHWAP has been to obtain a better characterisation of UK household wastes, analysing variations in waste generation accounted for by a range of factors including:

- variations in household size and structure and other demographic and socio-economic factors;
- variations in the nature of different local authority areas (urban versus rural, retirement resorts versus mining valleys, inner city versus suburban, etc.);
- seasonal effects; and,
- the effects of different forms of waste collection system (for example, wheeled bins or plastic sacks), and different local authority collection policies (e.g. restrictions on the number of containers, or the collection of garden wastes, etc.).

1.14 The data generated under the NHWAP has been derived by taking representative household waste samples from households of different types in carefully selected local authorities across Britain. A '2-dimensional' sampling frame has been used, applied at two levels. At the first, higher, level, a set of local authorities has been selected as representative of the different types of local authority area that exist in Britain (for example, retirement resorts, outer London Boroughs, new towns, rural districts, etc.). At the second, lower, level, groups of properties within individual collection vehicle rounds have been selected as representative of the different household types that exist in Britain (for example, middle class families with young children, pensioners living alone, affluent older suburban families, families living on the poorest council estates, etc.).

1.15 Both classifications have been based on cluster analysis of national census data, using the subset of census data variables adopted by CACI in the development of its ACORN[1,2] system. ACORN is used in an extremely wide range of applications in a broad range of sectors, particularly in consumer marketing and in the provision of personal services (financial services, healthcare etc.). It has been shown to be a powerful and discriminating tool for analysing consumer behaviour, and the propensity to consume materials

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1 A Classification of Residential Neighbourhoods

2 This tradename is used for the purposes of identification only and does not imply endorsement by the Department of the Environment or the Environment Agency.

and discard wastes (or recycle them) is, of course, just another aspect of consumer behaviour.

1.16 Waste samples were taken from selected collection vehicle, sub-sampled using mechanical sorting techniques and subjected to detailed weighing and physical and chemical analysis. The standard 11-fold categorisation of waste components is that shown in Table A1.2, but a further finer sub-division into 33 components is also routinely carried out, together with a particle size distribution within each category. In addition the Waste Collection Authorities provided weekly weight data for each round sampled over a 12 month period. The data derived has produced a substantial body of information characterising the average weekly weight of waste produced by different household types in different parts of Britain, and the composition of that waste (Department of the Environment, 1993b; 1994; 1995).

Using NHWAP Data in LCA

1.17 In using LCA for policy analysis at a national level it will be most appropriate to use a weighted aggregate representing the 'average' characteristics of UK household waste. This average can be modified to reflect the presumed effects on waste characteristics of changes in national waste management policy or the achievement of national targets (for example, increasing the proportion of waste recovered by composting, or achieving the recycling of 37% of steel cans by 2000).

1.18 At a local or regional level an analysis should be at a finer level of resolution. The assumed characteristics of the household waste stream should reflect as accurately as possible those of the local authority areas under consideration. The effects of waste minimisation measures or of materials re-use can then be modelled by making appropriate changes to the assumed composition of the waste streams that are the input to the LCA. Waste minimisation and re-use might be achieved in a variety of different ways, dependent upon the kinds of community initiatives or education programmes the local authority chooses to promote. The composition of the reduced waste stream will be correspondingly modified, with changes in the relative proportions of the principal constituents. It is this modified and reduced waste stream that then defines the materials flow into the system across the system boundary. This point remains the physical boundary of the household.

The Waste Management Industry

1.19 The main players in the management of non-hazardous controlled wastes are local authorities, private waste management contractors and large industrial organisations who handle their own wastes in-house. The institutional arrangements which govern these organisations and their inter-relationships are set by regulations passed under the Control of Pollution Act (1974) and amended by the Environmental Protection Act (EPA, 1990) and the Environment Act (1995). These identify and define the powers of regulatory authorities, establish a system of licensing for waste management operations and to an extent define the activities which certain types of organisation may undertake. In addition, the Duty of Care under Section 34 of the EPA, 1990 places a statutory obligation on waste producers to demonstrate that their waste storage, handling and disposal arrangements are properly controlled, and supported by accurate waste descriptions and proper waste transfer notes and other contract documentation.

1.20 In England and Wales, local authorities currently have the responsibility to establish:

- *Waste Collection Authorities* (WCAs), responsible for arranging for the collection and delivery of waste and implementing recycling plans; and,
- *Waste Disposal Authorities* (WDAs), responsible for arranging for waste disposal via commercial arrangements made with arms-length companies owned by the local authority or by private contractors.

Waste regulation is the responsibility of the Environment Agency in England and Wales, the Scottish Environmental Protection Agency in Scotland and the in Northern Ireland.

1.21 In addition, local authorities operate services for the collection of household waste and some commercial waste, and disposal authorities may also be involved in the operation of waste disposal and treatment sites through the establishment of Local Authority Waste Disposal Companies (LAWDCs). LAWDCs must be established at 'arms length' from other local authority institutions and operate commercially in competition with private contractors.

1.22 Private sector waste management contractors may also compete for contracts to collect household, commercial and industrial waste and may operate the full range of waste treatment and final disposal facilities.

1.23 Large-scale industrial waste producers may treat and dispose of their own wastes on-site, but are unlikely to compete with waste management contractors in the open market.

Waste Collection, Treatment and Disposal Processes

1.24 A wide range of processes may be involved in the collection, treatment and final disposal of non-hazardous wastes. The principal processes for household and commercial waste are outlined below (for more detailed information see Department of the Environment, 1992).

Collection

1.25 Householders generally place their waste in some form of container for doorstep collection. The traditional dustbin has been largely replaced by plastic sacks or plastic wheeled bins of various design. In high-rise accommodation householders may deposit plastic sacks of waste via chutes in large communal wheeled bins or skips. The waste is then collected by purpose-built refuse collection vehicles (RCVs) of various design operated by the local authority or its contractors. Where householders are participating in local recycling schemes readily recyclable materials such as glass, textiles, cans and paper may be separated and deposited by the householder in recycling banks located in shopping centres etc., or via charity schemes (so-called 'bring systems'). Alternatively, a number of local authorities have established schemes whereby householders put recyclable materials in separate containers or plastic sacks for kerbside collection (so-called 'collect systems').

1.26 Local Authorities also provide 'Civic Amenity' sites where local residents can bring bulky items of household waste such as garden waste, appliances, old carpets, etc. The private motor vehicle is the usual method of transporting materials to these sites, which also generally serve as recycling centres.

1.27 Waste from shops, offices and other commercial premises is usually placed in larger wheeled bins or skips and collected by private waste contractors or the local authority in purpose-designed RCVs.

Transfer

1.28 In order to maximise transport efficiencies, waste collected in individual RCVs is often taken to bulking depots known as 'Transfer Stations'. Here the waste is tipped into large bunkers and then compacted into containers or loaded into bulk vehicles for onward transport to the final disposal site. In a few notable cases river barge or rail is also used for onward bulk transport of the waste.

Materials Recovery Facilities (MRFs)

1.29 Facilities to extract single materials from pre-segregated household waste, by using electro-magnets to remove ferrous scrap, for example, have been developed into the concept of the MRF. MRFs employ a wide array of different separation technologies, ranging from hand-picking through to sophisticated mechanical processes, to maximise the proportion of recyclables recovered. For effective operation MRFs rely on the pre-segregation of recyclables, generally into a paper/board stream and a mixed recyclables stream (glass, metals, and plastics). This often requires the direct participation of householders and has repercussions for collection arrangements.

1.30 At the present time there are a limited number of MRFs operating on a commercial basis in the UK, and the majority of these were established as pilot schemes only. The precise configurations of existing MRFs vary considerably depending upon local conditions and objectives. At one end of the spectrum 'low-tech' MRFs typically employ less technology, but are labour intensive and focus on hand-sorting of different materials. Conversely, 'high-tech' MRFs are heavily automated and capital intensive and use sophisticated screening and separation technology. For further information see Department of the Environment, (1993c).

Landfill

1.31 Landfill is the practice of depositing wastes in voids, usually below ground level. In the UK old mineral workings are generally used for this purpose. Landfill is the final disposal option currently used for about 90% of household waste and the final residues from other disposal options, such as ash from incineration, also need to be landfilled.

1.32 There are around 4,000 landfill sites currently operational in the UK and the physical and design characteristics of these sites and the operational regimes in place vary considerably. The main environmental problems experienced with these sites surround uncontrolled releases of leachate and landfill gas (LFG). Leachate is the liquor produced within a landfill, by infiltrating rainwater, containing the products of bio-degradation of wastes and the dissolution of the waste components. Substantial volumes of highly polluting leachate may be produced which can contaminate ground and surface waters. LFG is generated during the biodegradation of wastes via a complex series of aerobic and anaerobic microbiological processes. The gas primarily contains methane and carbon dioxide, with hydrogen sulphide and other trace components in varying minor concentrations. A major hazard arises from the flammability of methane and its potential for forming an explosive mixture with air. In addition, methane is an important greenhouse gas. Both leachate and LFG may continue to be generated from a landfill site for several decades after the site has ceased to be operational.

Figure A1.2: Electromagnetic Separation of Ferrous Metals in a MRF

(Photo courtesy of Aspinwall and Co.)

1.33 Current best practice for the design and operation of landfill sites includes:

- siting facilities only in geologically suitable locations;
- engineering measures to contain, monitor and control leachate and LFG;

- tight control of operational procedures, (for example, measures to control litter, vermin, odour and dust); and,
- proper aftercare provisions.

1.34 New landfill sites are now generally of the 'containment' type, where wastes are effectively isolated from the environment for many years until they are no longer polluting. Containment is achieved by using a clay and/or man-made liner (e.g. butyl rubber) to cover the sides and base of the site. After the site has been filled, it is then covered with clay or other impermeable material, to prevent the ingress of rain water. Leachate is collected in drains and passes through some form of treatment before discharge. Similarly, LFG is collected through a forced or passive ventilation system and then either vented or burnt at a flare or used as a fuel. In September 1996, there were reported to be at least 67 live schemes utilising LFG as a fuel in the UK. A schematic representation of a typical modern landfill site is shown in Figure A1.3.

1.35 The method of waste deposition in a landfill site will also have important environmental consequences. The first consideration will be to determine which types of waste are permitted at a given site, and the proposed EC Directive on landfill, distinguishes between:

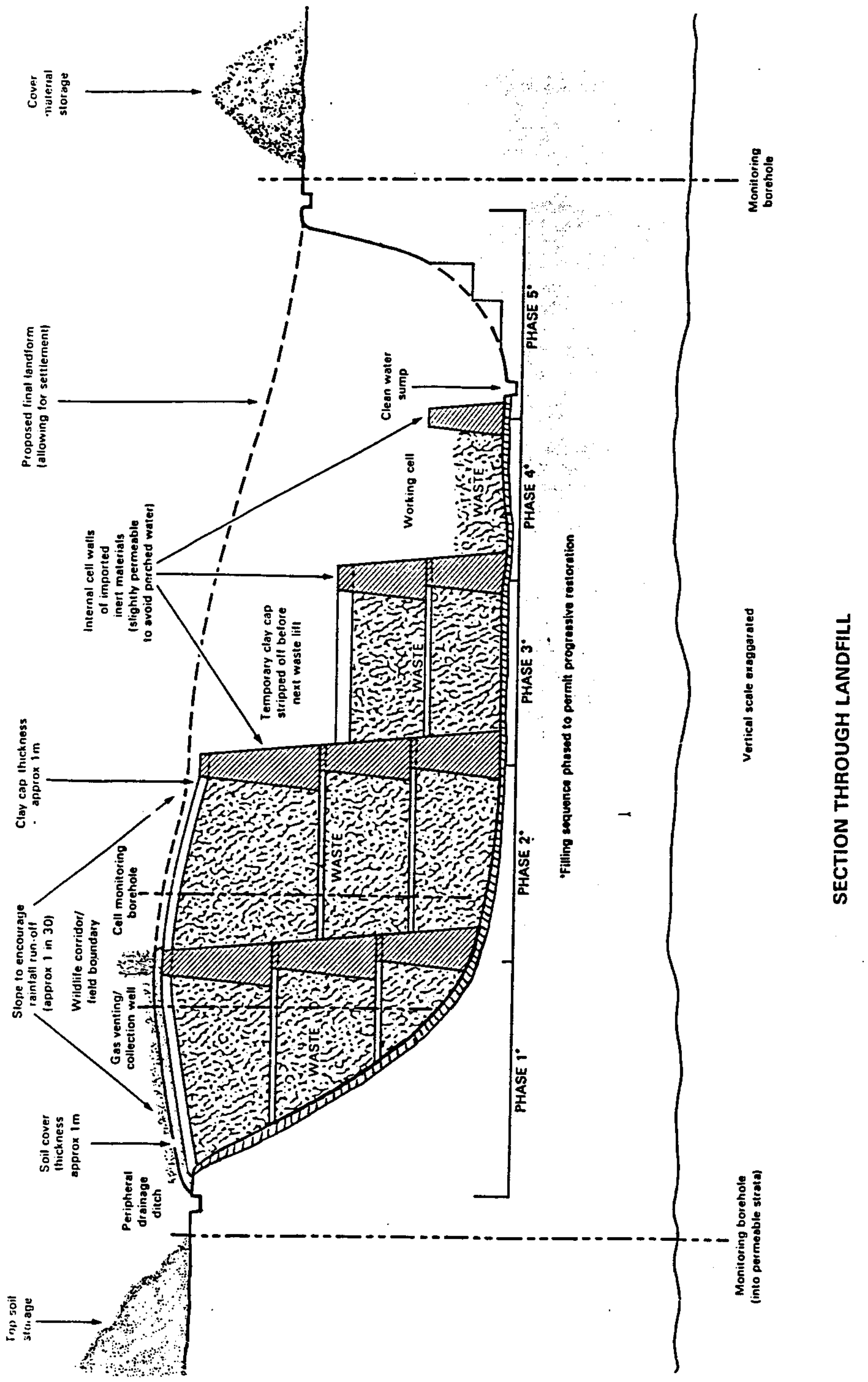
- inert waste sites, licensed to receive only biologically and chemically inert wastes;
- household waste sites, licensed to receive household, commercial and biodegradable industrial wastes; and,
- hazardous waste sites, licensed to receive difficult and special industrial wastes.

1.36 Following best practice, waste will then be deposited in 'cells' formed by pre-constructed bunded areas within the void space. A wide range of mobile plant, including compactors and earth movers is used to handle and compact the wastes to reduce the spread of litter and to provide land stability. At the end of each working day, the waste is covered with relatively inert material to minimise odour emissions and prevent infestation by flies and vermin. Further explanation of landfilling practice is given in Department of the Environment (1986; 1991).

Incineration

1.37 About 6% of UK municipal waste is currently burned in 7 municipal incinerators. Incineration enables operators to substantially reduce the volume of wastes ultimately going to landfill and destroys most of the biodegradable waste components which can generate LFG and leachate in landfills. These incinerators also recover some of the energy content of the waste, which is then used to generate electricity or in district heating schemes.

Figure A1.3: Section through a modern landfill



1.38 Three of the incinerators were built in recent years and incorporate advanced gas cleaning equipment to meet the requirement of European and UK legislation. The other plants were originally built in the 1960s and 1970s and have recently been modified to meet new emissions standards (Directive on the reduction of air pollution from existing municipal waste incineration plants, 89/429/EC). Some 30 incinerators that did not include energy recovery plant closed in the early 1990s. Six additional new plant are at an advanced stage of planning and it is estimated that by 2005 the UK incineration capacity will be in the region of 2.7Mt/y.

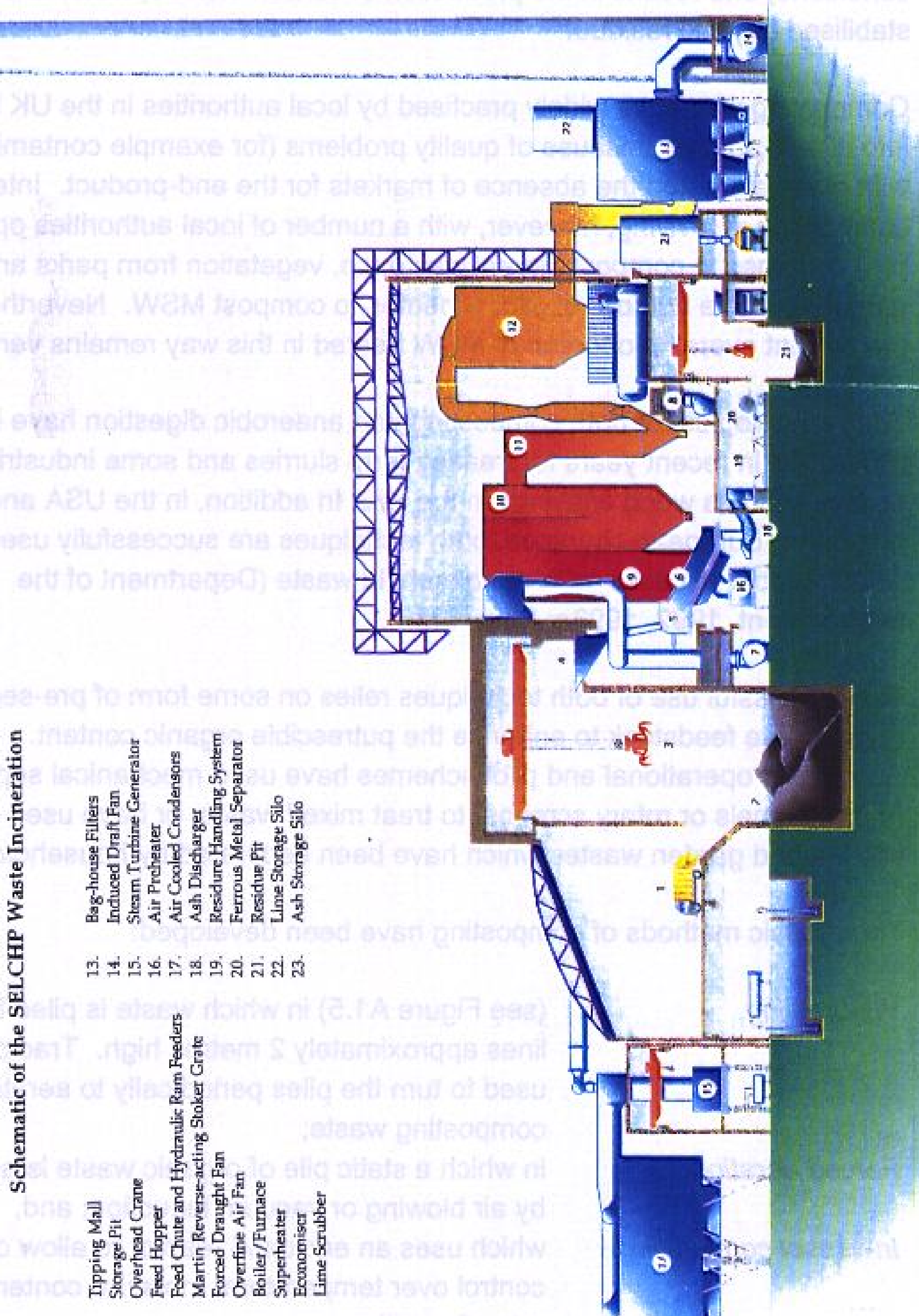
1.39 Current incinerators in the UK are typically large mass-burn plants designed to handle large volumes of household waste with no pre-treatment (Figure A1.4). Waste is delivered to a tipping hall and stored in a large refuse bunker, before being passed into the furnace. There are a number of different designs of furnace, but most incinerators in the UK employ moving hearths, consisting of a steel or cast iron conveyor which slowly moves the waste from the front to the rear of furnace. The residual ash falls off the end of the conveyor and may be quenched with water before passing to a storage bunker for final disposal at a landfill site. Furnace temperatures are typically at least 850° C and the exhaust gases are cooled to about 300° C in the boiler stage. The flue gases are generally cleaned by semi-dry or dry scrubbing to remove HCl and SO_2, followed by bag filters to remove particulate material.

Refuse Derived Fuel (RDF)

1.40 Another approach to recovering the energy content of household waste, is to separate out the combustible fractions to produce fuel pellets for use by industry. Considerable research effort has been devoted to the development of RDF, but at the present time only 3 out of 10 production facilities which have been built in the UK are still operational.

1.41 Two main types of RDF have been produced, coarse (cRDF) and densified (dRDF). cRDF is the fraction which remains after an initial separation of metals, glass and other non-combustible material. dRDF is produced by further processing to remove putrescible and heavy material and comprises mainly the paper, plastic and textile fraction of the original waste (approximately 30% by weight). This fraction is then dried and pelletised to produce a fuel with an energy value about half that of coal. The UK has tended to concentrate on dRDF in the past, but there is interest in developing cRDF technology for use with fluidised bed combustors.

Figure A1.4: Schematic of the SELCHP Waste Incinerator



Composting

1.42 Composting is a biological process in which organic material is broken down by the action of micro-organisms in the presence of air (i.e. aerobic conditions) and results in the production of carbon dioxide, water and a stabilised organic residue.

1.43 Composting was once widely practised by local authorities in the UK but fell into disuse, largely because of quality problems (for example contamination with glass etc.), and the absence of markets for the end-product. Interest in composting is reviving, however, with a number of local authorities operating pilot schemes to compost 'green' waste (i.e. vegetation from parks and gardens), and a number of pilot schemes to compost MSW. Nevertheless, the current overall proportion of MSW treated in this way remains very small.

1.44 The technologies for both composting and anaerobic digestion have been well developed in recent years for treating farm slurries and some industrial wastes such as wood shavings in the UK. In addition, in the USA and a number of European countries, both techniques are successfully used in a small number of cases to treat household waste (Department of the Environment, 1992, 1993a; Saw, 1988).

1.45 The successful use of both techniques relies on some form of pre-segregation of the waste feedstock to enhance the putrescible organic content. Successful operational and pilot schemes have used mechanical separation (e.g. trommels or rotary screens) to treat mixed waste, or have used domestic kitchen and garden wastes which have been separated by householders.

1.46 Three basic methods of composting have been developed:

Windrowing,	(see Figure A1.5) in which waste is piled in long lines approximately 2 metres high. Tractors are used to turn the piles periodically to aerate the composting waste;
Forced aeration,	in which a static pile of organic waste is aerated by air blowing or vacuum induction; and,
In-vessel composting,	which uses an enclosed reactor to allow close control over temperature, moisture content, and rate of aeration.

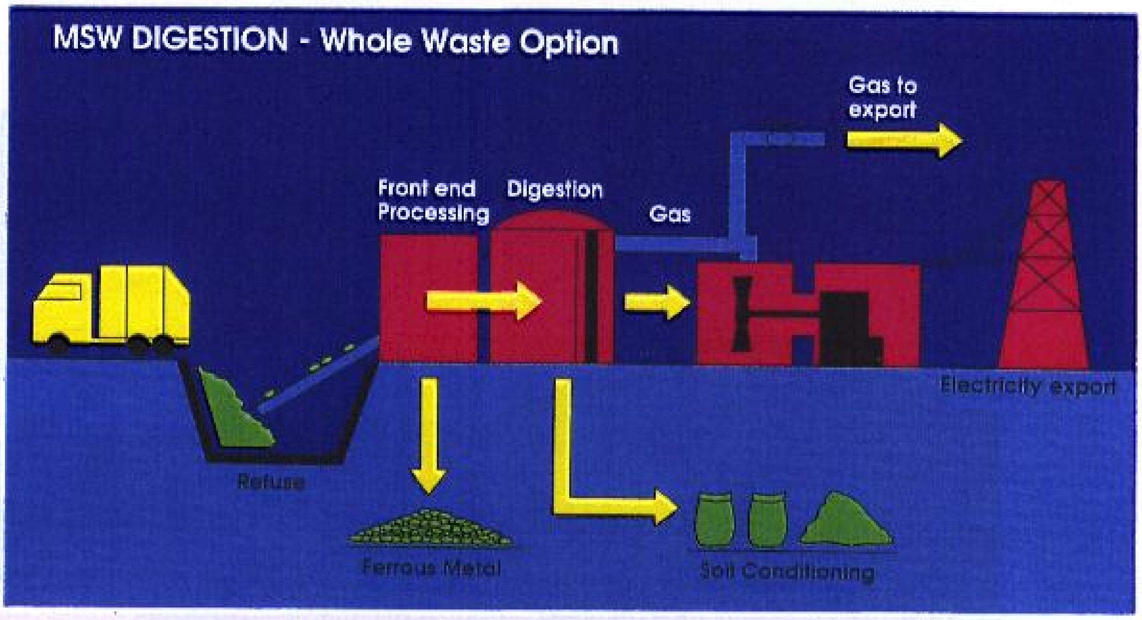
Figure A1.5: Composting Operation Showing Windrows

Anaerobic Digestion

1.47 Anaerobic digestion takes place in the absence of air and produces a carbon dioxide and methane gas mixture ('biogas') and a stabilised residue.

1.48 A number of commercial anaerobic digestion systems are available, which are all based on the use of closed reactor vessels. One particular attraction of the technique is the opportunity to recover energy from burning the biogas which is collected within the closed system. The principal experience to date has been with waste streams such as sewage sludge, farm slurries and a number of industrial effluents with a high moisture content. However, pilot and commercial plants have been established abroad for processing MSW. A typical anaerobic digester system layout of the type which has been used for treating household waste in Europe is shown in Figure A1.6.

Figure A1.6: Schematic of Anaerobic Digestion System



What Happens to Non-Hazardous Waste?

1.49 The exact route followed by a given quantity of waste, from the point of its arising to the point or points of final disposal, will depend on local policies, facilities and arrangements. Because the waste management processes described above may be used in a wide variety of combinations, and involve the interplay of several different organisations, it is not possible to identify a standard disposal route which is followed consistently for a particular type of waste.

1.50 However, despite recent developments in waste management techniques, the disposal pathway most commonly followed for household waste in the UK today probably remains that shown in Figure A1.7 and outlined below:

A householders place all their waste in plastic sacks, wheeled bins or dustbins for doorstep collection by the local authority. (The extent to which readily recyclable items such as glass bottles, newspapers etc. are taken separately to recycling banks will vary enormously between households and therefore the waste which is collected from doorsteps in a particular neighbourhood may generally be considered to be mixed waste material);

B an RCV transports the mixed waste to a transfer station or direct to a landfill site;

C waste is unloaded at the transfer station and is either compacted or bulk-loaded into a dedicated vehicle;

D the bulk-load vehicle transports the waste to a landfill site; and,

E the mixed, waste is deposited in the landfill site.

Where mass burn incineration is practised, the procedure will be as shown in Figure A1.8.

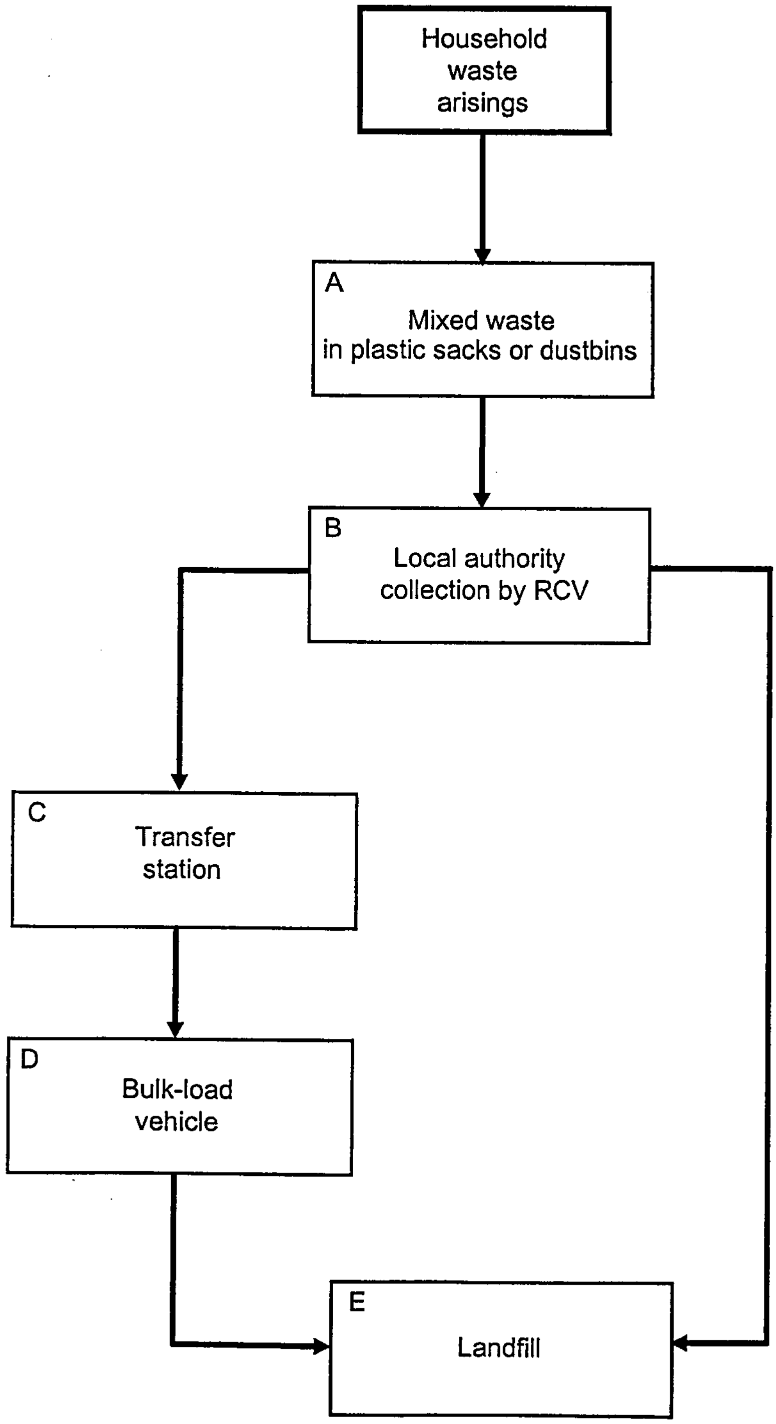
1.51 But, as modern developments in collection techniques, materials recovery and new waste treatment technologies are implemented, these simple models for waste management are replaced with those which are more complex. For example, considering only the waste collection step, the custom of placing all household waste arisings in a dustbin for doorstep collection, is being replaced by a range of different possible options:

1. items such as glass, cans, newspapers and textiles may be taken by the householder to recycling points in the neighbourhood. This may be done on foot, but is most likely to involve the use of a private motor vehicle;
2. these recyclable materials may be placed in specially provided containers for kerbside collection by local authorities or contractors using dedicated collection vehicles;
3. bulky items and recyclables may be taken by the householder to Civic Amenity sites. This generally involves the use of private transport. In some instances local authorities will undertake special collections for bulky items; and,
4. other mixed waste will be placed in a plastic sack or dustbin for collection.

1.52 Thus the steps involved in transporting the weekly waste arisings from one household to the point of first processing (e.g. the transfer station) potentially widen to include a mixture of:

- walking;
- use of local authority RCV;
- use of private vehicle;
- use of specialised vehicles (to empty recycling banks); and,

Figure A1.7: Typical Disposal Route for Household Waste



- use of fork lifts and small tractors at Civic Amenity sites.

Clearly, as additional materials recovery and waste treatment steps also become involved, the number of different routes which an item of household waste may follow grows even further. The main possible disposal routes are shown in overview in Figure A1.9.

1.53 The increasing complexity in the range of waste management processes, and the combinations in which they may be used, needs to be fully recognised when considering the environmental effects of waste management. This project deals with this complexity by identifying and separating all the generic transport and processing steps which may occur from the point of waste arising to the point of disposal, and then further breaking down each step into a number of unit operations. The intention is that the full range of actual waste management options that might be encountered will be capable of being described in terms of different combinations of these common unit operations (Volume 1, Chapters 4 and 5).

Figure A1.8: Typical Disposal Routes for Household Waste with Incineration

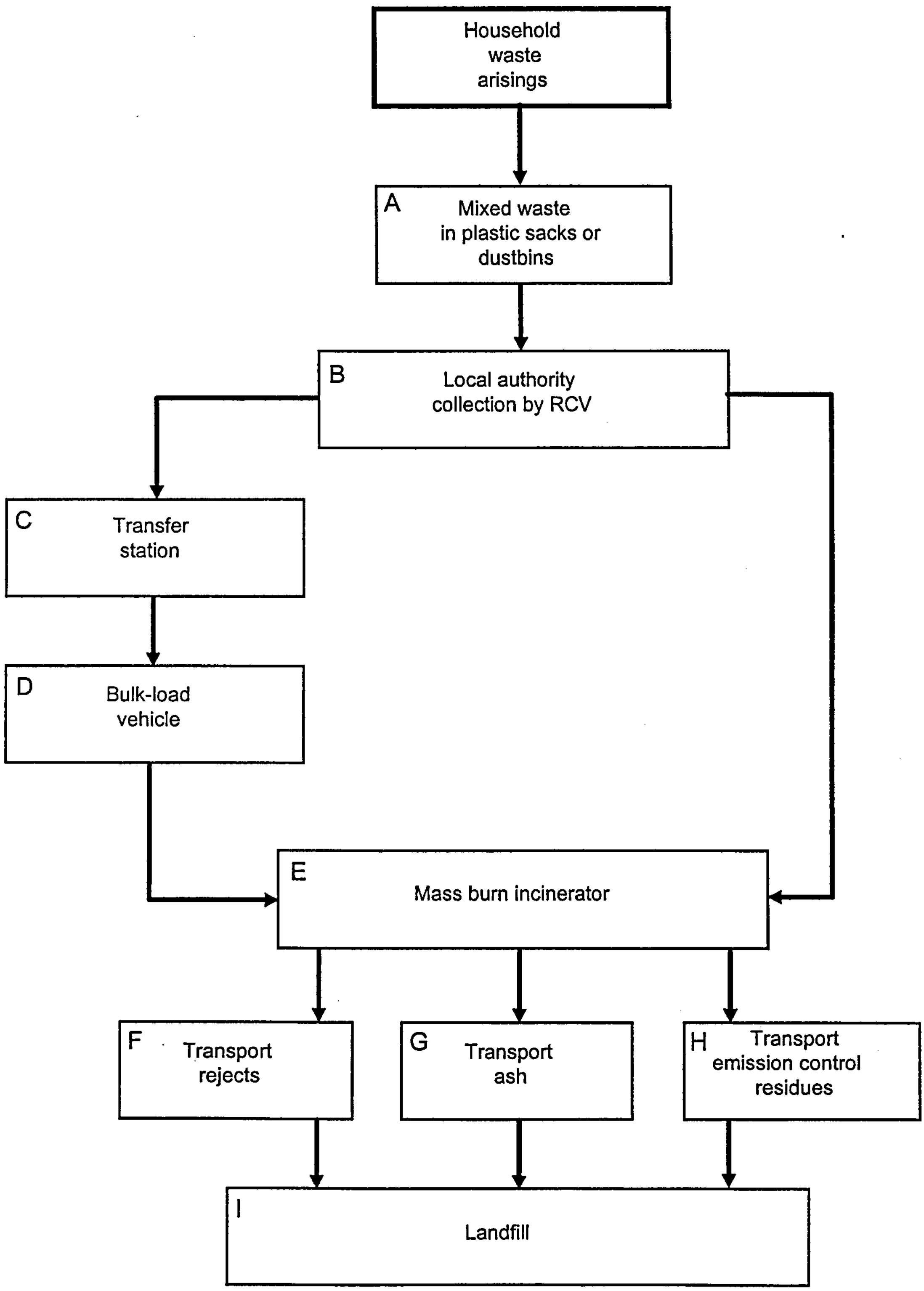
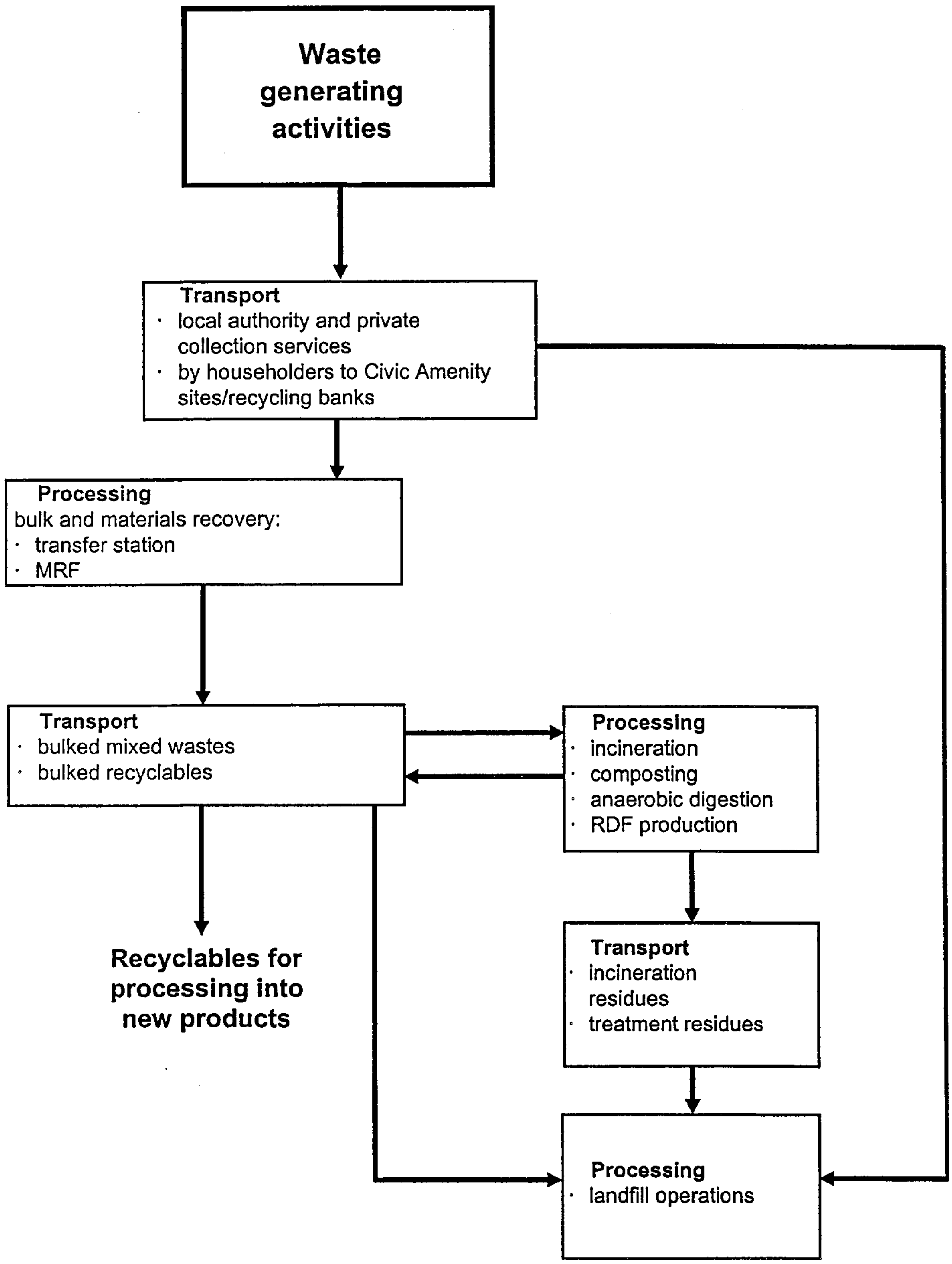


Figure A1.9: Principal Non-Hazardous Waste Management Routes - Overview



Overview of Life Cycle Assessment 2

Introduction

2.1 This chapter provides a more detailed description of the environmental management tool known as 'Life Cycle Assessment' (LCA). It is intended to provide further background to Chapter 2 of Volume 1 of this report.

2.2 The question of terminology has been referred to in the main report, and this Annex uses the same guidance. 'Life Cycle Assessment' encompasses all four stages of the process. 'Life Cycle Inventory Analysis' is used to denote the process of compiling the Inventory Table, and the data in the table itself are referred to as the 'Life Cycle Inventory'. Any study not including impact assessment is therefore a 'Life Cycle Inventory Analysis' study. The term 'Life Cycle Analysis' is avoided.

Historical perspective

2.3 Udo de Haes (1993) has reviewed the development, in the 1960s, of the concept of Life Cycle Assessment, and the early attempts to produce a standard methodology. The energy crisis of the 1970s led to a focus on energy use and conservation, with LCA developed as a basis for comparing different energy supply systems (see Curran, 1992). However, the scope of LCA has widened considerably over the past two decades, with attempts to incorporate other environmental concerns such as ozone depletion, global warming, acid deposition, ecotoxicity, biodiversity and human health.

2.4 During the 1980s LCA studies were carried out in several European countries and in North America, but using disparate methodologies with no common framework. Since then the efforts of the international community have been focused on developing harmonised procedures with the ultimate objective of a commonly accepted 'best practice' documented in international standards.

Further development of LCA methodology

2.5 Various individual organisations, sometimes combined through international initiatives, are currently working to develop LCA methodology further. Generally these concentrate on impact assessment. The Society for Environmental Toxicology and Chemistry (SETAC), the principal scientific body involved in LCA, has established a number of working groups both in Europe and in North America to address unresolved problems and remove some of the limitations in current practice. Relevant sections of this report are informed by the most recent, and as yet unpublished, deliberations of the SETAC-Europe Working Groups.

Standardisation

2.6 In parallel with the work undertaken to develop LCA methodology further efforts to standardise LCA methodology are being progressed by the International Standards Organisation (ISO). ISO has five Working Groups seeking to define standardised procedures in relation to:

- Life Cycle Assessment - principles and framework;
- Life Cycle Inventory Analysis - general;
- Life Cycle Inventory Analysis - specific;
- Life Cycle Impact Assessment; and,
- Life Cycle Interpretation.

2.7 In the UK the British Standards Institution (BSI) has established a technical Committee to shadow the efforts of ISO. It also provides a focal point through which to reach a consensus on the UK viewpoint regarding the issues being discussed and draft documents generated. The UK is represented in each of the Working Groups referred to above, as well as at the Sub-Committee level. The Sub-Committee oversees the work of the Working Groups and provides the forum for voting on draft documents prior to them becoming Draft Standards.

2.8 Inevitably there has been much debate within ISO on the extent to which LCA methodology can be prescribed. While many aspects of inventory analysis can be standardised the degree of standardisation possible for impact assessment, and to an even greater extent interpretation, is still a matter for debate.

2.9 One of the main areas where standardisation in the field of LCA is seen to be important is with regard to defining standardised procedures for reporting. Transparent reporting is essential if the assumptions made, details concerning data quality and the calculation procedures used, as well as the steps taken to validate the study, are all to be evident to those examining the results. It has been argued that some system of verification or certification by competent, independent, third parties might be one way of providing confidence in LCA studies and their results.

2.10 The first ISO standard, *'Life cycle assessment principles and framework'*, was raised to a draft international standard in March 1996. More detailed standards will be published subsequently. *'Goal Definition and Scope and Inventory Analysis'* will become a draft international standard in April 1997. *'Impact Assessment'* and *'Interpretation'* are due to become draft international standards by the end of 1997.

General applications of LCA

2.11 LCA has been used both to identify and to quantify the environmental impact of individual products (for example Nordic Council of Ministers, 1992; Heijungs *et al.*, 1992; Guinée *et al.*, 1993a, 1993b), and also as an approach to comparing the performance of alternative systems or processes which provide the same function (Klopffer, 1992; Keoleian and Menerey, 1993; Azapagic and Clift, 1994; Clift *et al.*, 1995). The applications of LCA are summarised in Table A2.1.

2.12 A distinction is usually drawn between 'internal' applications, where some form of LCA is used in-house by a company, and 'external', for public information or policy development. Internal applications usually place less emphasis on transparency of reporting because the information normally comes from company sources and is not for external release. Transparency is more of a concern for external applications where public confidence, and hence transparency, are important. Different studies also vary in their level of detail. Some have applied the methodology qualitatively, usually to ensure that changing a product or service does not have upstream or downstream impacts. Other LCA studies have attempted a fully quantitative analysis, based on a full LCI.

2.13 During the 1980s, LCA (or more strictly speaking, LCI) was used primarily for 'internal' applications within commercial organisations. Inevitably the full reports from the vast majority of these studies have never entered the public domain, mainly for reasons of confidentiality. Where results have entered the public domain they have normally done so as the basis for marketing claims. There are numerous examples where such results, from different studies examining the same products, have been contradictory. However, comparing the results of such studies is meaningless without access to the information which shows all the assumptions made, the detail of how the calculations were performed, data quality goals, etc. This situation highlighted the need for a generally accepted, standardised, approach.

Table A2.1: Life Cycle Assessment Applications

Governments	Companies	NGOs/Consumers
Certification	Product Improvement	Purchase Behaviour
Ecolabelling	Product Design	Life Style
Deposit Systems	Company Policy (purchasing waste, engineering, marketing)	Pressure Group Action Against Products, Materials
Subsidy/Tax		Action Directed at Companies
Waste Policy	Information	Action Directed at Government
Transport Policy	Advertising	
	Negotiations (with other companies, governments on e.g. emission reduction alternatives)	

2.14 'External', i.e. public sector, uses of LCA have become more prominent in the 1990s. For example, in the Netherlands, the Dutch Government has chosen to take adopt a 'Life Cycle' approach for developing their policy on products and the environment (Hague, 1994). Their policy document states "*...proper assessment will require application of the integrated Life Cycle Principles*". The emphasis of the Dutch LCA approach is for communicating environmental information to all interested parties, including the consumer. LCA was chosen because "*...such an approach reduces the likelihood of the solution to one environmental problem precipitating others, or of environmental problems merely being shifted from one market actor to another*".

2.15 Another prominent 'external' application has been in developing criteria for the award of an Ecolabel, intended to identify consumer products which have a better overall environmental performance than equivalent competing products (Clift, 1993a; Udo de Haes *et al.*, 1994).

2.16 Further, it has been suggested that LCA may act as a bridge between government, industry and NGOs as a vehicle for forming general consensus on environmental issues (Udo de Haes, 1993). However, concerns remain that industrial companies and groups may misuse or manipulate LCA studies to support a commercial position, and that environmental groups may misuse LCA to undermine specific industries (Elkington, 1993). Some NGOs have been hostile to LCA, at least in part because it can sometimes contradict certain accepted environmental beliefs, notably that recycling is always the preferred environmental option (Clift, 1993b).

2.17 More recently, there have been moves to integrate LCA directly in product design (Keoleian, 1993; Keoleian and Menerey, 1993) and to use it as a tool for design of industrial processes (von Blottnitz, 1994; Azapagic and Clift, 1995). A current trend is the attempt to incorporate socio-economic considerations into LCA, alongside environmental impacts (Curran, 1992; Doig *et al.*, 1994, 1995). Application of the methodology to waste management is still in its infancy: specific studies are reviewed later in this Chapter.

The Methodology of Life Cycle Assessment

Current status

2.18 As described in Chapter 2 of Volume 1 of this report, a full LCA comprises four stages. The overall process should, however, be iterative, and the earlier phases should be revisited and updated as the study proceeds. This section summarises the four stages. Goal Definition and Scope and Inventory Analysis are of primary concern in this report, and are therefore covered in more detail later in this Chapter.

2.19 The four components are not equally well developed. Table A2.2 summarises the state-of-the-art of written documents setting out procedures for the four stages, taken from ISO working documents. Goal Definition and Inventory Analysis are relatively well developed. Impact Assessment is still under debate, albeit with a consensus emerging on a number of methodological considerations, though with much work still required. Interpretation is still primarily a matter for determination on a case-by-case basis, and is therefore not discussed further in this report.

Introduction to goal definition and scope

2.20 It is generally agreed that the goal of any LCA must be stated clearly at the outset (SETAC, 1993). The statement should encompass the purpose or intended use of the study.

2.21 The scope of a study should be defined clearly enough to ensure that the analysis is compatible with the stated purpose, and sufficient to address it. The essential decisions at this stage concern the functional unit, defining the service which the system delivers, and the boundaries of the system under study. The functional unit and system boundary must be defined as transparently as possible because this can prejudice the conclusions of the study (Udo de Haes *et al.*, 1994).

Table A2.2: Current Status of the Components of LCA

LCA Components	State-of-the-art of written documents
Goal definition and Scoping	Defined and documented
Inventory Analysis	Well defined, understood and documented
Impact Assessment	
- Classification	Defined
- Characterisation	Conceptually defined
- Valuation	Conceptually defined
Interpretation	Not yet defined

2.22 In order for an assessment of the relative performance of alternative waste management options to be meaningful it is essential that like is compared with like. LCA systems are defined on the basis of their function, and thus for systems to be compared their function must be equivalent. In general, the functional unit should be clearly defined and measurable, and should be described as a function or service rather than as a material output (SETAC, 1993). However, in order to be able to perform the calculations necessary to produce an inventory table, the functional unit will usually have to be capable of being expressed in terms of some quantity of material or energy. To take a commonly quoted example, comparison of alternative packaging systems should be based on a specified quantity of material packaged, or delivered, not on a specified quantity of packaging material.

System boundaries

2.23 Tillman *et al.* (1994) emphasise that "*...choice of boundaries is closely related to the goal definition*". Drawing the system boundary to extend from 'cradle' to 'grave' is the particular characteristic of Life Cycle Assessment and the basis of its claim to be an 'holistic' approach. For a complete LCA, it will be necessary to assess the full cycle, encompassing:

- the extraction and processing of raw materials;

- manufacture;
- transportation and distribution;
- use;
- re-use;
- maintenance;
- recycling; and,
- final disposal.

SETAC (1993) give preference to 'complete' life cycle studies, but accept that *"...much useful information may be derived from studies whose boundaries are narrower than 'cradle-to-grave'"*. Keoleian and Menerey (1993) also recognise that there may be benefit in assessing a partial life cycle or individual stages or activities. It may suffice to analyse only those aspects in which competing systems differ. This is particularly the case where the purpose of the study is to compare alternative systems which deliver the same function, as in this report.

Introduction to life cycle inventory analysis

2.24 The next stage is to define the resource inputs and the emissions to air, water and land with respect to the functional unit. This Inventory Analysis stage, amounts to quantifying the material and energy flows between the system and the environment. The resources used and associated releases to air, water and land are collectively termed the 'environmental burdens'. More detailed definitions of these and other terms are given below and in the Glossary.

2.25 Inventory Analysis is basically a data-gathering exercise. Its outcome should be a complete list of environmental burdens called an Inventory Table. It is generally recommended (Heijungs *et al.*, 1992; SETAC, 1993; Guinée *et al.*, 1993a) that the Inventory Table should be as complete and 'fine-grained' as possible, consistent with the goal of the study.

2.26 It is also recommended that a complete list of environmental burdens should be included unless it is known that any particular burden contributes less than some predetermined proportion of all the environmental impacts (SETAC, 1993). The argument for this rule of thumb is that if the contribution of a burden is small then it is unlikely to be significant in comparing alternative systems or products (Udo de Haes *et al.*, 1994) and it should be excluded according to the *de minimis* principle. Ideally 'sensitivity limits' should be established when compiling an Inventory Table by undertaking a preliminary study. However, whilst this may be satisfactory for the exclusion of small contributions to a single environmental burden, it cannot be used to exclude one of a number of burdens since the relative impacts of burdens cannot be inferred from their magnitude alone. Thus, there are insufficient grounds for excluding burdens until the study is carried through to the impact assessment phase. Until a body of studies is built up and the sensitivity of conclusions to inventory data can be investigated systematically the recommendation must be to attempt to include all burdens.

Allocation

2.27 Beyond data gathering there remain some issues in Inventory Analysis which are not completely resolved. One of these is the problem known as Allocation (Huppes, 1992; SETAC, 1993; Huppes and Schneider, 1994). This is concerned with how the environmental burdens associated with a multi-output system should be apportioned between the different outputs or inputs. A waste management example would be mass burn incineration, where it may be difficult, or indeed impossible, to allocate the air emissions to individual components of the waste being burned. SETAC (1993) identifies waste management and recycling as specific cases where 'the allocation problem' must be addressed. This report recommends an approach which either avoids addressing allocation directly or resolves the problem in a way which is consistent with current thinking (see below and Volume 1, Chapter 4).

2.28 A further issue concerns the quality and availability of the data assembled in the Inventory Table (Keoleian and Menerey, 1993; Guinee *et al.*, 1993a). A Netherlands policy document on environmental product design (Hague, 1994) notes that:

"At present, about eighty per cent of the time and energy expended in carrying out environmental life cycle analyses goes into the collation of data on raw materials use, emissions, processes, energy consumption, waste, etc. Much of this data is not (yet) easily obtainable, say in the form of data files. Many companies are not yet in a position to provide the necessary data or generate it internally."

2.29 The quality of data available to the user will directly affect the precision and completeness of the LCA, and could therefore lead to bias in the results. This is a particular problem for a new area of application such as using LCI or LCA to set policy towards waste management practices. Here consensus has yet to be reached on which data are needed, recognising that inventory data are the vital link which will enable determinations of environmental impacts to be made. Further discussion, leading to specific recommendations on data needs and data quality, is given below and in Chapter 3 of the main report.

2.30 The Inventory Table conventionally records transfers of material and energy across the system boundary. Some environmental impacts, such as land use, loss of habitat and visual impairment, called non-flux burdens following Clift *et al.* (1995), are not usually quantified or assessed in the Inventory Table of raw data on burdens. However, while these non-flux and socio-economic considerations, such as employment, are important, and would certainly have to be taken into account in any decision making process, they are currently outside the scope of most Life Cycle Inventory Analysis (Curran, 1992). Although these impacts can be significant in solid waste management it has been argued that attempts to widen the scope of LCI to include factors better dealt with by other methods will only result in weakening the technique.

2.31 Other burdens not conventionally covered include accidents. However, SETAC (1993) recommend that, where accident levels are significant, then expected accident rates should be incorporated into the inventory.

Impact assessment

2.32 Impact Assessment is the third stage in carrying out a full LCA and attempts to quantify the effect system burdens have on the environment. Conventionally (SETAC, 1993), Impact Assessment is considered to involve three sub-steps:

Classification,	in which the different categories of environmental impact to be considered are defined explicitly;
Characterisation,	in which the contribution of each of the burdens in the Inventory Table to each individual impact is evaluated; and,
Valuation,	in which the relative importance of the different environmental impacts are weighted against or compared with each other.

2.33 Detailed discussion of Impact Assessment is beyond the scope of this report. However, because Impact Assessment has a bearing on the way the Inventory Analysis is carried out, a general overview will be given. It is based in part on discussions in the SETAC-Europe working group on Impact assessment - (Udo de Haes, 1994). A recent publication from this working group 'Towards a Methodology for Life cycle Impact Assessment' (SETAC, 1996) develops the concepts described further.

Classification

2.34 Different authors or institutions have used or proposed slightly different categories for classification. For example, Assies (1992) argues that workplace safety and product safety should also be included as impact categories. Others argue (for example, Udo de Haes *et al.*, 1994; Clift *et al.*, 1995) that these considerations are internal to the system and therefore should not be treated as environmental impacts. The lack of any generally agreed list is the reason why classification is treated as a distinct sub-step. Table A2.3 illustrates a range of reported categories.

Characterisation

2.35 Having identified the impact categories to be considered the contribution to each impact of each total burden in the Inventory Table is estimated. Each total burden is first weighed according to its effect on selected impacts. Then these weighted values are aggregated to give a net impact for all burdens. Thus the Inventory Table, which typically contains hundreds or even thousands of entries, is reduced to a relatively small number of quantified impacts.

Characterisation

In linear algebra terms (Azapagic and Clift, 1994 and 1995), Characterisation amounts to the operation:

$$C = F.B$$

where B is the vector of environmental burdens, $B_1,.....B_J$; i.e. the quantities of each emission or waste and of each primary resource consumed per functional unit provided;

F is the matrix of impact weighting factors; e.g. $F_{i,j}$ gives the contribution of unit burden j to impact i; and,

C is the vector of environmental impacts, $C_1,.....C_I$.

Table A2.3: Illustrative Impact Categories

Resource Depletion	Non-renewable resources (or abiotic resources) - fossil fuels - mineral reserves Biotic resources Water Space or land area
Pollution	Global warming Depletion of stratospheric ozone Acidification Eutrophication (including impact of organic material) Photo-oxidant formation Ecotoxicological impacts (including impacts of ionising radiation) Human toxicological impacts (including impacts of ionising radiation)
Physical Disturbance	Physical impacts on ecosystems: - soil - hydrology - flora and fauna Physical impacts on humans: - accidents - disamenity ('non-flux burdens')
Social Welfare Impacts	Agricultural productivity Aesthetics Employment Damage to the built environment

2.36 The key to Characterisation thus lies in the impact weighting factors, to which there are two distinct approaches, the 'critical volume' and the 'problem orientated' approach (see below for more detailed discussion). The underlying assumption is that the contributions of individual burdens to all environmental impacts have a linear relationship to the burden and also are additive. In general, neither of these simplifications is true, an inherent limitation in LCA. The two approaches to characterisation are as follows:

- *Critical volume approach* (BUWAL, 1991), which estimates the volume of air or water needed to dilute any substance below a critical or threshold concentration; and,

- *Problem-orientated approach* (Heijungs *et al.*, 1992; Nordic Council of Ministers, 1992; Guinée *et al.*, 1993b), which attempts to assess different environmental effects explicitly; i.e. the contribution of a unit burden to an impact is determined directly. For example the contribution of a unit release of methane to global warming.

2.37 The critical volume approach is most appropriate for assessing toxicological effects. It is, however, subject to the criticism that critical or threshold concentrations are not universal, and are frequently defined by legislation on air and water quality. Nevertheless it is included here because it can potentially be useful in assessing impacts from operations like landfilling (see below and Volume 1, Chapter 4).

2.38 There are two main approaches to problem orientated assessment; the Dutch Methodology Project (for example, Heijungs *et al.*, 1992; Guinée and Heijungs, 1994; Guinée *et al.*, 1993b), which is non site-specific, and the approach of the Nordic Council of Ministers (for example, Nordic Council of Ministers, 1992), which attempts to include site-specific aspects.

2.39 The Dutch problem-orientated approach has probably become the most widely used (Haydock *et al.*, 1993). At least in part this is because it is relatively simple to apply, needing only a standard set of impact weighting factors. To the extent that these factors are available and reliable, they are based on universal 'globalised' impacts. For example, a kilogram of sulphur dioxide is assumed to have the same environmental impact wherever, whenever, and in whatever stream or concentration it is emitted. This may be valid for global warming or ozone depletion, but it is clearly a gross simplification for impacts which are not global in scale. In effect this approach assesses potential rather than actual environmental impact. The level of simplification is at least consistent with the assumptions of linearity and additivity mentioned above.

2.40 While some generalised assessment of environmental impacts may suffice as a basis for a national waste management strategy, local development decisions will inevitably involve site-specific impacts. Recognising that impact assessment for solid waste management remains to be addressed, this nevertheless implies that inventory data must be compiled at a greater level of detail than is appropriate for more generalised impact assessment. Some refer to this approach as introducing 'spatial awareness' into LCA.

Valuation

2.41 Valuation attempts to assess the relative importance of the impact categories, with the aim in some cases to aggregate them into a single measure of environmental performance.

> **Valuation**
> In linear algebra terms this measure is given by:
>
> $$P = WC = \sum_i W_i C_i$$
>
> where C is the vector of environmental impact scores comprising the environmental profile (see previous box) and W is the vector of relative weights; i.e. W_i is the relative weighting attached to impact i.

2.42 The underlying problem in valuation is the relative weighting of disparate impacts. While one viewpoint is that all environmental impacts can be reduced to the common metric of financial cost (for example Hunt, 1993; Pearce *et al.*, 1994) it is not scientifically robust and defensible. Combining incommensurable effects in this way may give a false impression of precision or objectivity, thus obscuring the value of LCA in providing a transparent account of possibly conflicting considerations.

2.43 In between these extremes lies the approach which SETAC (1992, 1993) and others (for example Udo de Haes *et al.*, 1994; Udo de Haes, 1994) have attempted to develop. This recognises that the relative weightings should be guided by social or political priorities, and will depend greatly on the aims and purpose of the LCA.

Review and validation

2.44 SETAC (1993) strongly recommended that any major LCA study must be validated by expert peer review. Ideally, this review should comprise three phases:

i) at the beginning of the study, to review the goal and scope of the study, the proposed system boundary and functional unit, and the data requirements;
ii) following initial data collection and modelling, to review progress and provide an independent review of the non-aggregated data; and,
iii) towards completion of the study, to validate the results and any conclusions drawn.

2.45 Because system definition may prejudice the outcome of a comparative LCA study, stage (i) should be mandatory, to ensure transparency of, and confidence in, any public sector application of LCA (Udo de Haes *et al.*, 1994).

Life Cycle Inventory Analysis

2.46 The Foreword to Volume 1 makes it clear that this report is concerned with providing guidelines for compiling inventories of burdens for waste management options. These inventories will then be used to guide decision making by those responsible for waste management at a national and local level. The intention is to use LCA methodologies where they are appropriate in compiling the inventories, but this should not restrict the means by which the inventory is interpreted to those techniques which are currently part of LCA.

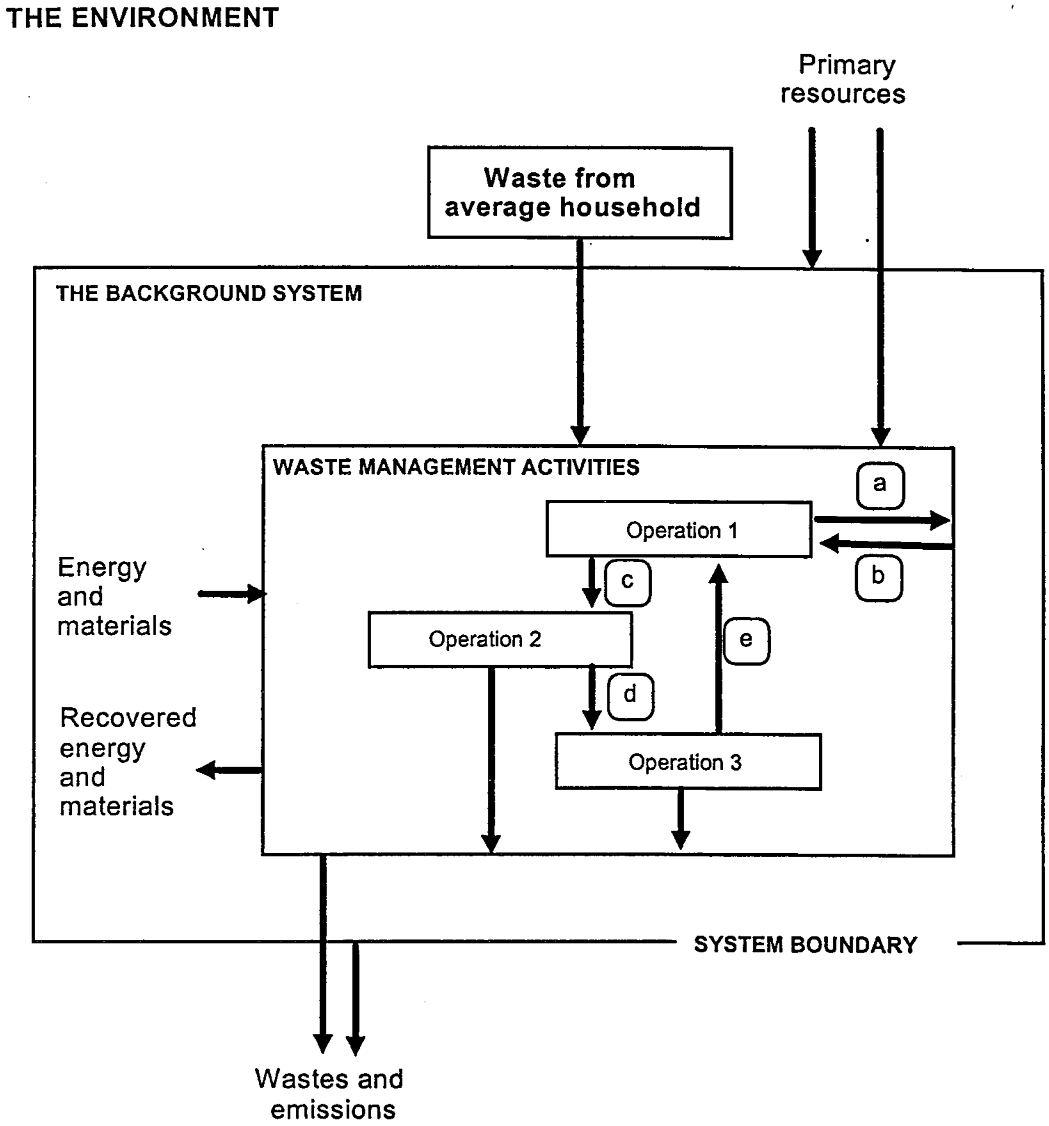
2.47 The preceding section dealt with LCA *in toto* to provide an outline of the methodology to the reader. This section will concentrate on the Life Cycle Inventory Analysis methodology alone, identifying approaches which are both appropriate and generally accepted, and, in particular, present a practicable framework for analysing waste management systems.

Waste management activities and the background system

2.48 Figure A2.1 is adapted from Huppes (1993) and von Blottnitz (1994) and introduces the distinction between 'waste management activities' and 'the background system', which is central to the LCI methodology developed in this report (see Volume 1, Chapters 3 and 8).

2.49 'Waste management activities' incorporate the operations and processes which are central to the study or which differ between the options being compared. The 'background system' represents all other economic activities which interact with the waste management activities which are to be considered by the study and have been defined as within the system

Figure A2.1: System Boundaries for Waste Management



Note: Material flows a & b are 'intermediary' and c,d & e are 'internal' flows

boundary. It is likely to include the activities which generate the materials and energy (notably electricity and transport fuels) which are used by the waste management activities. The system, waste management activities plus the background system, provides functional outputs. It uses primary resources and generates environmental burdens, i.e.wastes and emissions. It may also use materials and energy from activities which have been defined as outside the system boundary.

Allocation

2.50 Allocation is the process of assigning environmental burdens between the different outputs from, or inputs to, the system. SETAC (1993) have identified waste management and recycling as specific areas where allocation should be addressed. This is due, in part, to the incomplete understanding of how burdens are formed. Many waste management systems have multiple outputs, and, without a robust approach for allocation, it may be difficult to assess the relative performance of different options with any degree of confidence. Several approaches have been used for allocation, and these are discussed below. Ideally allocation should carried out on the basis of responses of environmental burdens to marginal changes in individual outputs (Azapagic and Clift, 1994). However there are rarely sufficient data to allow the problem to be solved in this way.

Splitting

2.51 In some cases it is possible to split a multi-output or multi-input process into several smaller unit operations, each with only one valuable output or input. Materials of low value can be regarded as open loop outputs rather than burdens, and leave the system without contributing to, or subtracting from, the environmental burdens of the system (see box).

> **Allocation by splitting**
> A factory produces both a high quality injection moulded product and a low grade moulded material which uses the waste plastic from the high quality process. If the study addresses only the high quality injection moulded item, then the operation could be split at the point at which the plastic waste is produced. The plastic waste is assigned as an open loop output with the environmental burdens of collection, cleaning and reprocessing allocated to the secondary product, i.e. the low grade moulded material. All other burdens are allocated to the primary product, i.e. the high quality injection moulded product.

Allocation by weight

2.52 The environmental burdens can be allocated to the 'valuable' outputs or inputs in proportion to their weight (see box).

Allocation by weight

The steam cracking of naphtha (a hydrocarbon feed stock) which yields a mixture of shorter chain length hydrocarbons (including ethylene and propylene) which are then separated and used as raw materials for many different processes. One method of dealing with this type of process is to split the environmental burdens between the useful outputs in proportion to the weight of the products. The burden of producing 1kg of ethylene then becomes precisely the same as that for producing 1kg of propylene or any other of the 'valuable' outputs of this process, (taking no account of the changes in operating conditions necessary to change the product spectrum).

Allocation by energy content

2.53 If the outputs or inputs have a high energy content and could be used as a fuel then a common method is to allocate environmental burdens in relation to the calorific values of the outputs.

Allocation by chemistry

2.54 Environmental burdens can be allocated according to the molar mass proportions of the products by reference to chemical reactions taking place in the process (see box).

Allocation by chemistry

The electrolysis of water yields 1kg of hydrogen for every 8kg of oxygen:

$$2H_2O(9kg) \longrightarrow 2H_2\,(1kg) + O_2\,(8kg)$$

Using the weight based allocation method, oxygen would take 8/9 of the burden. Allocating burdens on a molecular basis, however, the hydrogen produced would take 2/3 of the burden and the 8kg of oxygen only 1/3. The chemistry involved in most processes is more complex, and this is one reason why more simplistic approaches to allocation are widely used.

Allocation by economics

2.55 The relative monetary values of the outputs or inputs can be used to allocate environmental burdens. The main drawback of this method is the volatility of the world and local markets. If price were to be used as our method of allocation, the results of a study would be continuously changing.

Allocation by economics
A mining operation which produces a valuable low volume product (diamonds being an extreme example) together with a high volume, low value by-product (grit, for example). For some mines the grit may be sold for use in the construction industry and may form an important part of the economics of their operation. The grit should therefore be allocated a proportion of the environmental burdens. For other mines producing the same main product in a more isolated locality the grit may simply be dumped. Allocation by weight of 'used' output would clearly not give sensible results. The economic method of allocation would be to consider the contribution the output made to the existence of the operation. If, at the end of the year, the diamonds contributed 95% of the plant's income then they could be allocated 95% of the plant's environmental burdens. In this case the remaining 5% of burdens would be allocated to the much larger mass of grit produced.

Avoided burdens approach

2.56 Where the system produces secondary products an alternative approach is to 'credit' the system for the burdens which are avoided by displacing the production of the secondary product by some other processes. This amounts to extending the system boundary, as recommended by Tillman *et al.,* (1994). Against the advantage that this 'avoided burdens' approach is a more representative method of computing burdens there is the disadvantage that the system analysis and data requirements are increased (see box).

Allocation by avoided burdens
The diamond mine mentioned previously which sells grit to the construction industry. The normal source of grit in this area might be a shallow grit pan from which the grit is extracted and washed. The diamond mine is operating at a considerable depth and so uses much greater resources in extracting the minerals and also involves energy intensive separation methods. The burden of the diamond mining operation could be calculated by taking the total burden of the operation and subtracting the emissions that would have been made to produce the grit by its normal method of extraction.

The 'four step' approach

2.57 In recognition that each of the above procedures have their own limitations (see Huppes and Schneider, 1994), a more rational approach has been sought, culminating in a four-step procedure first described by Huppes (1992). This approach was proposed originally for multi-product systems. However, it applies to any multi-function system and is therefore adopted in this report as a sound basis for assessing waste management systems. It can be restated as follows.

2.58 ***Step 1;*** operations specific to one system are identified, to define the basic distinction between the alternative systems.

2.59 ***Step 2;*** common processes and operations which contribute to the alternative systems in exactly the same way and to the same extent are not considered further in the comparison. It should be noted that common elements can be excluded **only** if they are equal in magnitude, or where the difference between them is explicitly taken into account. Where environmental burdens common to two or more systems are excluded in this way, the decision and rationale must be made clear.

2.60 ***Step 3;*** an inventory of environmental burdens arising from processes and operations which remain in the comparison after the simplification in steps 1 and 2 is compiled. These burdens are now allocated between outputs, wherever possible on the basis of physical causality. As a specific example, Huppes (1992) mentions cadmium emissions from municipal waste incineration which obviously should be allocated to the cadmium-containing items in the waste (primarily electric batteries).

2.61 ***Step 4;*** where allocation cannot be based on physical causality, for example if the outputs from the system cannot be varied independently of each other, the environmental burdens may be allocated between 'co-products' in proportion to their economic values (see Huppes, 1992).

2.62 Azapagic and Clift (1994) proposed that the physical relationships in step 3 should be expressed by allocating burdens between different outputs according to the marginal changes resulting from marginal changes in each output, with all the other functional outputs kept constant. For a full analysis of a complex system, this approach may require a detailed system model. However, it leads to some useful simplifications which are used for waste management in this report.

2.63 The 'avoided burdens' approach is a specific application of the general approach of Azapagic and Clift. Where materials and energy are recovered from waste, these are fed back into the rest of the economy. The burdens so avoided are evaluated as the marginal changes resulting, with the functional outputs of the economy constant so that the recoveries displace other activities. These 'avoided burdens' are often separated from other indirect burdens coming more conventionally from the background system due to the use of material or energy. The distinction between 'product related' and 'process related' burdens, developed in Annex 3 and used in Volume 1, is also an application of the 'marginal allocation' approach.

An example: material recycling versus energy recovery

2.64 A specific problem, comparison of recycling of waste paper compared against incineration with heat recovery, will be used to illustrate the 'four-step' approach to allocation. The system diagrams describing these two options are shown in outline in Figures A2.2 and A2.3.

2.65 This example is selected because it corresponds to a waste management problem which has received significant attention in LCI/LCA studies, which are reviewed below. Although none of the studies was presented as a problem in allocation, all were implicitly based on the more generalised approach recommended in this report.

Allocation by marginal change

For a system providing K different outputs X_k $(k=1,.....K)$ and generating J environmental burdens B_j $(j=1,.....J)$, the value of burden j allocated to one unit of output k should be evaluated as:

$$b_{j,k} = {\delta B_j}/{\delta X}$$

The partial derivative in this equation must be evaluated with all the other outputs constant (see Azapagic and Clift, 1994). This is possible in principle provided that the outputs can all be evaluated independently. Where this is not possible, i.e. where two or more outputs arise in fixed proportion, step 4 of Huppes' procedure must be used.

Most specific applications of LCI to waste management can be developed without explicit use of this equation. However, it is valuable as a formal statement of the principle of marginal allocation according to marginal change in the system output.

2.66 Step 1 defines the operations specific to each system, and these constitute the 'waste management activities' in each case. The functional 'output' delivered by the waste management activities in each case is processing of paper waste. This describes those stages of the life cycle where that waste paper is recycled to produce more paper or incinerated with heat recovery. Transport steps are included explicitly, because in general they will differ between the two waste management activities in each system.

2.67 Step 2 identifies the processes and operations common to the two alternatives. These fall in the 'background system', which represents all the activities whose interaction with the waste management activities is considered. These include primary paper manufacture and the supply of energy and other services.

2.68 Step3 is to compile the Inventory for the two cases, allowing for the burdens associated with both waste management activities and the background system. The alternatives are compared on the basis that other outputs, including paper usage, from the system are held constant with burdens according to marginal changes in the system. Step 4 is unnecessary in this example.

2.69 The primary input from the background system to the waste management activities is waste paper. The other inputs of materials and energy to the waste management activities can also be treated as flows from the background system. The main return flows, from waste management activities to the background system, are recycled paper or recovered energy. Because the system provides constant outputs, these return flows imply changes in the operation of the background system. However, if the recovered material is not actually used, then it does not affect the background system and hence still constitutes a waste (see White *et al.*, 1995). For recycling primary paper production is reduced so that some of the environmental burdens associated with paper manufacture are avoided. For energy recovery, energy production in the background system is reduced, so that some of the environmental burdens associated with energy production are avoided. The Inventory Table for each option would include:

- environmental burdens associated with waste management activities; plus,
- environmental burdens associated with the background system arising from energy and materials supplied to the waste management activities; and minus,
- environmental burdens associated with the background system avoided because of recycling activities in the waste management activities part of the system.

Data quality considerations

2.70 The credibility of LCI results, and therefore of the decisions based on them, are dependent on the quality of data used. A number of general principles are applicable to all studies:

- data quality goals should be established in the scope of the study;
- data should be assessed against the data quality goals as the study proceeds; and,
- data quality assessments for LCA studies should be available for review and evaluation particularly by those carrying out the critical review (see above).

Figure A2.2: System boundaries for Waste Paper Recycling

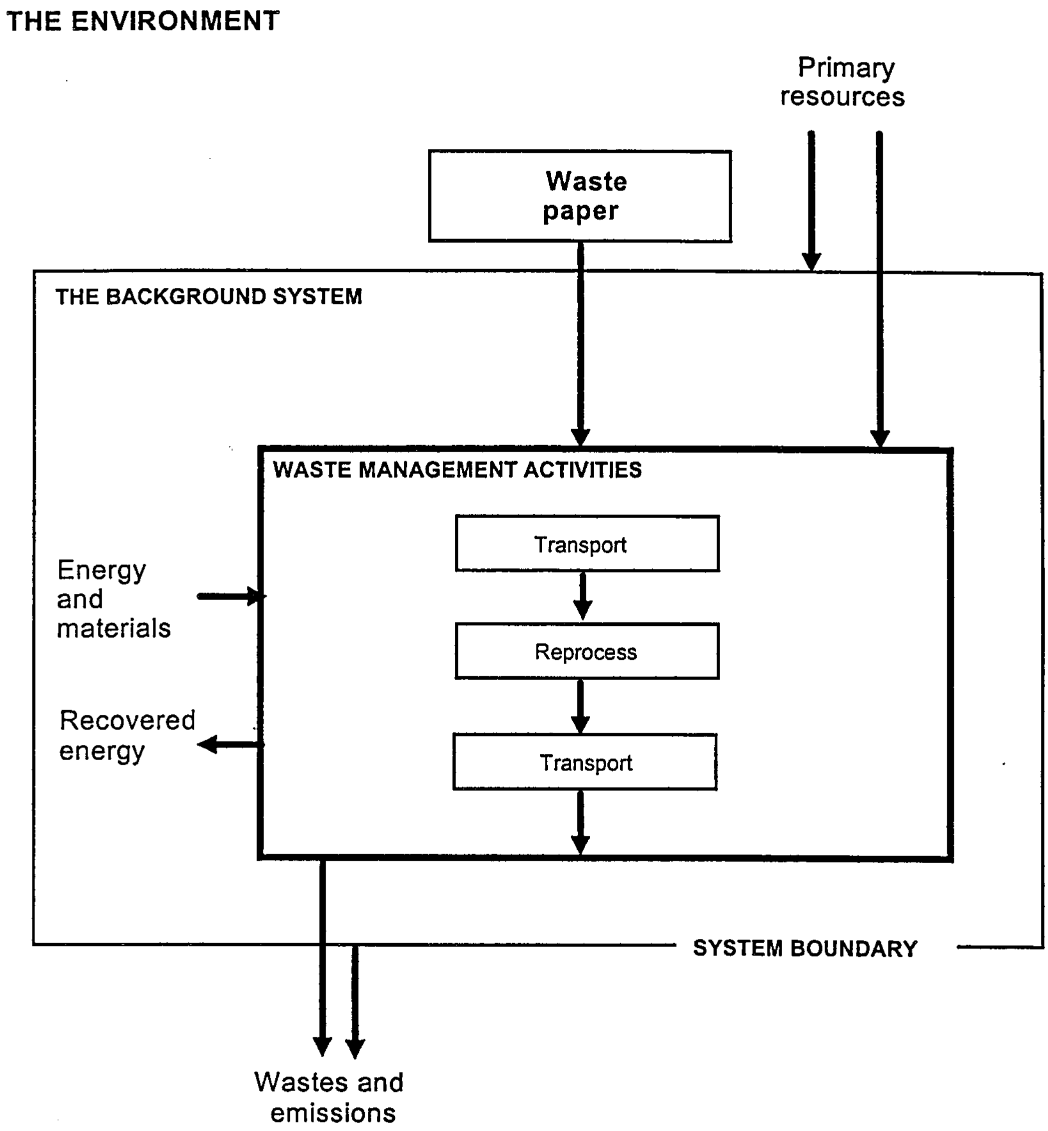
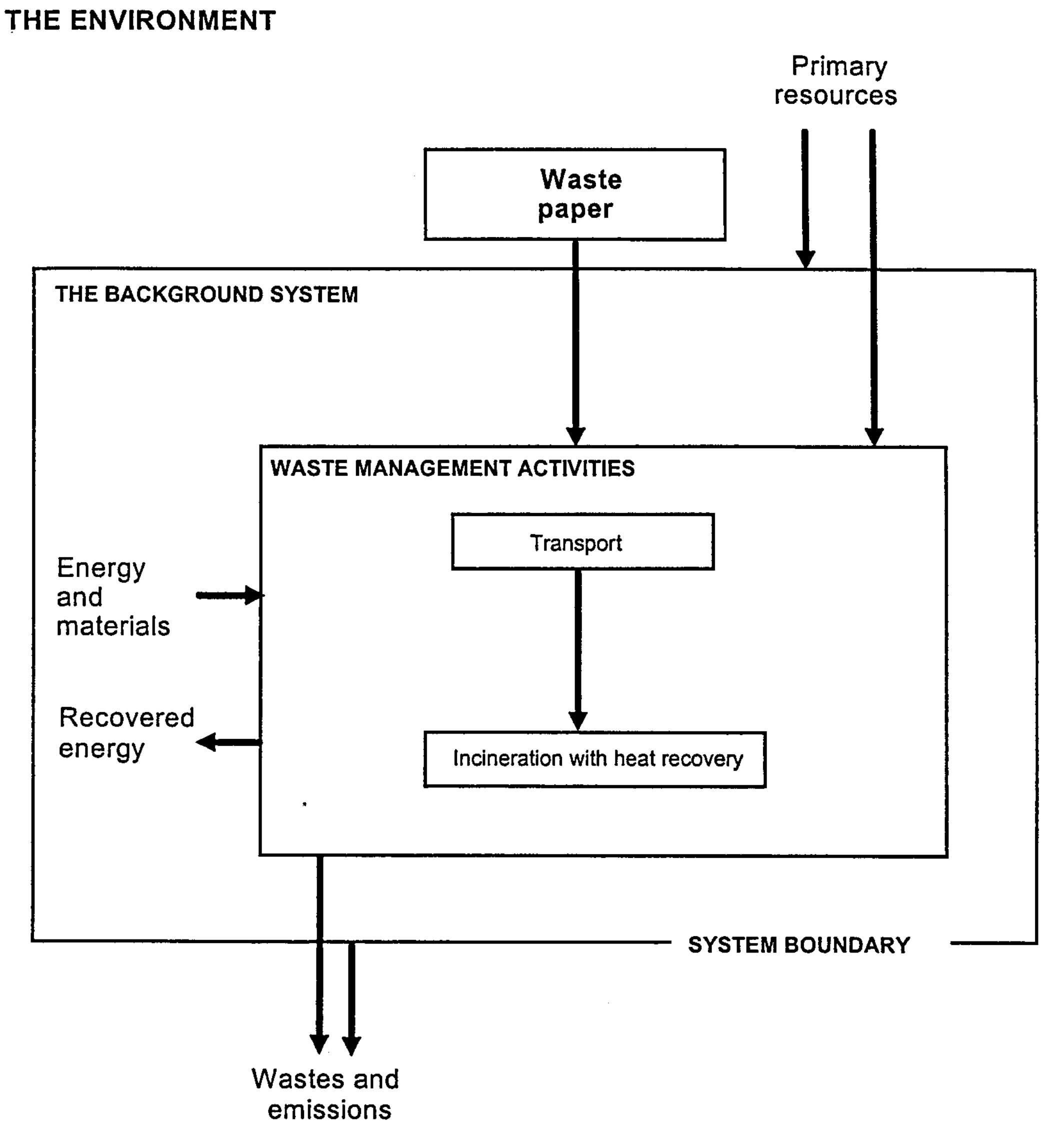


Figure A2.3: System boundaries for Energy Recovery from Waste Paper



Data quality considerations

- data source (spatial representativeness) - global, continental (for example Western European), regional, national (for example UK) or company or site specific;
- data age (temporal representativeness) - an indication of the age of the data should be given, and the most recent data should be used wherever possible;
- data representativity - are the data representative of best, worst or average technology?;
- data accuracy/variability - this can be assessed by, for example, comparing different sources of data; and,
- data completeness - data gaps must be noted and treatment of missing data specified, i.e. estimated or excluded; any assumptions made must be clearly stated.

2.71 Data should be used that are specific to the system under consideration, and where specific data are not available, data from other sources may be used. Such sources include the proprietary LCA databases, government and industrial databases, published literature, laboratory testing, engineering calculations based on process chemistry and technology and estimates from similar operations. Data gathered for a particular operation should ideally be averaged over a reasonable time frame, commonly one year, to take account of atypical behaviour or seasonal changes. Where any uncertainty exists regarding the accuracy of data, or estimates and assumptions have been made sensitivity analysis should be performed.

Sensitivity analysis

2.72 Where data are uncertain or variable sensitivity analysis allows the consequences of that error on the results of the study to be estimated. The validity and credibility of the results of the study are thus enhanced. Sensitivity analysis can substantially reduce the work and time involved in data collection. It allows the importance of a particular piece of data to be assessed and can therefore determine the amount of work necessary to obtain data that meets the needs of the inventory, i.e. whether values require specification to a higher level of accuracy or not. Sensitivity analysis can be used in the following ways.

1. As a check in cases where data are used whose quality is suspect or unknown and where data values are missing. A range of values for the missing data can be put into the model and, by running calculations, the importance of the missing data on the final results can be assessed. Where a sensitivity analysis reveals that results are highly dependent on particular sets of data, or are particularly sensitive to the data values used, these data should be clearly identified and steps taken to check the data and, if necessary, obtain more accurate or site specific data.
2. To determine the influence of any assumptions made on the overall results.
3. To help identify parts of the life cycle which are responsible for the majority of the environmental impacts. By running calculations with, and without, a given life cycle stage, its importance in terms of effect on final results can be determined. The identified critical steps can then be analysed in more detail.
4. As part of the basic goal of the study, such as assessing changes caused by different waste management options.

Capital goods and equipment

2.73 SETAC (1992) concludes that "*...capital goods should be included only when the investments are clearly and significantly different in compared alternatives".* Whether or not capital goods will contribute to the comparisons needed in assessing waste management strategies will only become clear when necessary sensitivity analyses have been carried out, and thus such an analysis should be included in the study.

2.74 In each case, the burdens arising from routine operation will be routinely included, as for any other processing operation. However, unless specific sensitivity analyses are carried out, one cannot be certain as to the significance of data relating to the environmental burdens associated with equipment maintenance.

Non-Flux Burdens

2.75 The current approach to Impact Assessment in LCA is based on the premise that environmental impacts can be related to quantified environmental burdens. In fact, all environmental impacts are to some extent 'socially constructed', i.e. the extent to which a burden becomes a recognised environmental impact is determined by the reactions of people who are affected by or perceive the burden (Clift *et al.*, 1995). Conventionally LCA avoids this problem until it attempts to assign measures of relative importance to different environment impacts at the Valuation stage. However, some impacts can only be assessed in terms of a social or human impact which cannot be related simply to a transfer of materials or energy between the 'system' and the 'environment'. Examples of such non-flux burdens were introduced earlier in the Chapter. They include noise (because the impact depends on the frequency spectrum of the sound, not just the energy content or 'decibel level'), and aesthetic appearance or visual intrusion (which is self-evidently socially constructed).

2.76 Disamenity impacts do not fit readily into the conventional LCA framework for impact assessment, and, furthermore, are usually localised. They have therefore frequently been omitted, as noted above. Nevertheless, they are a matter of serious public concern about waste management facilities and will inevitably affect development decisions. Non-flux burdens should therefore be recognised and recorded during the LCI process. Assessment of their impacts remains to be developed, but it is likely to depend on key variables such as the number of households affected by disamenity. Difficulties at the Impact stage will be reduced if these key data are also reported with the more conventional Inventory data.

Applications of LCI/LCA to Waste Management

2.77 The generic problem of applying LCA to solid waste management has been discussed in the literature (for example Allen and Rossalot, 1994; Aumônier, 1995; Ekvall, 1992; Kirkpatrick, 1995; Eggels and van der Ven, 1994; Finnveden, 1994; Karlsson, 1994; Kirkpatrick, 1996; Lox, 1994; Morris and Canzoneri, 1992; Schonert and Goldhan, 1994; Tillmann *et al.*, 1994). Recently, White *et al.*, (1995) have published generalised Inventory data on solid waste management. However, studies of specific issues are limited. The case most thoroughly considered is the comparison of alternative approaches to managing waste paper (Porteous, 1992; ETSU, 1993; Virtanen and Nilsson, 1993; Johnson, 1993; Daae and Clift, 1994). Although not stating it explicitly, all these studies have adopted approaches which fit into the general framework developed in this report, distinguishing between foreground and background systems.

2.78 In varying levels of detail, these studies have followed the material through the whole chain from virgin material production, through manufacturing and use to final disposal, incineration or recycling. The main interest has been on the comparison between recycling and incineration with heat recovery (Figures A2.2 and A2.3). The avoided burdens turn out to be critical.

2.79 All the studies conclude that it may be environmentally more sound to burn paper as a fuel rather than to recycle it, provided that the virgin fibre is produced from sustainably managed forests. The main consideration is the large energy requirement for reprocessing. Virgin fibre production in mills with integrated energy management derives most of its energy from biomass arising from forest management and from parts of harvested trees which are not used for paper products. However, if the recycling is carried out at a site where little or no biomass is not available as a source of energy, in the UK, for example, then the energy required for reprocessing is derived mainly from fossil fuels. Incineration, on the other hand, generates an energy supply which offsets the use of fossil fuels. Further burdens from the foreground recycling system arise from the need to de-ink the paper and from water consumption. Virtanen and Nilsson (1993) go further and argue that reduced demand for virgin paper has a negative effect on forest management, although the reduced requirement for intensively managed forest is not considered.

2.80 Porteous (1992) considers landfilling the waste paper, and concludes that this would lead to far higher greenhouse gas emissions than recycling. However, this analysis does not account for the option of landfill gas combustion. Furthermore, it has also been argued elsewhere that landfilling waste paper should be encouraged as a carbon sink.

2.81 Some of the studies emphasise the difference between the use of paper from sustainable forests in Northern Europe and the destruction of 'old growth' forests by the North American forest products industry. Johnson (1993) concludes that, for paper produced in the UK, *"...there is a trade-off between the relative impacts of recycling and incineration, and the final decision depends on the relative values placed on the impact categories, such as global warming"*. One of the more important outcomes of these studies may be the conclusion that sustainability of production rather than waste management is the more important concern.

2.82 The above results are specific to waste paper. Quite different conclusions have been derived from other materials. Ekvall's (1992) comparison of recycling and incineration reached the same conclusions for paper as the studies summarised above, although he also points out that paper recycling increases the potential for energy extraction from forests. However, for other wastes he concluded that incineration is environmentally the worse option. The difference lies in the high energy requirement for paper recycling and the renewable source of the primary material.

2.83 For tin-plate containers, Porteous (1992) concluded that there is a significant environmental advantage in recycling compared with landfilling, arising from the avoided burdens associated with primary production of steel from iron ore. However, there is uncertainty in the results arising from difficulties in defining process boundaries and obtaining data on burdens, primarily for tin production. Porteous also included collection of tin-plate containers, and concluded that kerbside collection is more energy intensive than magnetic extraction from the mixed MSW stream.

2.84 Guelorget *et al.* (1993) have reported a very preliminary study on waste tyre disposal. At this stage the lack of operating data, particularly on tyre pyrolysis plants, inhibits firm conclusions. However, it is worth noting that one possible disposal route previously recommended in the US, incorporating tyre 'crumb' into new road surfaces, has effectively been abandoned. The reason is that road surfacing materials normally pass through a 'cascade of uses' with material from the surface of motorways re-used in lower specification surfaces, ending up in car parks or playgrounds. Incorporating tyre crumb reduces or prevents this re-use so that it ultimately leads to an increased quantity of tar rich but incombustible waste (Organ, 1994). This represents an interesting cautionary tale, where initial failure to consider the whole Life Cycle led to the wrong choice of disposal option.

2.85 The uncertainties arising when data availability is limited and the data are uncertain are illustrated by the debate on incineration of waste. The Royal Commission on Environmental Pollution (RCEP, 1993) estimated that waste incineration with energy recovery emits less global warming gases than does landfill where the landfill gas is recovered and burned with energy recovery. However, Wallis (1994) reached the reverse conclusions. The differences between the two analyses include the estimates used for the efficiency of energy conversion in a waste-to-energy plant, the extent of methane emission from a landfill, and the greenhouse warming potential of methane. Some of these uncertainties are considered in more depth by Aumônier (1996), who concludes that the best estimate favours incineration. Scientific opinion is converging on an agreed figure for the last of these uncertainties (see Heijungs *et al.*, 1992), but the other two key parameters remain uncertain and to some extent site-specific.

Process Related and Product Related Burdens — 3

3.1 For any processing operation, a matter of concern is the extent to which each individual burden depends on the composition of the waste or on the quantity of each individual constituent in the waste. This is an important distinction as resolution of this problem would greatly ease the prediction of burden levels during the quantification stage. For most operations, this dependence is unknown and adoption of the twin track approach (see Volume 1, Chapter 4) does not avoid the need to address this issue for direct burdens.

3.2 However, research at the TNO Institute of Environmental and Energy Technology (Eggels and van der Ven, 1994) has considered this issue for the specific case of emissions from waste incineration. Eggels (1994) has suggested that the general approach may be applied to other operations.

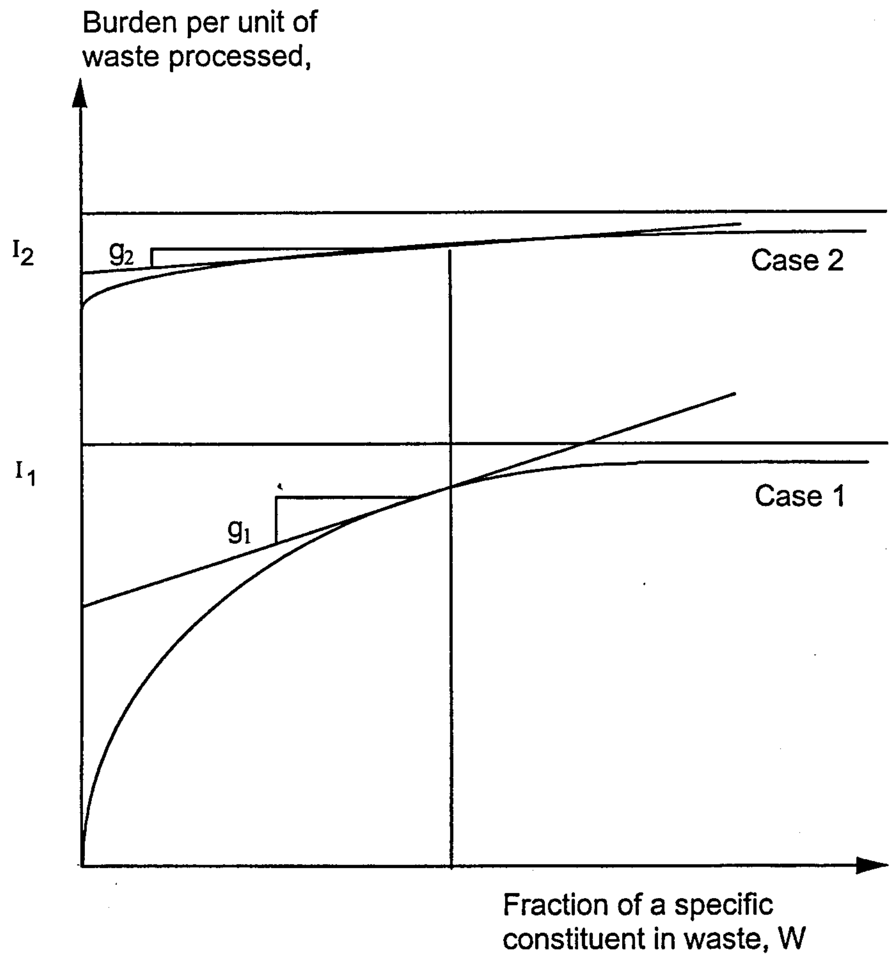
3.3 The approach is a further application of the 'marginal allocation' approach (see Annex 2). The principle is that the changes in burdens resulting from marginal changes in the quantity and composition of the waste passing through a process are evaluated. This enables a broad distinction to be made between *process related* burdens which depend on the process and on the quantity of waste passing through it (waste independent burdens), and *product related* burdens which depend on the composition of the waste (waste dependent burdens).

3.4 The distinction is illustrated schematically in Figure A3.1. The ordinate shows some burden per unit quantity of waste processed (i.e. per functional unit, see Annex 2). The abscissa shows the fraction of some specific constituent in the waste processed. Two curves are shown, corresponding to two different types of burden.

3.5 For *Case 1*, the burden depends on the waste composition. The case shown schematically in Figure A3.1 refers to a burden which arises solely from the constituent in question, a specific example is chlorine containing emissions (for example, dioxins and furans) which are absent if there is no chlorine in the waste. However, the quantity of the burden does not vary linearly with the quantity of the constituent in the waste. For at least some burdens, including dioxins and furans from waste combustion, the burden approaches an asymptotic value, so that marginal changes in waste composition have very little effect on the burden. The value of the asymptote depends on the specific technology used. For dioxins and furans, for example, it depends on combustion conditions, the subsequent gas temperature profile and gas cleaning.

3.6 *Case 2* represents a burden which varies very little with waste composition over the whole composition range. Examples are particulate emissions from combustion processes, where the burden is again more dependent on the combustion technology than on the nature of the solid waste, or burdens arising from transport of solid waste.

Figure A3.1: Product Related and Process Related Burdens



3.7 In general, decisions over waste management strategies will be concerned with waste of specified composition, or at most with minor variations in composition about some mean. It will suffice therefore, at least at this stage in development of the methodology, to consider only marginal charges about one composition, shown schematically as *W* in Figure A3.1. These changes are represented by the tangents to the curves. The intercept of each tangent, I_1 and I_2 in Figure A3.1, represents a fixed burden, arising whenever waste passes through this particular operation whatever its composition. Following Eggels and van der Ven (1994), these burdens are termed *process-related.* The gradient of each tangent, g_1 and g_2 in Figure A3.1, corresponds to the variation of the burden in question with waste composition. Thus the total of burden j arising from processing unit quantity of waste containing fraction w of the constituent in question is:

$$B_j = I_j + g_j w \qquad (3.1)$$

3.8 The term $g_j w$, representing the burden which varies with waste composition, is known as *product related* (Eggels and van der Ven, 1994). Generalising Equation (3.1) to a waste containing K constituents, the fraction of constituent k being w_k, the resulting value of burden B_j is:

$$B_j = I_j + \sum_{k=1}^{k} g_{j,k} \, w_k \qquad (3.2)$$

3.9 Equation (3.2) provides a general basis for LCI comparison between different waste management strategies. However, data in this form are rarely, if ever, available at present. It is therefore introduced in this report for two reasons. It is proposed as the framework within which data on burdens associated with specific operations should be interpreted as they become available. More immediately, it enables a pragmatic distinction to be made between burdens which can be treated entirely as process related (i.e. those for which I_j is the dominant term) and those which are effectively entirely product (waste) related (i.e. those for which the terms in $g_{j,k} \, w_k$ dominate). For burdens in the former category, it suffices to report the quantity of waste processed. For burdens in the latter category, the dominant constituents of the waste should be identified, as those with the dominant values of $g_{j,k}$. It then suffices to report the fractions of these dominant constituents in the total waste processed.

3.10 Equation (3.2) is an example of the 'marginal allocation' approach discussed in Annex 2 and also accounts fully for all the burdens arising from any operation (see Eggels and van der Ven, 1994). It is therefore fully consistent with the general methodology proposed in this report. If 'capital' burdens are to be included, then equation (3.2) will take the form:

$$B_j = f_j + W\left[I_j + \sum_{k=1}^{k} g_{j,k} \, w_k \right]$$

where B_j is the total burden j associated with a facility which processes W units of waste during its operating life, and f_j is the burden j arising from construction, maintenance and decommissioning of the facility.

3.11 Following the TNO approach in practice (Eggels, 1994; Eggels and van der Ven, 1994), the distinction between product related and process related burdens does appear to provide a convenient basis for producing inventory data for waste dependent burdens associated with atmospheric emissions from waste combustion. Making the crude division into two groups of emissions, Eggels and van der Ven (1994) proposed the classification in Table A3.1 for MSW incineration. The classification is derived from process data, but in general shows features which are not unexpected. Major burdens, e.g. carbon dioxide and acid gases, depend on the proportion of the essential element present, and are therefore product related. Trace emissions represent mainly material which penetrates the gas cleaning system, and are therefore process related.

3.12 However, it must also be borne in mind that this classification depends on the waste and the process. For example, the scrubber residue in Table A3.1 refers to wet scrubbing (see Eggels, 1994), which is being supplanted progressively by dry or semi-dry scrubbing for waste incineration. Because dry scrubbers are usually operated with constant sorbent throughput, dry scrubber residue is likely to be process, rather than product, related. Similarly, some of the trace emissions could become product-related if the fraction of the key element is low (see Figure A2.1). Dioxin and furan emissions from combustion of a material which is very low in chlorine, waste tyres for example, may be low and dependent on the chlorine content of the feed. Therefore, under these circumstances, dioxin and furan emissions become product related burdens. However, this applies only from a plant dedicated to combustion of low-chlorine material. If batches of different materials are processed in succession, these emissions may remain in the process related category.

Table A3.1: Classification of Atmospheric Emissions from Municipal Waste Incineration (from Eggels and van der Ven, 1994)

Product Related Burdens	Process Related Burdens
CO_2	CO
SO_2	Hydrocarbons
HCl	Poly-aromatic Hydrocarbons
HF	Dioxins
Heavy Metals	Furans
Solid Residue	
(Wet) Scrubber residue	Particulates

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Glossary

In this report, the following terms and definitions apply:

Aerobic process: A microbiological process which requires the presence of oxygen.

Allocation: Technique whereby environmental burdens are partitioned between multiple inputs or outputs of a defined system.

Anaerobic process: A microbiological process which requires the complete absence of oxygen. Anaerobic bacteria are often poisoned by the presence of oxygen.

Avoided burdens: Environmental burdens associated with the background system which are avoided because of recycling of materials or energy recovery taking place in the waste management activities.

Biogas: A mixture of gases generated by microbiological processes, typically in landfills and anaerobic digestors, which comprises methane and carbon dioxide in varying, but often equal proportions, and with methane seldom more than 60% by volume. Also contains small amounts of other gases.

Bottom ash (clinker): The residue that collects in the bottom of the burning chamber of an incinerator. Bottom ash includes all the solid materials that pass through the furnace un-burnt, such as glass, metals, rocks, soil, car parts and broken appliances.

Bring facilities: These are recycling facilities which require clean segregated material to be delivered and deposited by members of the public at dedicated collection sites such as glass and paper banks.

Calorific value: The quantity of heat produced by the complete combustion of a given mass of a fuel, usually expressed in Joules per kilogram.

Characterisation: Substep of the LCA Impact Assessment in which the classified inventory parameters are processed into a common unit characterising the impact category and, where possible, aggregated.

Civic amenity site (CA site):	A dedicated site provided by the Local Authority for local residents to dispose of bulky household items such as garden wastes, old appliances, carpets, etc.
Classification:	Substep of the LCA Impact Assessment in which all input and output flows of the system are assigned to one or more impact categories representing an environmental effect.
Closed-loop recycling:	A recycling process in which an output from a system, which would otherwise be a waste, is returned to the system, with or without treatment, to contribute to production of the main product.
Data quality:	The degree of confidence in individual input data from a source, aggregated data and in the dataset as a whole. LCA data quality is described by the data quality indices (DQIs) selected for the study.
Data:	LCA data is the collective term for all data and information (quantitative and qualitative) used in performing LCAs. This may include raw data as well as intermediate data obtained through manipulation. LCA data come from disparate sources and are of various types.
Depletion:	Reduction in the global stock of raw material as a result of extraction of non-renewable resources (for example, mineral extraction or crude oil production), or extraction of renewable resources faster than they can be renewed (for example, de-forestation).
Direct burdens:	Environmental burdens arising from the foreground system/waste management activities.
Environmental burden:	Energy and raw materials used and waste released to air, water and land.
Environmental impact:	Any change to the environment which, permanently or temporarily, results in loss of natural resources or deterioration in the natural quality of air, water or soil. The consequences for human health, for the well-being of flora and fauna or for the future availability of natural resources attributable to the input and output streams of a system.

Fixed burdens: These are 'process related burdens' that arise due to the physical existence of the operation alone, for example, visual intrusion, land use and burdens associated with construction and decommissioning.

Fly ash: The fine particles of ash in flue gases that are captured and collected by pollution abatement technologies.

Functional unit: The unit of measure of performance of the main functional output of the product or service system.

Goal definition: Part of the goal definition and scoping element of the LCA process leading to an unambiguous statement of the reason for carrying out the LCA, the intended use(s) of the results the intended audience, the initial data quality goals and the type of initial review process to be employed (if any).

Impact assessment: The element of the LCA process aimed at a technical, quantitative and qualitative classification, characterisation and valuation of the magnitude and significance of environmental impacts based on information to the inventory analysis.

Indirect burdens: Environmental burdens associated with the background system.

Inherent energy (also intrinsic energy or energy of material resources): The gross calorific value of material inputs.

Interpretation: Interpretation is the part of LCA where the inventory and impact assessment results are assessed in line with the goal and scope of the study.

Inventory analysis: The element of the LCA process where data are compiled to quantify all environmental burdens throughout the life cycle of a given product or service system.

Kerbside facilities or collect systems: These facilities require the householder to put out clean recyclable materials for specific collection from outside the property.

Landfill: The engineered practice of depositing waste into or onto land with final restoration to provide land for alternative use.

Landfill gas: Produced as a result of the decay of the organic components of waste deposited in landfill sites, under anaerobic conditions, by a mixed population of micro-organisms. The gas is comprised principally of carbon dioxide and methane, in varying, but often approximately equal concentrations, depending on the age and nature of the waste and a number of environmental factors. The gas also includes trace concentrations of a range of other gases.

Leachate: The result of liquid seeping through a landfill or other waste management processes and by so doing extracting substances from the deposited wastes.

Life cycle assessment: A systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle.

Life cycle: The consecutive and inter-linked stages and all directly associated significant inputs and outputs of a system, from the extraction or exploitation of natural resources to the final disposal of all materials as irretrievable wastes or dissipated energy. Also termed 'the cradle to the grave'.

Local authority waste disposal company (LAWDC): Local Authority Waste Disposal Company established at 'arms length' from other Local Authority institutions to provide waste disposal services in a fully commercial environment and in competition with private sector waste management companies.

Mass burn: Incineration plants which combust MSW without any processing or separation other than the removal of exceptionally large items that are too large to be fed into the combustion unit.

Materials recovery facilities (MRFs): A facility to process single materials from recycling schemes using a combination of mechanical technologies and hand picking techniques.

Municipal solid waste (MSW): All wastes collected by local authorities or their contractors from householders, commercial premises, and from CA sites delivered by local residents.

Non fossil fuel obligation (NFFO): Electricity generated from non-fossil fuel sources can, if awarded a contract, attract premium prices under the Non-Fossil Fuel Obligation introduced under the Electricity Act 1989. A number of Renewable Energy Orders have been made for England and Wales and similar Orders placed for Scotland and for Norhtern Ireland.

Non-renewable resource: A natural resource that cannot be replaced or regenerated or brought back to its original state once it has been exploited (or used as an input to an economic system).

Open-loop recycling: A recycling process in which an output from a system, which would otherwise be a waste, is used as an input to another system, with or without treatment, to contribute to the production of a useful product.

Putrescibles: Waste which is liable to decay rapidly, including food, vegetable and fruit wastes and may sometimes include garden wastes. Does not include all organic material which may decay under anaerobic conditions (e.g. paper, wood etc.).

Recycling: A set of processes for diverting materials that would otherwise be disposed of as wastes, into an economic system where they contribute to the production of useful material.

Refuse derived fuel: This is produced by mechanical processing of waste using screens, shredders and separators to yield a combustible product. There are two man types of RDF, coarse and densified. Coarse RDF (c-RDF) is more suited for direct on-site use since it cannot be stored for any considerable period. Densified RDF (d-RDF) is produced by further processing including drying and pelletising to produce a fuel.

Renewable resource: A natural resource that is capable of regeneration when part of its stock is exploited (or used as input to an economic system), for example plants and animals, hydro and wind power.

System boundary: The interface between the system being studied and the environment or other economic systems (all inputs and outputs compiled in the inventory table enter or leave the system across the system boundary).

System: A collection of materially and energetically connected operations which performs one or more defined functions.

Transfer station: A facility where refuse collection vehicles deliver waste to a central transfer station where it is loaded into vehicles or containers for onward bulk transport.

Trommel: A cylindrical drum with holes of specific size that rotates about its central axis. 'Undersize' material (material smaller in diameter than the holes) falls through the holes and is thus separated from the 'oversize' material.

Technosphere: The full sphere of human activity.

Unit operation/ process: The smallest portion of a system or activity for which data are collected.

Valuation: Substep of the impact assessment element of the LCA process in which the results of the characterisation are compared (note: the valuation may involve the interpretation, further aggregation, weighting and ranking of data).

Waste dependent burdens: These are 'product related burdens' due to the combination of unit operation, throughput and the nature of the waste.

Waste independent burdens: These are 'process related burdens' due to the quantities of waste flowing through the operation irrespective of the specific characteristics of the waste.