Environmental and Economic Decision Support Methodology for End-of-Life Products

In one volume

Aurora Dimache

Submitted for the Degree of Master of Engineering

Research carried out at: GMIT, Galway, Ireland
Research Supervisor: Dr. Kate Goggin

Submitted to the Higher Education and Training Awards Council

July 2003

DECLARATION

I hereby declare that the work presented in this thesis is my own and that it has not been used to obtain a degree in this university or elsewhere.

Aurora Dimache

To my husband Laurentiu

and my parents

ABSTRACT

Many producers are becoming environmentally conscious due to legislative, consumer and business pressures. The proposed EU Directive on Waste Electrical and Electronic Equipment (WEEE Directive) sets targets for the reuse and recycling of electrical and electronic products reaching the end of life stage. How a producer determines which is the best strategy for his/her products (reuse, part reclamation, remanufacturing, recycling) is not addressed. Producers must meet targets in the WEEE Directive, consider other environmental regulations, and make sure they are economically efficient. The question then is how to incorporate both economic and environment into their business decisions.

A methodology that intends to overcome this difficulty is developed and presented in this thesis. The challenge is to calculate environmental and economic indicators per product for each end-of-life option. A product model and end-of-life option models are proposed to assist in calculations development. An algorithm for calculation of environmental indicators per product is developed and the absorption costs method chosen for calculation of costs per product. However, economic costs and values are expressed in money, environmental impacts in a multitude of units. The difficulty for decision-makers is the comparison of dissimilar criteria (€, kg CO_2 equivalent, etc.). The Analytical Hierarchy Process (AHP) is proposed to support the decision as to choice of end-of-life strategy for electrical and electronic products. Thus, environmental considerations and constraints stated by legislation along with the economic judgements are incorporated in the decision-making process for end-of-life products.

PUBLISHED WORK ASSOCIATED WITH THIS THESIS

Dimache, Aurora; Dimache, Laurentiu & Goggin, Kate – *Analytical Hierarchy Process (AHP) in Decision-Making for End-of-Life of Products*, Proceedings of the 2nd Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, June 2003;

Dimache, Laurentiu; Dimache, Aurora & Goggin, Kate – *Products End-of-Life Scenario Modelling Using Linear Algebra*, Proceedings of the 13th SETAC (Society of Environmental Toxicology and Chemistry) Conference, April 2003.

The research described in this thesis was funded by the EEDSS project. The EEDSS (Environmental and Economic Decision Support System for End-of-Life Products) project is a basic research project funded by Enterprise Ireland.

ACKNOWLEDGEMENTS

I would like to thank, first of all, my supervisor, Dr. Kate Goggin, for all the help and advice during the development of the thesis, and for giving me the opportunity to work in research for these two and a half years.

Thanks to Camelia and Ovidiu, Elena and Dana in CIMRU who always gave me a hand when I needed it. Again thanks to Camelia and Ovidiu who made my stay here in Ireland much better with parties, barbeques, movies, trips and long talks on Sunday evenings.

Special thanks to David, the greatest Irish guy. Always there when I needed some help. And he never said no to an invitation to a pint or to a weekend away. Good luck with your PhD and your project in Norway. To Colin and Derek, some other Irish guys who made me feel more comfortable while away from home.

To Carine, who never said no to a cup of coffee and made me feel better after a short break in the canteen. To Jean-Philippe and Laurence for the good time we had in the Training Restaurant.

Special thanks to my parents who miss me a lot but understood that my career is important for me and supported me.

And finally, thanks to Laurentiu who was always there for me.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

1.1. INTRODUCTION

The final stage of the life cycle of a product, retirement, is one that has been often ignored. The retirement stage begins when the customer no longer wants the product. What happens to a product after the end of its usage is of growing importance to the producer because of consumer demands and other growing pressures such as new legislation that mandates recovery and recycling of some products by their manufacturers. The electronics industry is particularly under increasing pressure as new legislation (The Directive on Waste from Electrical and Electronic Equipment – WEEE Directive) is being prepared at the EU level setting targets for the reuse and recycling of electrical and electronic goods reaching the end of their useful life.

The decision-making process as it relates to determination of end-of-life option is not an easy task as it involves consideration of variables which cannot be easily quantified into monetary units, and the decision-making process is likely to be influenced by multiple criteria [Tiw99], rather than by an exclusive single criterion.

1.2. THESIS MOTIVATION

At the product's retirement stage, there are a variety of possible alternatives. There are multiple options that do not include disposal, such as *reuse/part reclamation*, product recovery (*remanufacturing*) or material recovery (*recycling*) [Spi97], but there are also disposal options like *incineration with energy recovery* or simply *disposal to landfill*.

Figure 1.1 presents a hierarchy of the end-of-life treatment options of the current situation and practice, and the hierarchy recommended by the European Commission under its sustainable development initiative [COM93]. According to this hierarchy, when products enter the waste stream, first priority should be given to reuse or remanufacturing or to their recycling for the purpose of manufacturing new products. Disposal without any material or energy recovery is to be regarded as an option of last resort.

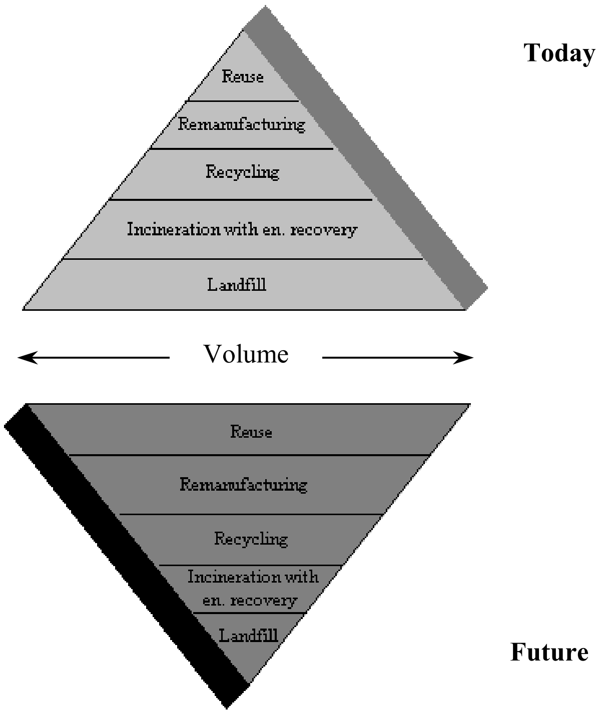

Figure 1.1. Hierarchy of end-of-life treatment options [Gog98, modified]

The hierarchy aim is to recommend the most favourable end-of-life option from an environmental perspective but it does not always represent the best option in economic terms [Gog98]. Actually, even from an environmental point of view the hierarchy is contested by environmentalists and those involved in the recycling industry as the Commission does not specify on which criteria this hierarchy is based (is it waste reduction, conservation of resources, energy consumption, environmental impact?). Therefore, in order to provide a hierarchy of the possible end-of-life options rigorous criteria should be defined first.

But environmental impact is not the only criterion producers would consider when deciding upon the most suitable end-of-life option for their products. Economic impact is another issue that has to be considered in the decision-making process.

So, when it comes to the end of life of products a decision must be made whether to recover or not but the factors that influence this decision are complex, comprising both environmental and economic issues. Current methods are not specifically applicable to end-of-life treatment analysis. Tools exist for performing a life cycle analysis (LCA) but focus on the life cycle in its entirety. Existing economic methods and tools also exhibit deficits as they do not take account of, for example, external costs or markets for recycled materials or products. One of the most common techniques used in decision-making has been the cost-benefit analysis. The main limitation of such an approach is that all the effects of an activity are evaluated in monetary terms, so that when aspects that cannot be quantified into monetary units (such as environmental issues) are dominant, the method is completely inappropriate [Col99].

In recognition of the complexity involved in integrating environmental and economic impacts into a ‘sustainability index’, the United Kingdom Government in its consultation paper *Sustainability Counts* (1999) commented that “while some of these currently available ideas are useful as tools for raising awareness, they are not yet scientifically valid or technically robust and so cannot be used to monitor progress year on year in a reliable way” [UKG99].

Therefore, considering all the aspects presented above, the decision-making process in the end-of-life products area necessitates an **environmental and economic decision support methodology** that helps in **choice of best end-of-life option for waste products**, the decision being based on **very clearly defined criteria**.

1.3. THESIS STRUCTURE

This thesis aims to provide a methodology to assist in decision-making as it relates to recovery of end-of-life products. The methodology provides decision support based on well-defined environmental and economic criteria.

Chapter 2 is a review of some current methodologies for quantifying environmental and economic impacts of products. It presents some methodologies used for environmental assessment – Life Cycle Assessment (LCA), Environmental Impact Assessment (EIA) and Eco Indicators – as well as methods of calculating production costs – Absorption Costing and Activity-Based Costing (ABC) – and assesses the potential for application of these methods to end-of-life products. This chapter highlights the deficit related to methodologies capable of quantifying both environmental and economic impact of products and transferring them into a single unit/number.

Chapter 2 highlights the need for a product description in connection with the end-of-life processes that must be provided in order to calculate the environmental and economic impact of end-of-life products; chapter 3 investigates product models – Bill of Materials

(BOM), Computer Aided Design (CAD) models and STEP standard (Product Data Representation and Exchange) – and the possible end-of-life options for products. The necessity for a product model especially designed for end-of-life use arises.

Chapter 4 addresses multi-criteria analysis. Decision-making for end-of-life products involves a multitude of criteria rather than a single exclusive criterion. Several methods used in decision-making – such as Quality Function Deployment (QFD), Cost-Benefit Analysis (CBA), Cross-Impact Analysis, Analytical Hierarchy Process (AHP), PROMETHEE and ELECTRE) – are presented and their potential for application to the decision-making for end-of-life of products investigated.

In chapter 5 the environmental and economic decision support methodology is developed. The methodology is intended to support compliance with the EU WEEE Directive and can be applied to end-of-life electrical and electronic goods. It proposes a product model that permits information exchange between producers and processors, and the calculation of environmental and economic indicators. Possible sequences of processes for each end-of-life option are presented. Based on the Eco Indicators methodology presented in Chapter 2, environmental indicators are chosen and an algorithm for their calculation is developed. The absorption costing method is used for calculating the most important economic indicator from the producers' point of view: processing cost. Finally, the Analytical Hierarchy Process (AHP) is proposed to assist in the decision-making process, as it is a powerful tool that helps decision-makers structure and evaluate different end-of-life options based on the environmental and economic indicators calculated.

Finally, chapter 6 concludes the thesis. In this chapter the thesis is summarised and conclusions drawn while developing the thesis are noted. Recommendations are made for further work.

1.4. CONCLUSIONS

Increasing pressures are put on producers to take back their products for recovery. However, there are many end-of-life options for these products and a decision must be made as to determination of one option. The decision-making process for end-of-life products is a difficult task as it has to consider many criteria, both environmental and economic. The diversity of environmental impacts and the multitude of units they are expressed in, and the complexity of the economic aspects pose problems to monetisation of *all* the criteria. That is why, for the complex environmental and economic decision-making process, a new methodology capable of giving solutions to make economic as well as environmental sense needs to be developed.

CHAPTER 2. METHODOLOGIES FOR QUANTIFYING THE ENVIRONMENTAL AND ECONOMIC IMPACTS OF PRODUCTS

2.1. INTRODUCTION

Sustainable development encompasses three basic areas: environmental protection, economic development and social equity. In order to measure a company's progress towards sustainable goals, the firm's economic performance, as well as its environmental and social performance must be quantified.

The economic performance of companies is measured by various financial indicators that give a good image of the business and that all decision-makers are familiar with. Financial information is generally reported in company annual reports. A company's financial ledger contains the information that forms the basis for the company's financial statement. The reporting of financial data has been ongoing for many years and is well organised and standardised.

The environmental performance of an organisation is of increasing importance to internal and external interested parties. As concern grows for maintaining and improving the quality of the environment, organisations of all sizes are increasingly turning their attention to the potential environmental impacts of their activities, products or services. Every product has some impact on the environment, which may occur at any stage of the product's life cycle – including the end-of-life treatment options (reuse/part reclamation, remanufacturing, recycling, incineration, discard to landfill). Recently, as a result of the forthcoming EU Directives on end-of-life product treatment – especially the Directive on Waste Electrical and Electronic Equipment (WEEE Directive) [WEEE02] – pressures are being put on companies to recover products at the end of their useful life for reuse, remanufacture or recycling. The environmental performance of companies involved in activities at the end-of-life of products is a matter of great importance for original producers as well as national and international bodies (such as the Environmental Protection Agency - EPA).

Corporate social responsibility is business's contribution to the third pillar of sustainable development: social progress. The social performance of a business measures its contribution to social progress. In fact, social performance of a company measures the business performance in relation to its impact on different stakeholder groups (communities, employees, suppliers, etc.).

The purpose of this study is to develop a methodology for environmental and economic decision support for end-of-life products, therefore it considers sustainability from two points of view: environmental and economic performance. This chapter will present several methodologies for quantifying environmental and economic impacts of products and the potential for their application to end-of-life products.

2.2. METHODOLOGIES FOR QUANTIFYING THE ENVIRONMENTAL IMPACT OF PRODUCTS

Three methodologies for quantifying the impact of products on environment have been studied – life cycle assessment, environmental impact assessment and eco-indicators – and they are briefly presented in this section.

2.2.1. Life Cycle Assessment (LCA)

The first international body to act as an organisation for the development of Life Cycle Assessment (LCA) was SETAC (the Society of Environmental Toxicology and Chemistry), a scientific organisation, that has offered a science-based platform for the coherent development of LCA as a tool [Gui01]. SETAC defines LCA as "*a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and released to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, reuse, maintenance; recycling, and final disposal*" [SET93].

Another international organisation that plays an important role in the development of LCA is the International Organisation for Standardisation (ISO). It developed a series of standards relating to LCA (the ISO 14040 series) that concern the technical as well as organisational aspects of an LCA project. ISO 14040 defines LCA as "*a technique for assessing the environmental aspects and potential impacts associated with a product by:*

- *Compiling an inventory of relevant inputs and outputs of a product system;*
- *Evaluating the potential environmental impacts associated with those inputs and outputs;*
- *Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study*" [ISO97].

Life Cycle Assessment is a tool for the systematic evaluation of the environmental aspects of a product or service system throughout the product's life (i.e. cradle-to-grave [SET98]) from raw materials acquisition through production, use and disposal. Emissions and consumptions of resources appear at every stage of the life cycle of a product. Life cycle thinking is required [UNS00] in order to address the environmental impacts from the entire life cycle of products and services.

2.2.1.1. LCA Methodology

The 1990 SETAC conference in Vermont was the first to analyse LCA into three main stages [Bou02] – *inventory, interpretation* and *improvement.* By cycling through the three phases it was hoped to optimise the environmental characteristics of the system.

The LCA approach developed originally by SETAC has been set down in the ISO 14040 series. The first in the series is ISO 14040 (*Life Cycle Assessment – Principles and Framework*), a gentle introduction into the subject matter that defines the framework for the field of LCA [Mar00]. Figure 2.1 presents the Life Cycle Assessment framework as laid down in this standard. According to ISO 14040 there are four phases of Life Cycle Assessment [UNS00]:

- *Goal and scope definition* – developed in *ISO 14041 – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis*
- *Inventory analysis* – developed in *ISO 14041 – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis*

- *Impact assessment* – developed in *ISO 14042 – Life Cycle Assessment – Life Cycle Impact Assessment*
- *Interpretation* – developed in *ISO 14043 – Life Cycle Assessment – Life Cycle Interpretation*.

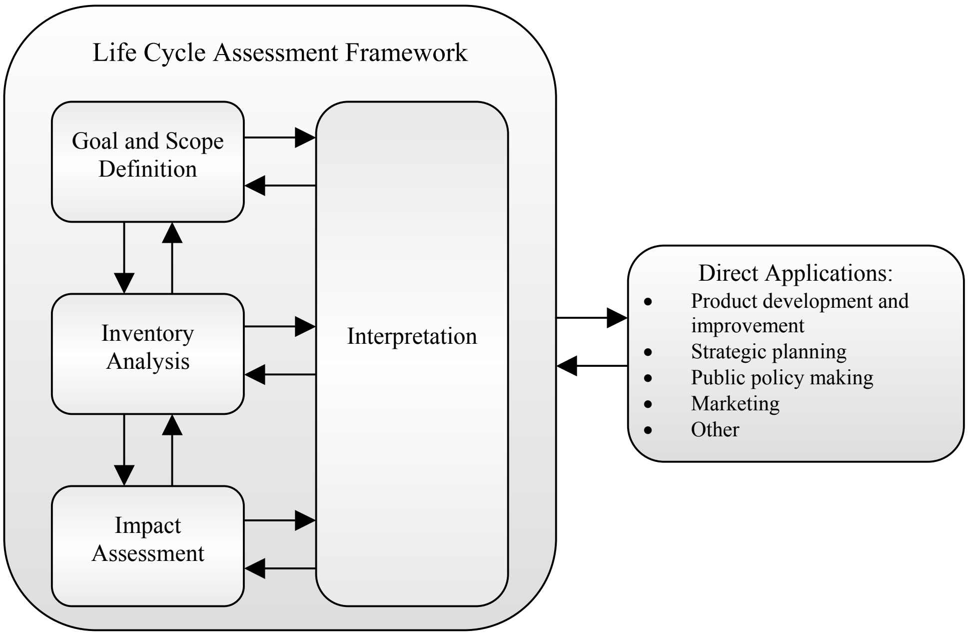

Figure 2.1. Life Cycle Assessment framework [Lec99]

ISO 14043 symbolises the roof of the Life Cycle Assessment architecture, which is made up of a foundation (ISO14040), two methodical building blocks standing as a support to this roof (ISO 14041 and ISO 14042), and precisely this integrative element which covers the entire procedure, ISO 14043 [Mar00].

Goal and Scope Definition

This stage is extremely important, as the result of the LCA is heavily dependent on the decisions taken in this phase.

As ISO 14041 states, "*the goal of any study shall unambiguously state the intended application, the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated*" [ISO98].

The *scope* of any LCA study should be sufficiently well defined to ensure that the breadth, the depth and the detail in which the study is conducted are both compatible with and sufficient to address the stated study goal [ISO98]. During the scoping, the product, process or activity is defined for the context in which the assessment is being made. A clear definition of the system boundaries is very important at this stage. This can be achieved by using a business/activity description, a technical overview and a presentation of related external systems [Zob02].

Although scoping is a part of LCA initiation, some of the aspects involved at this stage may need to be modified as the study progresses, and additional information collected.

Inventory Analysis

The inventory analysis can be used as a technical tool to identify and evaluate opportunities to reduce the environmental effects associated with a specific product, production process, package, material or activity. This tool can also be used to evaluate the effects of resource management options designed to create sustainable systems [Ase97].

At the inventory analysis stage data are collected and any necessary calculations are performed in order to quantify the relevant inputs and outputs of the system as a whole. Typically, inventory data include *inputs* (raw materials and energy consumption) and *outputs* (emissions of solid, liquid and gaseous wastes).

A popular format for inventory data that has seen increasing use recently is the ecoprofile (cradle-to-grave) study [Bou02] in which the inventory for the system and all auxilliary processes is calculated, starting with the extraction of raw materials and fuels from the ground and ending at the point at which the item under study leaves the system. With the information about each process of the life cycle, it is possible to draw up an inventory of all the environmental inputs and outputs associated with the product. The result is called the *table of impacts* [Ase99].

Impact Assessment

The purpose of Life Cycle Impact Assessment (LCIA) is to assess a system's life cycle inventory results with the aim of improving understanding with regard to their potential environmental significance. LCIA specifically uses impact categories and associated indicators to assign the inventory results with regard to one or more environmental issues (see figure 2.2 for the framework for LCIA as laid down in the ISO 14042).

Selection and Definition of Impact Categories

The issues of concern, or what to protect, are identified as LCIA *categories*. The selection and definition of impact categories can either align with traditional categories like global warming, acidification, and resource depletion, or it can define categories that represent specific issues for the decision-maker in the given procedure.

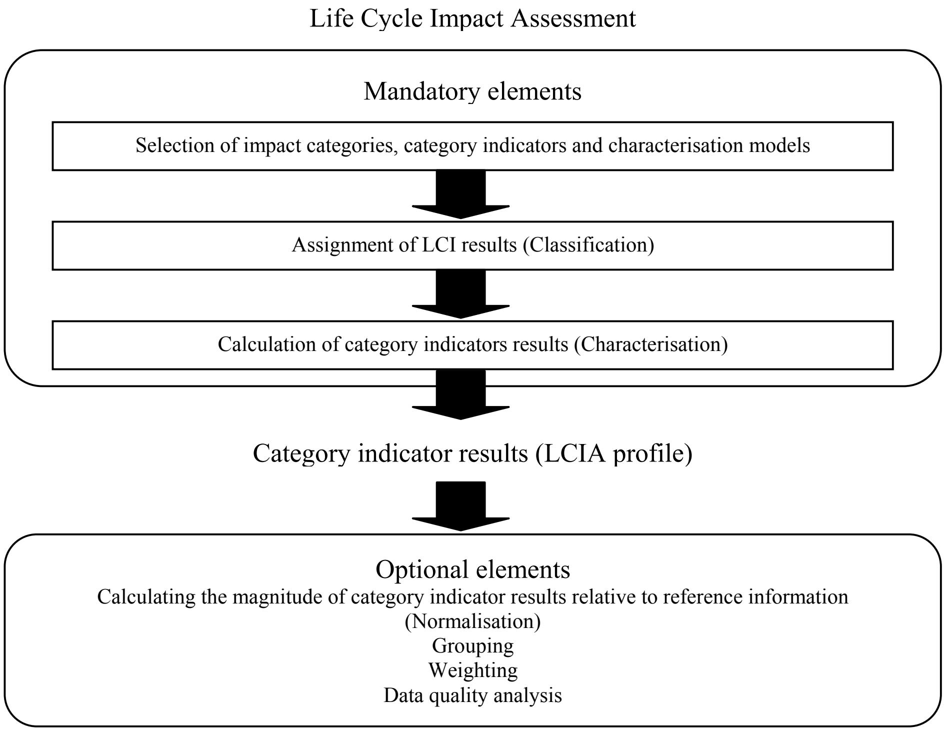

Figure 2.2. Elements of LCIA [ISO99]

Classification

The next element of the LCIA framework concerns classification, i.e., the assignment of the inventory results to the different categories.

Characterisation

At the characterisation stage, the inventory results within each category are converted into a category indicator. Each category model uses characterisation or conversion factors to convert inventory results into category equivalents, and the equivalents are then aggregated into a category indicator.

Normalisation

LCIA normalisation implies the normalisation of the indicator result by dividing by some reference value. Commonly, this reference is the total loading for the given category.

Weighting

The weighting phase of LCIA involves a formalised ranking, weighting, and possibly aggregation of the indicator results across impact categories into a final score.

Interpretation

The results are reported in the most informative way possible and the need and opportunities to reduce the impact of the products or services on the environment are systematically evaluated. The need for interpretation comes from requirements [Lec99]:

- Not to lose the findings which can be directly drawn from the inventory. ISO 14043 recommends basing the interpretation process on the inputs and outputs from the inventory and not only on the impact category indicators.
- To establish confidence in the results of the LCA study, by reference to the goal and scope definition.

2.2.1.2. Possible Application of LCA to End-of-Life Products

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product or service during its life cycle [Zob02] – see figure 2.3. But the LCA methodology could be adaptable to any stage of the life cycle of a product, including the end of life, for the purpose of surveying environmental aspects.

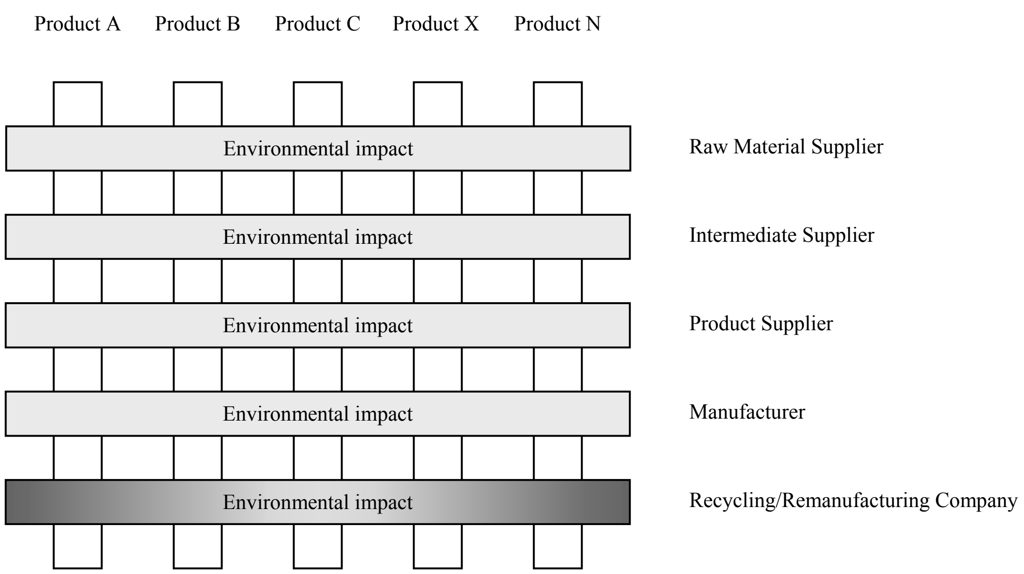

Figure 2.3. LCA methodology (adapted from [Zob02])

The four steps of the LCA process can be applied to any end-of-life (EOL) activity (reuse, remanufacturing, recycling, incineration, landfill). Considering a certain product, for each EOL option, the goal, scope and activity boundaries can be defined and an inventory of all environmental impacts associated with each process the product is subject to carried out. Then, once the impact categories are defined, an evaluation of all contributions of the inputs and outputs to different impact categories can be made and indicators calculated.

2.2.2. Environmental Impact Assessment

Following the definition of Munn, the Environmental Impact Assessment (EIA) can be described as "*a process for identifying the likely consequences for the biogeophysical environment and for man's health and welfare of implementing particular activities and for conveying this information, at a stage when it can materially affect their decision, to those responsible for sanctioning the proposals*" [Wat94].

EIA is a systematic identification and evaluation of the potential impacts of proposed projects, programs or legislative actions relative to the physical-chemical, biological and socio-economic components of the environment [Can96]. The main objective of EIA is to provide decision-makers with an indication of the likely consequences of their actions before the decision is made.

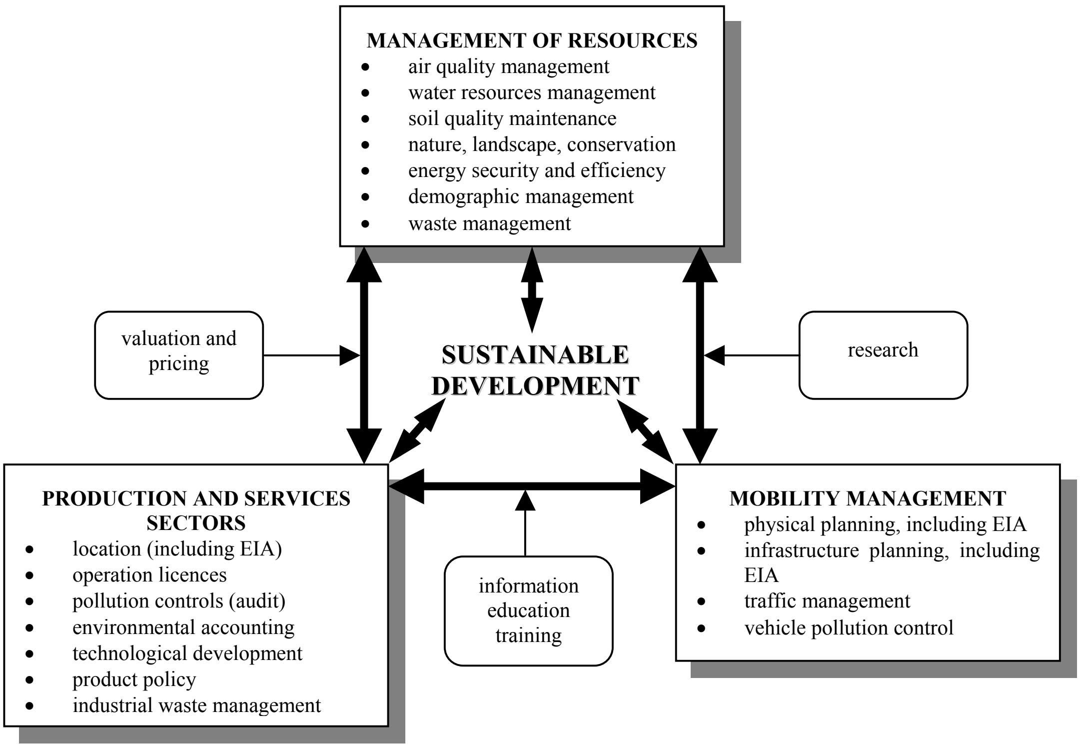

Figure 2.4. EU framework for sustainable development [Gla94]

The central role of EIA is as an instrument to achieve sustainable development. The interaction of economic and social development, and the natural environment is an issue considered by governments from local to international levels. Figure 2.4 illustrates the interdependence between resources, sectors and policy areas as laid down in the EU Fifth Programme on environment. Great emphasis on natural resource conservation is needed; therefore there is much scope for the better management of the use, renewal and conservation of all natural resources through the EIA process [Gil95]. EIA is a positive process that seeks a harmonious relationship between development and the environment.

2.2.2.1. The EIA Process

In essence, EIA is a systematic process that examines the environmental consequences of development actions in advance. The emphasis, compared with other mechanisms for environmental protection, is on prevention. The process involves a number of steps as presented in figure 2.5 [O'Su90]:

1. *Screening*
2. *Scoping*
3. *EIA Preparation*
4. *Review*
5. *Monitoring*
6. *Auditing*

Screening

At this stage it is decided which projects should be subject to environmental assessment. A variety of methods have been developed to assist in the screening process such as [O'Su90]:

- *The use of positive and negative lists* – these are lists of project types which are considered to be candidates for EIA (positive lists) or projects for which EIA will not be required (negative lists). The EU Directive on EIA is an example of where positive lists have been employed to help screen projects for EIA.

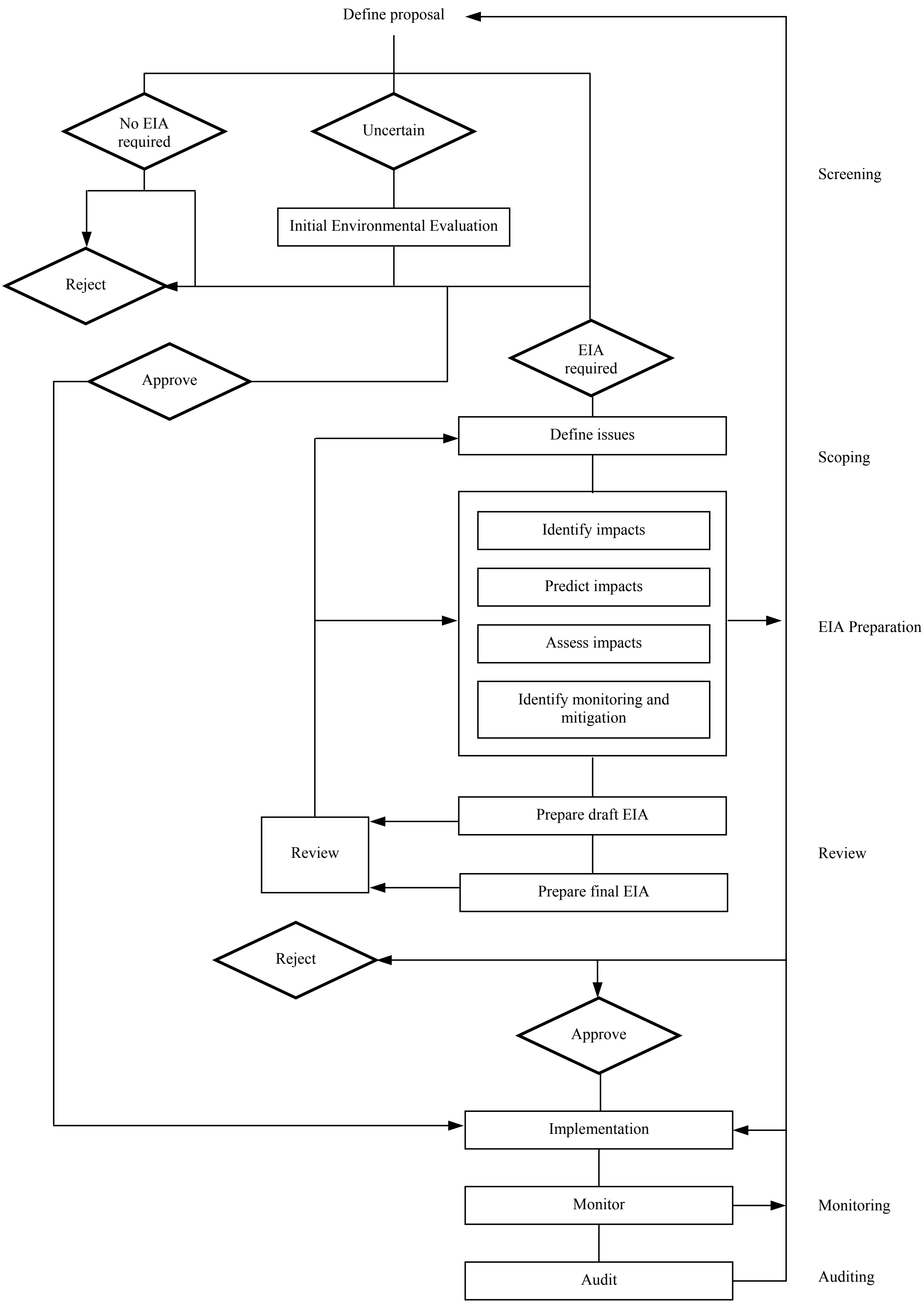

Figure 2.5. The main stages of an EIA process [Wat94]

- *The use of project thresholds* – thresholds can assist in project screening where projects exceeding predetermined thresholds (size, capital expenditure, amounts of raw materials used or quantities of emissions, area of land required, etc.) are considered to be candidates for EIA.
- *Matrices* – a screening tool developed in Canada. It relies on two matrices: the Level 1 matrix is a broad screening tool, employed to develop an overall understanding of the project and its likely environmental effect; in the Level 2 matrix, environmental consequences are more specifically defined and the more detailed consideration of the nature of a potential interaction is encouraged.

Scoping

The scope of EIA is the impacts and issues that it addresses. The process of scoping is that of determining, from all the project's possible impacts and from all the alternatives that could be addressed, those that are the key, significant ones [Gla94].

EIA Preparation

Several activities are required in an environmental impact study, including impact identification, preparation of a description of the affected environment, impact prediction and assessment and selection of the proposed action from the alternatives evaluated to meet identified needs [Can96].

Environmental Impact Identification

Numerous EIA methodologies have been developed to be used in impact identification. The most used methodologies can be categorised as [Can96], [Gla94]:

- *Interaction matrices* – A simple interaction matrix displays project actions or activities along one axis, with appropriate environmental factors listed along the other axis of the matrix. When a given action or activity is expected to cause a change in an environmental factor, this is noted at the intersection point in the matrix and further described in terms of separate or combined magnitude and importance considerations.
- *Networks* – Networks are those methodologies which integrate impact causes and consequences through identifying interrelationships between causal actions and the impacted environmental factors, including those representing secondary and tertiary effects.

- *Checklists* – Checklist methodologies range from listing of environmental factors to highly structured approaches involving importance weightings for factors and application of scaling techniques for the impacts of each alternative on each factor.

Description of the Affected Environment

Environmental indicators are useful tools for monitoring the state of the environment in relation to sustainable development and associated environmental threats. A preliminary set of indicators, 18 environmental indicators and 7 key economic and social indicators [Can96] are presented in Appendix A.

Impact Prediction and Evaluation

The objective of prediction is to identify the magnitude and other dimensions of identified change in the environment with a project in comparison with the situation without that project. Indicators are used for impact prediction. Once the impacts have been predicted, there is a need to assess their relative significance. Criteria for significance include the magnitude and likelihood of the impact and its spatial and temporal extent, the likely degree of recovery of the affected environment, the value of the affected environment, the level of public concern and political repercussions [Gla94].

Review

As environmental assessments are normally produced by the project proponent, it is usual for a review to be undertaken by a government agency or an independent review panel. The review panel guides the study and then advises the decision-makers.

Monitoring and Auditing

Monitoring involves the measuring and recording of physical, social and economic variables associated with development impacts. Monitoring can improve project management. It can be used as an early warning system to identify harmful trends before it is too late to take remedial action. It is also essential for successful environmental impact auditing.

Environmental impact *auditing* involves comparing the impacts predicted in the EIA statement with those that actually occur after implementation in order to assess whether the impact prediction performs satisfactorily.

2.2.2.2. Possible Application of EIA to End-of-Life Products

EIA is a procedure which aims to ensure that the decision-making process concerning activities that may have a significant influence on the environment takes into account the environmental aspects related to the decision. EIA is not a substitute for decision-making, but it provides a systematic examination of the environmental implications of a proposed action and of different alternatives, before the decision is taken. This is the similarity with the decision-making for EOL products: there are different alternatives (reuse, remanufacturing, recycling, incineration, discard to landfill) and each produces certain impacts on the environment but a choice must be made.

The EIA methodology might be adapted for decision-making for EOL products. The preparation stage of EIA (decision regarding the environmental factors that should be considered, calculation of indicators), which is quite similar to the impact assessment in LCA methodology, offers data necessary in the decision-making process for EOL products.

2.2.3. Eco-Indicators

During the design process a large number of options are usually generated. These solutions are analysed by the designer after which the best design options are chosen. To enable environmentally-aware designs to be produced it must be possible to include the environmental aspects of a product in the analysis and selection of design options. The standard Eco-indicator values have been developed as an instrument to do that; they are meant to be a tool for designers [Goe97]. It is a tool to be used in the search for more environmentally-friendly design alternatives.

Standard *Eco-indicators* are numbers that express the total environmental load of a product or process. The Eco-indicator of a material or process is thus a number that indicates the environmental impact of that material or process, based on data from a life cycle assessment. The higher the indicator, the greater the environmental impact.

Three versions of Eco-indicators have been developed: Eco-Indicator 95, Eco-Indicator 97 and Eco-Indicator 99. The idea behind all of them is the same: calculation of a number that represents the total impact on environment; the difference is in the underlying methodology (in this section two of these methodologies will be presented: Eco-Indicator 95 and Eco-Indicator 99).

The following steps must be followed to ensure correct application of the Eco-indicator [Goe00]:

- Describe the product or product component that is being analysed
- Define the life cycle
- Quantify materials and processes (materials and processes must be defined in such a way that "*they fit together like building blocks*" [Goe00]. The reason for that is that for the same quantity of a certain material, there are different indicators for different processes it is subject to)
- Find the relevant Eco-indicator values and calculate the scores
- Interpret the results.

2.2.3.1. The Eco-Indicator 95 Methodology

The Eco-Indicator 95 methodology is an extension of Life Cycle Assessment. Based on a weighting method, 100 Eco-indicators are calculated.

The Weighting Method

The weighting principle of Eco-Indicator 95 is based on the Distance-to-Target method (see figure 2.6). *Effects on the environment of different emissions and materials consumptions are weighted*. But first the classification and characterisation of the impacts must be done; the relative harm of an impact is converted into an effect score using weighting factors.

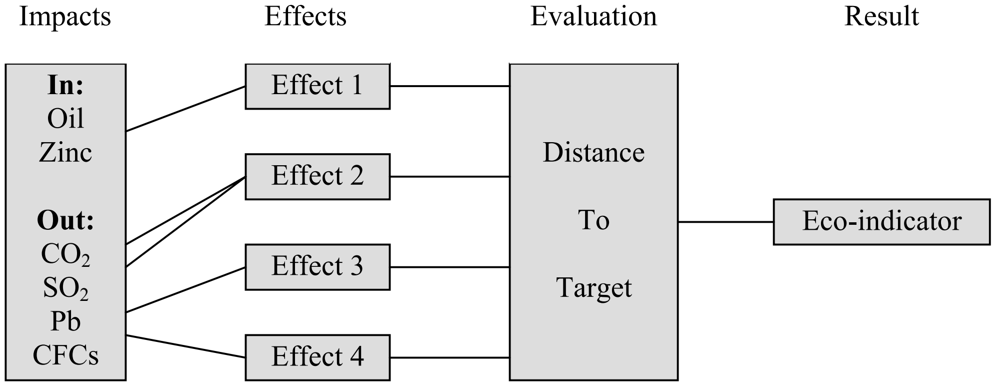

Figure 2.6. Weighting principle of the Eco-indicator 95 method [Ase97]

Environmental Effects

The Eco-indicator 95 methodology considers only the environmental effects which [Goe96]:

- Result in damage to ecosystems on a European scale
- Result in damage of human health on a European scale.

The environmental effects considered by the Eco-Indicator 95 methodology are [Ase97], [Ase99]:

1. greenhouse effect
2. ozone layer depletion
3. acidification
4. eutrophication
5. summer smog
6. winter smog
7. pesticides
8. heavy metals
9. carcinogenic substances.

Target Level and Damage

Based on the choice of effects the Eco-Indicator 95 method deals with two types of damage: damage to health and human fatalities, and damage to ecosystems. Extensive studies have been carried out and target values for these effects were established.

The Weighting Principle

The starting point for the weighting is the Distance-to-Target method. This means that the seriousness of an effect is related to the difference between the current and target values. In order to achieve a weighting, the following procedure has to be followed [Goe96]:

1. Determine the relevant effects that are caused by a process or product.
2. Determine the extent of the effect in Europe. This is the normalisation value. Divide the effect that the product or process causes by the normalisation value. This step determines the contribution of the product to the total effect. An important advantage of the normalisation is that all the contributions are dimensionless.

3. Multiply the result by the ratio between the current effect and a target value for that effect. The ratio, also termed the *reduction factor*, may be seen as a measure of the seriousness of the effect.
4. Multiply the effect by a so-called *weighting factor*.

The detailed Eco-Indicator 95 method is represented in figure 2.7.

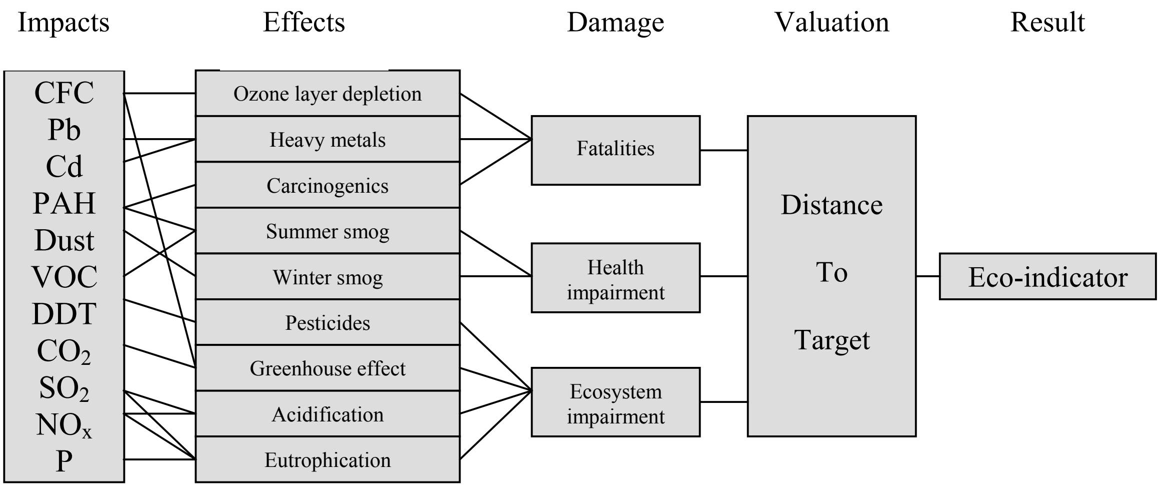

Figure 2.7. Detailed representation of the Eco-indicator 95 weighting method [Goe96]

Calculation of Eco-Indicators

Based on the methodology presented, 100 Eco-indicators were calculated for materials and processes. In order to do this, 100 inventory analyses have been made.

In the case of processes that result in more than one product the impacts must be allocated to these different products. This was done in different ways [Goe96]:

- Allocation on the basis of the product's economic value; this means that a product that provides say 60% of the revenue is also assigned 60% of the impacts
- Subtraction of avoided emissions; this is applicable in waste processes
- Allocation in accordance with the mass ratio when none of the above can be applied.

2.2.3.2. The Eco-Indicator 99 Methodology

Three *steps* are necessary in order to calculate the indicators [Goe00]:

1. Inventory of all relevant emissions, resource extractions and land-use in all processes that form the life cycle of a product

2. Calculation of the damages these flows cause to human health, ecosystem quality and resources
3. Weighting of these three damage categories.

Figure 2.8 presents these three steps. The light boxes refer to procedures, the dark coloured boxes refer to intermediate results. A detailed damage model is presented in figure 2.9.

The most important difference between Eco-Indicator 99 and other versions of Eco-Indicators is the much-improved methodology for calculating the indicators and the expansion of the indicator lists.

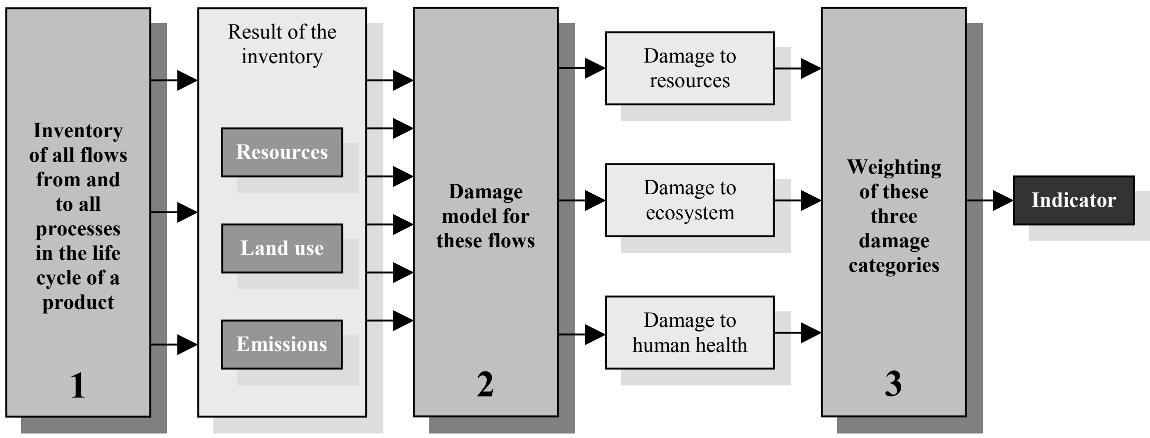

Figure 2.8. General procedure for Eco-indicator 99 methodology [Goe00]

The Damage Model for Emissions

For the calculation of the damages caused by emissions four *steps* were followed [Goe00]:

- *Fate analysis* – the transfer between compartments (air, water, soil) and the degradation of substances are modelled. As a result, the concentration in air, water, soil and food can be calculated.
- *Exposure* – based on the calculated concentrations, it can be determined how much of a substance is really taken in by people and by plants or other life forms.
- *Effect analysis* – once the exposure of a substance is known, it is possible to predict the types and frequencies of diseases and other effects.
- *Damage analysis* – the predicted disease can now be expressed into damage unit.

Figure 2.9. Detailed representation of the damage model [Goe00]

The Damage Model for Land-use

The disappearance of species is taken as the damage unit. Different types of land-use have different effects. A scale expressing the species diversity per type of land use was developed. Both regional and local effects are taken into account.

The Damage Model for Resources

The relation between the availability of resources and the ore grade on a logarithmic scale for a number of minerals. A steep line indicates that the availability increases sharply if mankind is able and willing to accept a slightly lower ore concentration. A flat line means that even at lower concentrations, the availability will not increase very much. A similar reasoning applies for fossil fuels.

Step 3. Weighting

Traditionally in LCA the emissions and resource extraction are expressed as 10 or more different impact categories such as acidification, ozone layer depletion, ecotoxicity and resource extraction. For non-experts it is difficult to give meaningful weighting factors for such a large number and rather abstract impact categories. That is why the methodology of Eco-Indicator 99 chose not to weight the impact categories but the different types of damage that are caused by these impacts [Goe00]:

- Damage to human health – expressed as the number of year life lost and the number of years lived disabled (Disability Adjusted Life Years – DALY)
- Damage to ecosystem quality – expressed as the loss of species over a certain area during a certain time
- Damage to resources – expressed as the surplus energy needed for future extractions of minerals and fossil fuels.

2.2.3.3. Possible Application of Eco-Indicators to End-of-Life Products

There are more than 100 Eco-indicators calculated with different Eco-indicator methodologies for different materials and processes. The idea is that materials and processes are defined "in such a way that they fit together like building blocks" [Goe00] which means that for the same quantity of a certain material there are different indicator values depending on the process it undergoes.

Therefore, the Eco-indicator method could be applied to end-of-life products provided that products are well defined in correlation with the different processes they are subject to. The method calculates effect scores which show the total impact of the end-of-life product on the environment and offers the possibility of comparing different EOL options.

2.3. Methodologies For Quantifying The Economic Impact Of Products

"*You can control only what you can measure*" [Rey73] – this is a statement managers must always keep in mind. Managers of businesses must constantly be alert to how the business is doing. Measurement of performance is essential.

Two issues in measuring business performance are *effectiveness* and *efficiency*. Here are the differences between the two:

Effectiveness is a measure of the degree to which a business achieves its goals [Fry98] (financial goals, customer goals, quality goals, innovation goals or any other goals).

Efficiency is a measure of the relationship between inputs and outputs [Fry98]. If the business can reach its sales goals while committing fewer human and financial resources, it becomes more efficient. Improved efficiency saves the business money and conserves its resources. It is important to measure efficiency because it shows how well the business is using its resources.

There is a group of specific indicators that can be very useful in determining the efficiency of a business and that any decision-maker is familiar with such as net sales, profit, cost, cash flow or ratio indicators such as gross profit margin, net profit margin, mark up or return on invested capital.

As regarding the EOL activities, the decision-makers involved in such activities are interested especially in costs. The WEEE Directive states that financing of the costs for the collection, treatment, recovery and environmentally sound disposal of waste from electric and electronic equipment is to be provided for by producers [WEEE02]. This is a good reason for producers to be interested in the processing cost involved in different end-of-life options when making decisions as to the end-of-life option for their products, as whatever the nature of the business, all will use materials, employ labour and incur overhead costs [Cas88].

Two methodologies for quantifying production cost per product – absorption costing and Activity-Based Costing (ABC) – have been studied and they are presented further in this section.

2.3.1. Production Cost

Cost is defined as the value of the resources used to produce a product or provide a service [Cas88]. The total cost comprises three main elements: *materials*, *labour* and *expenses* [Wil75]. All of these elements may be *direct* or *indirect* costs.

Direct cost is expenditure which can be economically identified with, and specifically measured, in respect to a relevant cost object or product [Pro02]. *Indirect cost* is expenditure on labour, materials or services which cannot be economically identified with a specific saleable cost unit or product. Indirect cost is also named *overhead* [Pro02].

The main *costing elements* for any business are [Hor87], [Cla95] (see figure 2.10):

- Direct materials cost
- Direct labour cost
- Production overhead (indirect manufacturing cost)
- Marketing and administration overhead

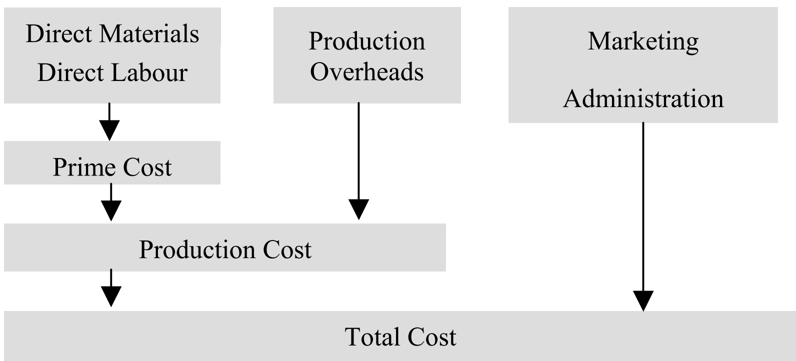

Figure 2.10. The costing system [Pro02]

Direct Materials Cost

Materials are a dominant element in the overall cost structure. Materials are issued to production on receipt of a materials requisition docket that indicates the type and quantity of materials and the purpose for which they are required. In turn, issues are recorded accurately on a stock record card. This system is referred to as a *perpetual stock (inventory) system* [Cla95].

The main difficulty with stock issues and closing stock valuation is in determining the cost as purchases at different times are made at different prices. It is usual to determine cost by one of the three valuation bases [Cla95]:

- First in first out (FIFO)
- Last in first out (LIFO)
- Average cost.

The most used base is FIFO, which considers that the first unit to be purchased is the first unit to be used. The valuation of closing stock is based on the cost of the most recent acquisitions [Cla95].

Direct Labour Cost

Labour as a resource is measured in terms of hours worked and the price of this resource is expressed as a rate paid per hour.

The problem with direct labour cost is that different employees are on different pay schemes. It is difficult to convert the variety of schemes to a uniform basis for costing purposes. However, calculating a rate per hour is sufficient to provide such a uniform basis, provided the number of hours worked is known. The cost of labour may then be determined by multiplying the hourly cost by the number of hours worked.

Production Overhead

Production overhead consists of all manufacturing costs other than direct labour, direct materials and direct expenses [Dru96]. Therefore it includes all indirect production labour and indirect materials cost plus indirect production expenses such as rent of factory or depreciation of machinery. Administration costs should not be included here as they are the costs of running the company (director's salary, advertising, etc.)

2.3.2. Absorption Costing

Using the absorption costing methodology, the product cost can be calculated by allocating and reallocating costs to one or more activities (departments) – named *cost centres* – for which a separate measurement of costs is needed [Hor87]. Allocation encompasses both direct and indirect costs.

Determining the direct production costs (prime cost) is relatively simple as the amount of them in each product can be measured but the indirect costs cannot be measured per product, therefore a methodology must be found in order to attach them to products. Such a method is allocation, apportionment and absorption of overheads.

2.3.2.1. Overhead Attachment Procedure [Pro02], [Dru96], [Hor87], [Cla95]

The overhead attachment procedure consists of the following *steps* (see figure 2.11):

1. Allocate or apportion the overheads to the production and service cost centres.
2. The total cost of the service centres is apportioned to the production centres so that all overheads end up in production centres.
3. Assign costs to products by means of overhead absorption rates (OAR).

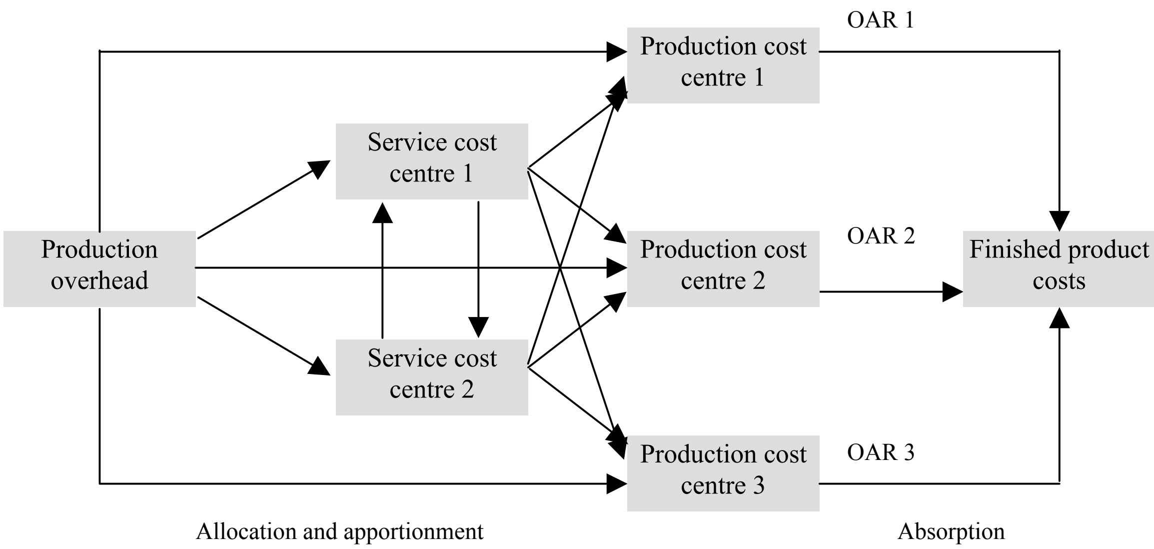

Figure 2.11. A simplified production overhead attachment procedure [Pro02]

Step 1. Allocate or Apportion the Overheads to the Production and Service Cost Centres

There are two main types of cost centres in any business:

- *Production cost centres* – those directly involved in the production activity
- *Service cost centres* – not directly involved in the production activity but provide essential backup.

Cost *allocation* represents the attachment of a cost to a single cost centre or cost unit. Cost *apportionment* represents the assignment of a cost between two or more cost centres/units. There are overheads which are directly attributable to each cost centre (and these are *allocated*) and overheads which have to be shared over a number of cost centres according to how the cost centres benefit from the cost incurred (and these are *apportioned*).

Some common methods of apportionment of indirect costs are presented in table 2.1.

Table 2.1. Examples of methods of apportionment of overhead costs to costs centres

Cost item	**Method of apportionment to cost centres**
Rent of building	Floor area of each cost centre
Insurance	Floor area of each cost centre
Lighting and heating	Floor area of each cost centre
Energy for machines	Number of machines in each cost centre
Production supervisor's salary	Number of employees in each cost centre
Canteen costs	Number of employees in each cost centre
Depreciation and insurance of machinery	Value of machinery in each cost centre

Step 2. Apportionment of service department costs to production cost centres

Service cost centres exist to support production but do not make a direct contribution to the product. Once the indirect costs of the organisation have been channelled into various cost centres, they must be reallocated from service cost centres to production cost centres.

There are two main methods by which service department costs are apportioned to production departments:

- The *direct method* – service department costs are assigned only to production departments and not to other service departments
- The *step (sequential) method* – starts with the most used or most expensive department and allocates its accumulated costs to other services and production departments.

Table 2.2 sets out the titles of some service cost centres and gives examples of some methods by which their costs could be apportioned to production cost centres.

Table 2.2. Methods of apportioning the total indirect costs of service cost centres to production cost centres

Service cost centre	Method of allocation to production cost centres
Maintenance department	Number of machines in each cost centre
Employees' restaurant and coffee bar	Number of employees in each cost centre
Stores department	Total value of stores requisitions from each cost centre
Finished goods quality inspection	Value of goods produced by each cost centre
Safety inspectors	Number of employees in each cost centre
Administration	Number of employees in each cost centre

Step 3. Assigning costs to products

This is the final stage of the attachment process where all the costs are collected in the production cost centres, ready to be assigned to products. To allocate a fair share of overhead to each product, *overhead absorption rates (OAR)* for each centre are calculated. There are four main overhead absorption bases that can be used to calculate the OAR:

- *Direct labour hours* – this is used when overhead costs are time related or associated with the amount of labour input.
- *Direct labour cost* – this should only be used when the labour hourly rates for each operation are nearly uniform.
- *Machine running hours* – this is used where production is highly mechanised and costs are clearly related to machine capacity and utilisation.
- *Direct material cost* – this method can only be justified where a major part of overhead is associated with materials handling.

Labour hours or machine hours are usually used, depending on whether the production process is labour intensive or machinery intensive.

The overhead is then allocated to each product, depending on the work done on the product. When allocating overhead costs to products it has to be known if it is a single product company or a multi-product company. If the company makes several different products, to absorb overheads into each product on an equitable basis needs the use of number of direct labour hours for each type of product or, if it is a machine intensive manufacturing environment, machine hours will be used.

Total cost of a product

The total cost of a product is the sum of product direct materials cost, product direct labour cost and product total overhead cost.

2.3.2.2. Possible Application of Absorption Costing to End-of-Life Products

Absorption costing is a traditional cost calculating method, designed for labour intensive products rather than machine intensive ones which include more indirect costs. Therefore, the method is not very accurate but it is mathematically sound and ensures that all the production overheads are absorbed by all production.

The absorption costing methodology can be applied to any business, including activities at end-of-life of products. It would be appropriate especially for labour intensive activities (such as reuse/part reclamation or remanufacturing).

2.3.3. Activity-Based Costing

Activity-Based Costing (ABC) is a methodology that measures the *cost* and *performance* of activities, resources, and cost objects (products, services, etc.). The first innovation of ABC is *assignment of costs to activities* based on measurements of resources used [Tur97]. The second innovation is the way in which *costs are assigned to cost objects* based on activity drivers that accurately measure product’s consumption of the activity [Tur97]. By understanding the activities and processes, the cost drivers that influence the cost of the activity, and whether the activity is needed or not, the cost of making items can be analysed and unnecessary costs eliminated.

Activity-Based Costing is especially useful to allocate indirect costs to items that are difficult to track and assign. The main benefit is more accurate product overhead costing.

ABC differs from traditional costing systems in three ways [Emb02]:

- In traditional cost accounting it is assumed that cost products consume resources whereas in ABC it is assumed that *cost products consume activities*.

- Traditional cost accounting mostly utilises volume related allocation bases while ABC *uses drivers at various levels*.
- Traditional cost accounting is structure-oriented whereas ABC is *process-oriented*.

Figure 2.12 illustrates these differences. The direction of the arrows are different because ABC brings detailed information from the processes up to assess costs and manage capacity on many levels whereas traditional cost accounting methods simply allocate costs down onto the cost products without considering any 'cause and effect' relations.

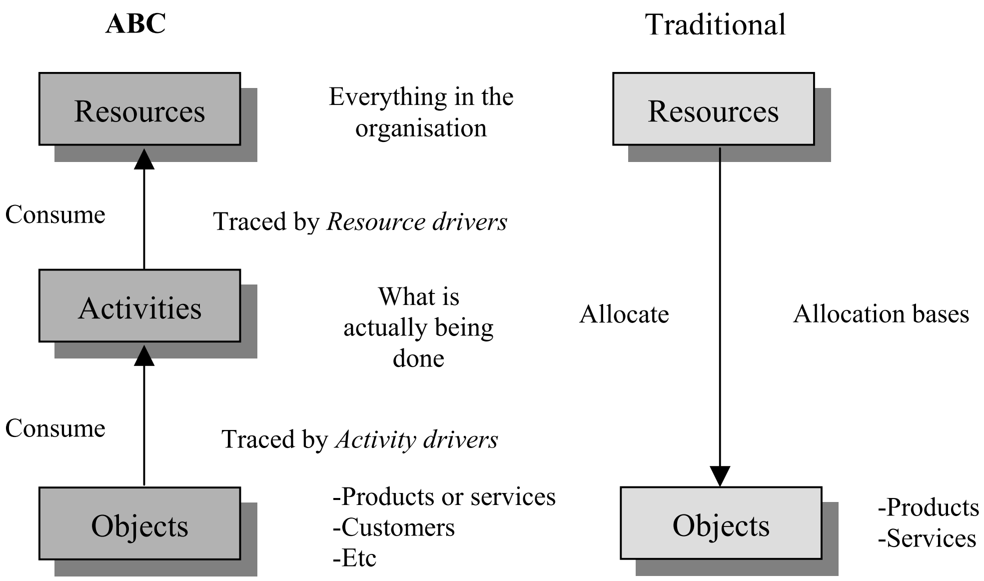

Figure 2.12. Differences between traditional cost accounting and ABC [Emb02]

Therefore, in ABC costs are assigned according to the *cause and effect* relationship between activities (the actual process) and cost objects, which is captured using drivers [Emb02] (these drivers work just as the allocation bases in the traditional costing system). These activity drivers occur on the following levels [Cla95], [Tur97], [Pro02]:

- Unit level
- Batch level
- Product level
- Plant level

The *causational link* is fundamental to ABC [Pro02]: products cause activities to happen, activities cause costs to be incurred.

2.3.3.1. The ABC Process

Activity-Based Costing has a very definite procedural flow, a set of *steps* that define the performance process [Pro02], [Tur97], [Inn98], [DoD95]:

1. Identify the different activities performed by the business
2. Calculate the total cost of each activity over a certain period (the cost pool)
3. Identify a cost driver for each activity and calculate the cost driver rate
4. Assign part of the cost of each activity to different products based on the extent to which each product has caused the activity to occur (apply the cost driver rate).

The ABC mechanism is presented in figure 2.13.

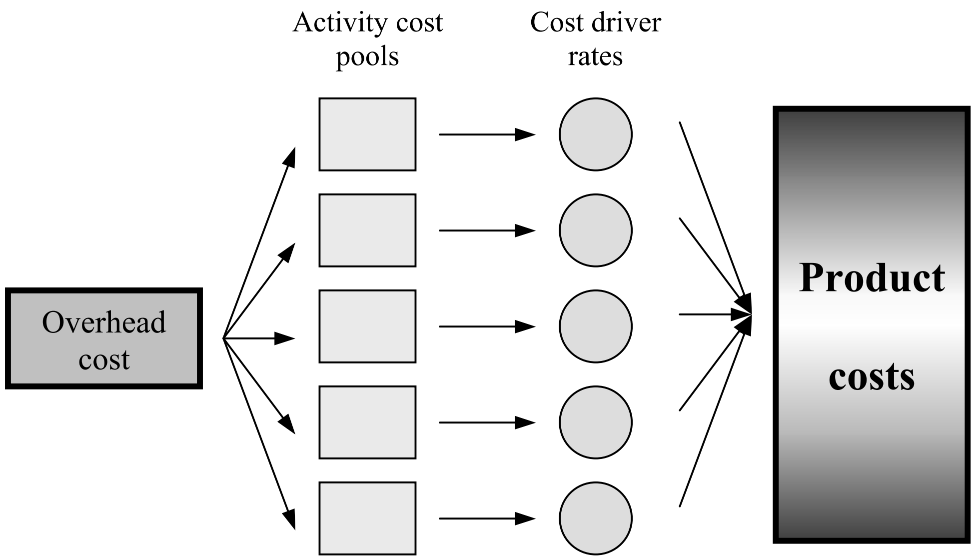

Figure 2.13. The ABC process [Pro02], [Inn98]

Identify Activities

Identifying the business activities and creating the activity model is a very important step as cost allocation cannot take place without it.

A very good activity model is the *node tree* (see figure 2.14) that describes the organisation's activities and their relationship [DoD95]. The activity model is *hierarchical*, consisting of multiple layers of increasing detail. At each node or layer of the model, a total of three to five activities are defined which encompass all of the functions at that node. The node tree can be decomposed as far as is necessary for effective study and evaluation. Normally this is no more than two or three levels. Whatever the number of levels, it is along the bottom (the greatest level of detail) that basic costs are assigned and analysed in relation to processes.

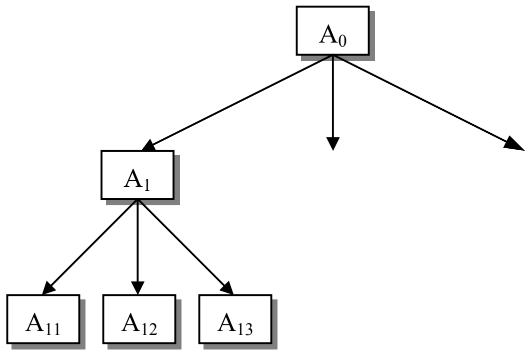

Figure 2.14. Node tree activity model [DoD95]

Calculate total cost of each activity (cost pooling)

The costs should be calculated at the lowest structural layer [DoD95]. Cost data is usually not perfect for ABC. Traditional accounting is not adequate for such a system. Therefore available cost data have to be adjusted for change, corrected for undocumented element costs, or combined with different types of data from alternate sources. All these add complexity to the process.

There are many cost categories that have to be identified for each activity: labour, supplies, rental equipment, direct materials, facilities, overhead expenses.

Some measure of cost apportionment may still be required at the stage of cost pooling as there might be overheads common to more than one cost pool [Inn98].

Identify the cost drivers and calculate cost driver rates

Once pooled, an appropriate cost driver must be used to attach costs to individual products. *Cost drivers* represent those activities or events that are significant determinants of cost [Cla95]. It is very important to identify cost pools that are *volume-driven* and cost pools that are *activity-driven* [Inn98].

Volume-based cost drivers include volume-based measures [Cla95] such as direct labour hours, machine hours and direct material usage. Examples of cost pools and volume-based cost drivers are presented in table 2.3.

Activity-based cost drivers include the output of support department [Cla95] such as purchasing, personnel or quality control. Examples of cost pools and activity-based cost drivers are presented in table 2.4.

Table 2.3. Examples of volume-based cost drivers [Cla95]

Activity (cost pool)	Cost drivers
Maintenance	Number of machine hours
Production	Volume of production
Packaging	Volume of production

Table 2.4. Examples of activity-based cost drivers [Cla95]

Activity (cost pool)	Cost drivers
Stores	Number of issues
Inspection	Number of inspections
Training	Number of people trained
General accounting	Number of supplies
Personnel	Number of employees
Customer service	Number of customer orders
Purchasing	Number of purchase orders

Based on the appropriate cost drivers, cost driver rates are calculated.

Assign costs to products

The last stage in the ABC process is to assign costs to products by multiplying the cost driver rate by the number of cost driver units consumed by the product.

2.3.3.2. Possible Application of ABC to End-of-Life Products

The main benefit from ABC is that it provides an accurate product cost. This is exactly what is needed for end-of-life products. It is a methodology that can be applied to any business, including end-of-life activities. ABC has some limitations, some costs may apply to more than one activity cost pool and they need to be divided, therefore a method of apportionment has to be used. Another problem with ABC is that it is more complex than traditional costing, consumes more resources and cost more to operate. Therefore, in some cases, the costs of introducing ABC may outweigh the benefits.

2.3.4. Environmental Accounting

The field of *environmental accounting* (*green* accounting) has made great progress in the past decades. Interest is growing in modifying national income accounting systems to promote understanding of the links between economy and environment.

Governments around the world develop economic data systems known as *national income accounts* to calculate macroeconomic indicators such as Gross Domestic Product (GDP) or the Gross National Product (GNP), but such indicators mask the depletion of natural resources and present an incomplete picture of the costs imposed by the polluting by products of economic activity. The *System of National Accounts (SNA)*, defined by the United Nations [UN03a] and used internationally, intends to use the environment into such accounts.

However, some *problems* appear when taking into account the environment [Hec99]:

- The cost of environmental protection may not be identified. For example, money spent on pollution control devices increases GDP, even though the expenditure is not economically productive.
- The fact that some environmental goods are not marketed though they provide economic value is misleading. Fuel wood gathered in forests, meat and fish gathered for consumption, and medicinal plants are examples.
- Valuing environmental services such as the watershed protection that forests afford and the crop fertilisation that insects provide is difficult.
- Another problem is that national income accounts treat the depreciation of manufactured capital and natural capital differently.

Environmental accounting is underway in several countries; more recently, a number of resource-dependent countries have become interested in measuring depreciation of their natural assets and adjusting their GDPs environmentally. Inclusion of environmental data into the national income accounting systems also allows these countries to anticipate the impacts of different growth patterns in compliance with international conventions on pollutant emissions [Hec99].

2.3.4.1. National Accounting and the SEEA

The need to consider natural capital has become a fact, as has the realisation that development encompasses the human and social dimensions as well. That was the reason why in the early 1990s, the United Nations Statistical Office (UNSTAT) developed a framework for preparing a *System of integrated Environmental and Economic Accounts (SEEA)* [UN03b]. With the UNSTAT framework, an *Eco-Domestic Product (EDP)* can be calculated as follows: depreciation of produced assets is estimated and subtracted from GDP to arrive at an NDP; then estimates for depletion of natural resources and degradation of the environment are made and subtracted from NDP to arrive at EDP [Ham96].

SEEA gives a comprehensive view as to what constitutes an asset - all assets that contribute to marketable production are included [FEETM]. Such assets include land, subsoil resources, cultivated plants and livestock, and non-cultivated natural assets that yield products such as timber.

SEEA recommends that integrated environmental and economic accounting should be done in *satellite accounts* [FEETM] that are linked with the main accounts of the National Accounts. Satellite accounts try to integrate environmental data sets with existing national accounts information, while maintaining SNA concepts and principles as far as possible [Ham96]. Environmental costs, benefits and natural resource assets, as well as expenditures for environmental protection, are presented in *flow accounts* and *balance sheets* in a consistent manner. That way the accounting identities of the SNA are maintained.

2.3.4.2. Environmental Accounting Inside the Firm

Most economic activities affect the environment, either through the use of natural resources as an input or by using the environment as a sink for pollution. The costs of using the environment in this way are called *externalities*, because they are side effects of the economic activity and their costs are not part of the prices paid by producers or consumers [CES03].

Therefore an *externality* is any action that affects the welfare of or opportunities available to an individual or group without direct payment or compensation [IFS03]. If the loss of welfare is accompanied by compensation, the effects are said to have been *internalised*.

Despite the physical presence of pollution, economic pollution does not exist if there is no loss of welfare. An example is solid waste disposal at a controlled dumpsite where the full costs of disposal are paid by the waste generator including the costs to society [Roo95].

Environmental costs are dispersed throughout most businesses and can appear long after decisions are made. Unfortunately, conventional accounting practices rarely emphasise environmental costs or stimulate better environmental performance (See figure 2.15).

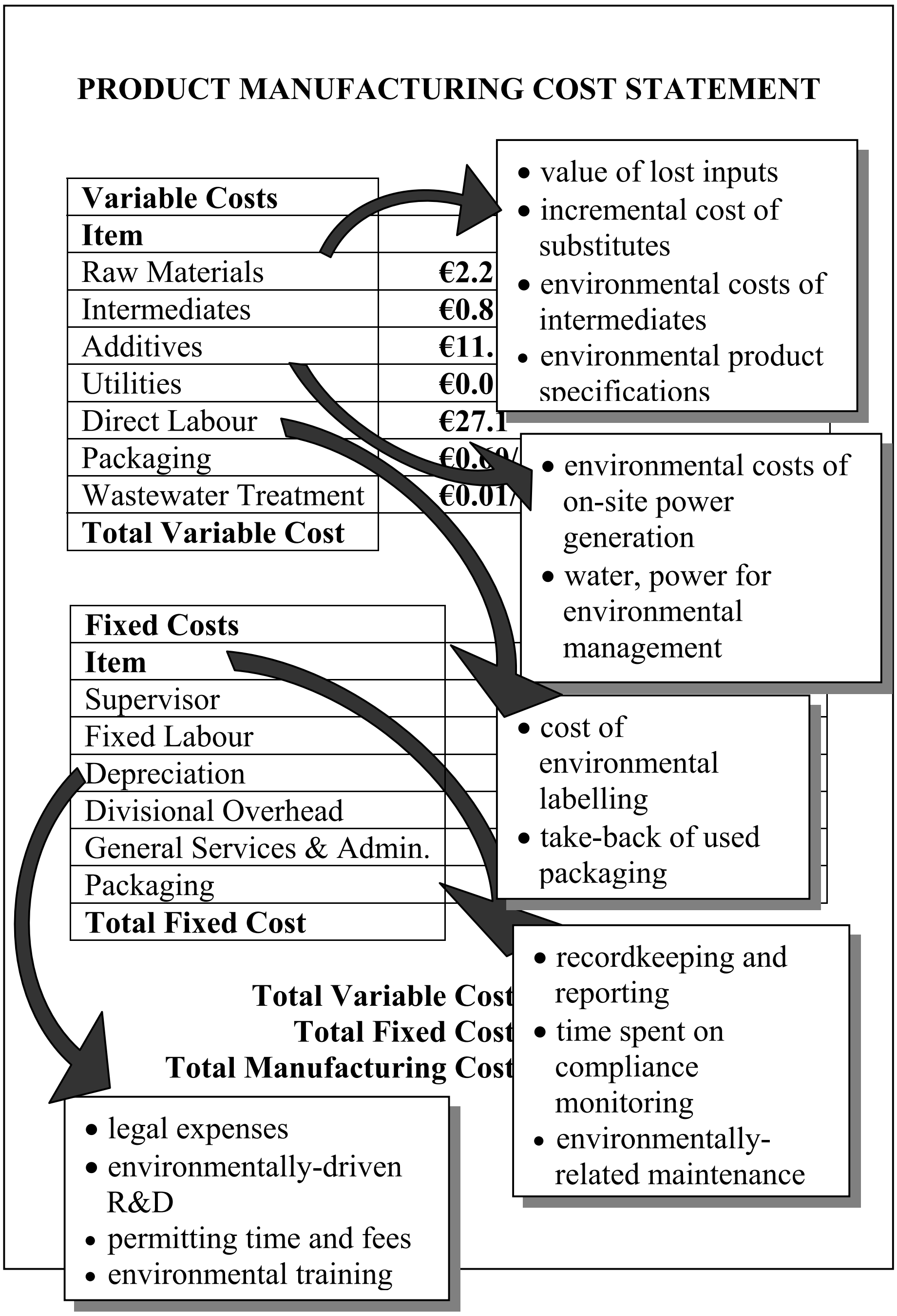

Figure 2.15. Environmental costs hidden in a typical cost statement [Dit95]

At the company level, it is important to distinguish between the environmental costs borne by the firm versus those imposed on society as *social costs*. Health effects from breathing polluted air, the impact of water pollution on fisheries, or soil contamination are classic examples of externalities. On the other hand, regulations, corporate policies, consumer preferences and community pressures shift some social costs back to firms. Discharge limits, emission taxes, product take-back requirements and other policy instruments also create economic incentives for firms to reduce potential environmental impacts – to make the polluter pay. Some of these costs are already being passed on to firms as expenses for pollution-control technology, environmental staff and permitting fees.

The push for environmental accounting is on. Outside stakeholders are driving firms to account for environmental costs. A growing number of state environmental regulations also call on firms to account for environmental costs and benefits.

But environmental limits do not simply constrain business. Rather, companies are finding environmental considerations increasingly infuse everything from product design to marketing, from purchasing to product stewardship. Now the challenge to corporations is to fully integrate environmental thinking into corporate decision-making [Dit95].

Environmental Management Accounting

Management accountants have a significant contribution to make towards improving the environmental performance of industry. The contribution involves the application of management accounting skills, knowledge and experience in a broad and significant new area: this is the challenge to provide company information and control systems that integrate economic and environmental criteria [Bir96] – what can be called *environmental management accounting (EMA).*

Environmental management accounting provides a service to management that is rooted in the internal functions of the firm but is outward-looking where appropriate. In many aspects, EMA is a straightforward development of management accountancy. The two desirable goals of economic and environmental efficiency coincide at company operations levels – money is saved if the use of physical resources is optimised.

2.4. ANALYSIS OF THE METHODOLOGIES REVIEWED

The purpose of this work is to develop an environmental and economic decision support methodology that permits decision-makers choose the best EOL option for their products reaching the end of life stage. Therefore, the methodology must offer the possibility to evaluate the environmental and economic impact of an EOL product and compare the possible EOL scenarios.

In order to evaluate the different methodologies presented in this chapter in terms of applicability to end-of-life products, the following criteria have been considered:

- Environmental indicators calculation per product per EOL option
- Processing cost calculation per product per EOL option
- Integration of environmental, economic and social impact of EOL product
- Comparison between EOL options
- Possibility of development into a software application
- Financial consideration (low cost)
- Traceability of products.

The comparison between the methodologies presented in this chapter is summarised in the checklist presented in table 2.5.

Table 2.5. Comparison between methodologies in the form of a checklist

	LCA	EIA	Eco-Indicators	Absorption Costing	ABC	Environmental Accounting
Environmental indicators calculation per product per EOL option	✓✓	✓	✓✓✓			✓✓
Processing cost calculation per product per EOL option				✓✓	✓✓✓	
Integration of environmental, economic and social impact of EOL product						
Comparison between EOL options	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓
Possibility of development into a software application	✓✓✓	✓	✓✓✓	✓✓✓	✓✓	✓✓
Financial consideration (low cost)	✓	✓	✓✓	✓✓	✓	✓
Traceability of products	✓✓✓	✓✓	✓✓✓			

LCA

Using Life Cycle Assessment, environmental indicators can be calculated per product per EOL option although the methodology of calculating indicators is not as well developed as in Eco-Indicators. It can be transferred into a software application, does not involve a high cost and offers a good traceability of products. The methodology has some disadvantages: it does not say anything about the economic impact of products and EOL options can be compared only with respect to environmental impact.

EIA

EIA is very similar to LCA in terms of possibility of application to EOL products. It calculates some environmental indicators but cannot say anything about the processing cost of an EOL product. The EIA permits comparison between different EOL options but only in terms of environmental impact.

Eco-Indicators

Any of the Eco-Indicators methodologies is very good for calculating the environmental impact of products, including EOL products. They offer a total score that makes comparison with respect to environmental impact a very easy task. They are suitable for transfer into a software application. Unfortunately this methodology does not give any information about the economic impact.

Absorption Costing

Absorption costing is a good methodology for calculating processing costs and makes comparisons between EOL options very easy from an economic point of view. It is possible to develop the methodology into a software application; the disadvantage is that it gives only economic impact, no environmental impact.

ABC

Activity-Based Costing is more accurate than the previous mentioned method for calculating costs, but again it does not calculate any environmental impact and it is more expensive as many companies do not have such a system implemented. It may be developed into a software tool and permits comparisons but only with respect to economic issues.

Environmental Accounting

Environmental accounting offers the environmental impact of any product processed in a company. Unfortunately environmental accounting is not developed in all countries or companies.

2.5. CONCLUSIONS

Each of the methodologies presented measure only the environmental impact or the economic impact of products. There is no methodology that could quantify both environmental and economic impacts of EOL products and transform them into a score to permit comparison between alternatives as there is no single unit for all of them. The economic impact may be expressed in one single unit (€), but the environmental impacts are expressed in a variety of units. That is why, for the complex environmental and economic decision-making processes, new techniques should be considered, such as formulation of alternatives which meet various environmental and economic criteria, and give a compromising solution that meets both sustainability principles and economic efficiency. Such techniques are multi-criteria analysis methods. Some of the multi-criteria analysis methods that could be used in environmental and economic decision-making processes will be presented further in this document.

To quantify the environmental and economic impacts it is essential to have a detailed description of the product in relation to different processes it may undergo at the end of its life. It is important, for the calculation of environmental indicators and for the costs, to know exactly what happens with each component and material of the product when it is subject to different EOL treatments. Some product models and possible EOL options are presented in the next chapter.

CHAPTER 3. PRODUCT DESCRIPTION AND END-OF-LIFE OPTIONS

3.1. INTRODUCTION

During a product's retirement stage, there are a variety of things that could happen. There are multiple disposal options, such as *incineration with energy recovery* or simply *disposal to landfill*, but there are also options that do not include disposal such as *reuse/part reclamation*, product recovery (*remanufacturing*) or material recovery (*recycling*) [Spi97].

These many different activities and processes associated with end-of-life products treatment, all use product data [Isa00]. Therefore, there is a need for product data coming from these activities performed at the end-of-life stage, data that need to be shared and communicated by the original producer.

Product models are the ones that deal with all aspects of information and data representing the product. Efficient definitions, modelling, use and applications of product models in this particular phase of the life cycle – retirement – are required to meet the processors needs.

3.2. PRODUCT DESCRIPTION

Product data must be described in a complete and unambiguous way to facilitate the storage, sharing and exchange of information, as well as searching for information. This representation, which is a formal specification defined by information modelling techniques, is called the *product model* [Isa00].

Different views on product models are presented in figure 3.1.

The need for data comes from all the activities in the product life cycle. Therefore, the product model must contain much of the data related to the product. Key elements of the product model are *product structure* and *geometric representation*, but also *configuration*, *engineering analysis* and *manufacturing planning* information are needed.

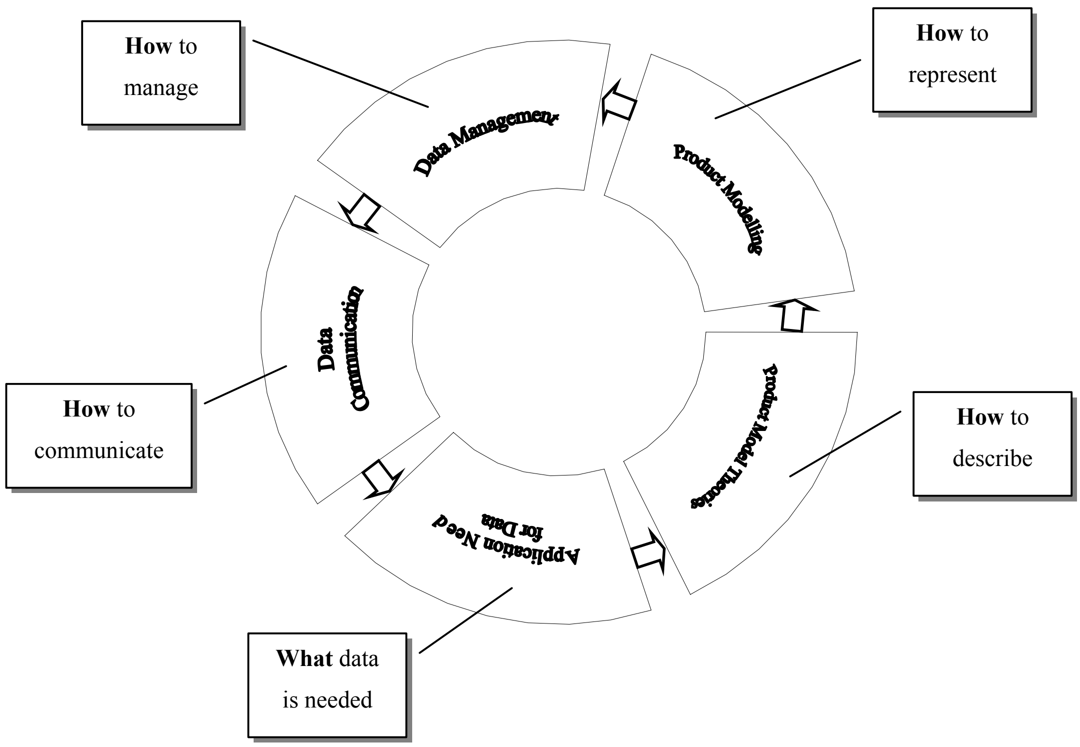

Figure 3.1. Perspectives of a product model [Isa00]

The characteristics of the product data required vary considerably depending on issues such as [Isa00]:

- *Length of the product life cycle.* The extremes encountered in the life of today's engineered products range from aircraft engines, with a life measured in decades, through to mobile phones, where new products seem to appear every few months.
- *Internal or distributed.* Information may only need to be accessible within a single company; however, enterprises might need to share data over company boundaries (for example recyclers or remanufacturers might need information).
- *Product complexity.* Products are becoming increasingly more complex. This is due to several factors including greater use of integrated electronics as well as increasing part commonality and product modularisation.
- *Reuse of parts.* It is becoming very common to reuse parts of a product, due to environmental concern.

In order to communicate data, to handle it, it is necessary to retrieve it from some *product data management system (PDM)*. As defined by CimData, a large consultant company in the PDM area, a PDM system is:

"…a tool that helps people manage both product data and the product development process. PDM systems keep track of the masses of data and information required to design, manufacture or build, and then support and maintain products." [Cim01].

PDM manages product data throughout the enterprise, ensuring that the right information is available for the right people, at the right time, and in the right format [Cim01].

3.2.1. Theories of Product Modelling

Until relatively recently, an engineer's view of product modelling has been a purely technical one, concerned with the problems of how to create a robust geometric model in a CAD or CAE system. However, as computer aided design and engineering environments have improved and data management systems allowed these data to be more easily shared, new problems have emerged and new solutions had to be found.

An increasingly important consideration is how to create a stable yet flexible model capable of representing the entire product.

There are many theories of product modelling. A widely implemented technique used to organise and structure information, initially created to support development of complex systems, is *Systems Engineering (SE)* [She98]. Another interesting theory describing how product models should be structured is the *Theory of Technical Systems (TTS)* [Hub88], a result of European research into engineering design.

Whilst sharing some features, SE is more concerned with analysis and life-cycle management and has been formalised in at least two standards – IEEE 1220 [IEEE95] and EIA 632 [EIA94] – whilst the European design research has a more product-oriented view, decomposing specification into a component structure using a so-called *chromosome model of a product* (see figure 3.2): the process determines the functions, the functions are created by the organs, and the organs are materialised by the components [Mal97]. The chromosome model has been extended by inclusion of a requirement specification model together with a life phase process model, to derive properties such as weight, cost etc.

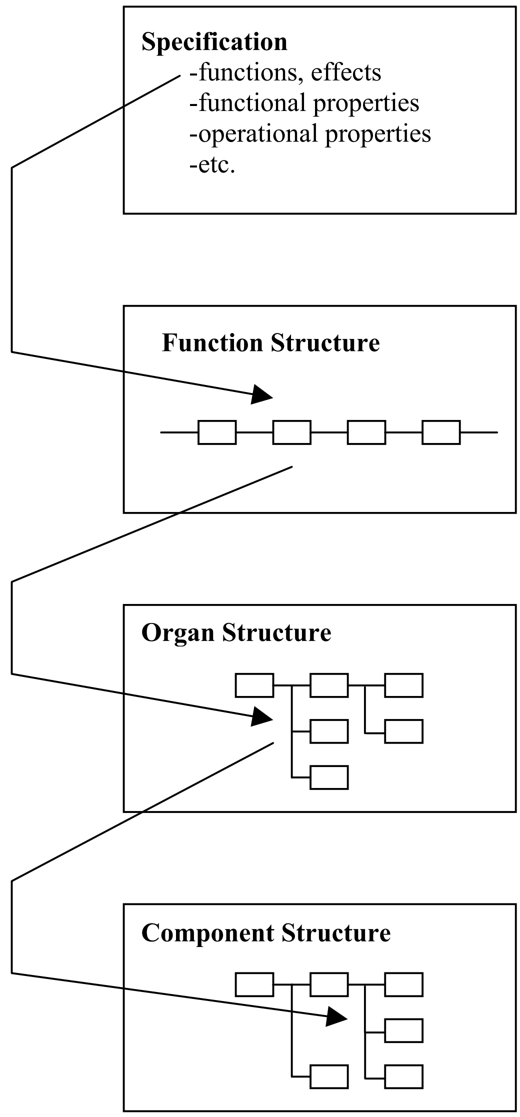

Figure 3.2. The chromosome product model [Isa00]

These techniques (TTS and SE) are concerned with high level structuring of product data. At a more detailed level, interest in techniques to formalise engineering know-how, often referred to as *knowledge-based engineering (KBE)*, is increasing. A KBE language is one of many kinds of tools that can be used to record different kinds of knowledge about how to engineer, design and configure a product in a way that allows it to be easily found, understood, reused and maintained [CET01]. KBE programs are object-oriented.

One core concept for information modelling is that it must be both human- and machine-interpretable. A well-defined information model is one way to ensure that data can be interpreted and used over a long time.

3.2.2. Product Modelling Methods

The capabilities of representation have evolved with the development of object-oriented techniques from lists of values defined by text documents (for example bill of materials) to product models that also take care of the semantics, internal relations, within the model.

There are a number of languages that are capable of handling product information together with semantics. The two languages used most today are the lexical language *EXPRESS* [Den96] and the visual language *UML (Unified Modelling Language)* [Che00], both are defined by international standards and are not based on any specific implementation technique or specific programming language.

This section presents several product modelling methods: a simple text document type (the bill of materials), CAD modelling and the most complex modelling method which is governed by a standard – STEP.

3.2.2.1. The Bill of Materials

An engineering *bill of materials (BOM)* identifies and lists all raw materials, subassemblies, and even intangibles that contribute to the costs of manufacturing a product [Cla97]. The BOM is considered an engineering document that accurately identifies and lists the components required to produce a given product.

An accurate engineering BOM is a prerequisite to developing other operating systems: it is a central source of information that supports product costing, inventory control, and engineering documentation.

A bill of materials may be in a *single level* form, an *indented* form or a *tree* form that accurately describes all materials and subassemblies of the parent (or level one) product. The *single level bill of materials* lists the first level of subassemblies and components used to produce the finished product [GPS00]. The *indented* and the *tree bill of materials* lists all of the subassemblies and components needed to produce the finished product down to the lowest level [GPS00].

Whether the tree or indented method is utilised, the key to understanding BOMs is their levelled structure. For example, level two components always go into the parent (or level one) finished product [Cla97]. However, not all components at a given level require a supporting or lower level. If a sub-assembly at level two is a purchased part, there is no need for a lower, or supporting level. Conversely, if a level two component is fabricated in-house, all materials that go into the level two component must be identified and listed at a lower or supporting level [Cla97].

BOMs can be designed to reflect varying degrees of complexity, depending upon the company needs. Utilised as a basic engineering document, the minimal requirements for BOM information should include [DED01], [Cla97]:

- structure level
- part number
- part name
- quantity required
- unit of measure
- materials required
- description
- source (make or buy)
- weight
- cost.

An example of an indented bill of material is presented in table 3.1.

BOMs can be enhanced to a cost-BOM that gives costing information by including material and labour cost in each lower level component and adding these costs from the bottom to the parent level. Application of overhead rates will then provide manufacturing costs.

The engineering BOM is one of the most important documents associated with the manufacturing process and MRP (Material Requirements Planning) [CCL97]. It is very important to maintain the accuracy of engineering BOMs especially when considering the impact that they have on product costing, inventory, and production management.

Table 3.1. An example of indented bill of materials for a PC [Cla97 modified]

Level	Part Name	Part No.	Quantity	Unit of Measure	Materials	Make/ Buy	Weight	Cost
1	PC	16843-23012	Parent	Piece		Make	25 kg	€ 1027
..2	CPU	15733-87006	1	Piece		Make	11.5 kg	€ 760
….3	Case	13872-25002	1	Piece	Metals + Plastics	Make	2.5 kg	€ 20
……4	Metal	1452	700	g	Ferrous Metal	Buy	2.0 kg	€ 15
……4	Plastic	1825	300	g	Thermo-Plastic	Buy	0.5 kg	€ 5
….3	Mother-board	18259-25863	1	Piece	PWB	Buy	1.3 kg	€ 300
….3	HDD	13586-22486	1	Piece	PWB, Metals	Buy	1.2 kg	€ 100
….3	Video card	14587-35698	1	Piece	PWB	Buy	0.5 kg	€ 100
….3	Sound card	14226-29987	1	Piece	PWB	Buy	0.5 kg	€ 20
….3	Power supply	17845-34458	1	Piece	PWB, Metals, Plastics, Hazardous Materials	Buy	2.0 kg	€ 20
….3	RAM	16544-49785	2	Piece	PWB	Buy	0.2 kg	€ 80
….3	CD ROM drive	13445-65587	1	Piece	PWB, Metals, Plastics	Buy	1.5 kg	€ 100
….3	Floppy drive	14147-26265	1	Piece	PWB, Metals, Plastics	Buy	1.3 kg	€ 10
….3	Connectors, wires	18298-55488	10	Piece	Metals, Plastics	Buy	0.5 kg	€ 10
..2	Keyboards	19999-45654	1	Piece	PWB, Plastics	Buy	1.7 kg	€ 10
..2	Mouse	16598-36367	1	Piece	PWB, Plastics	Buy	0.3 kg	€ 7
..2	Monitor	18778-44458	1	Piece		Buy	11.5 kg	€ 250

3.2.2.2. CAD Modelling

Engineering graphics is the process of defining an object graphically before it is constructed and used by consumers. There are mechanical design software packages – such as AutoCAD, Pro/ENGINEER and SolidWorks – that make possible for mechanical designers to quickly sketch out ideas, experiment with features and dimensions, and produce product models and detailed drawings.

The design methods used for parts, assemblies, and drawings represent a unique approach to the design process. With mechanical design software packages 3D-parts can be created, not just 2D drawings.

Some *characteristics* of the CAD Systems are [SWk01], [DED01]:

- Permit *visualisation* of product
- Offer *graphical display of hard to visualize information* (e.g. 3D warping of plastic part)

- They are *dimension-driven systems*: dimensions and geometric relationships between elements can be specified. Changing dimensions changes the size and shape of the part, while preserving the design intent (see figure 3.3)

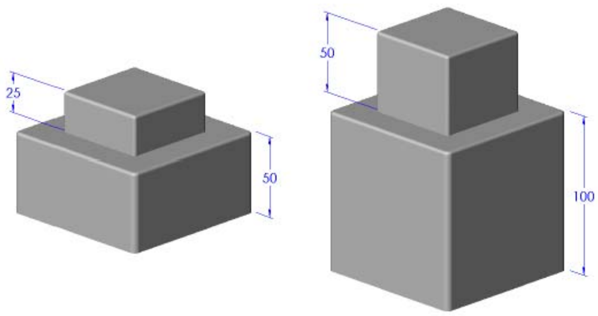

Figure 3.3. Changing dimensions of a part preserves the design intent [SWk01]

- *Sketches* can be created and used to build most features
- Possibility of using *features* (shapes and operations) to build parts
- *Provide structuring of part* (e.g. assemblies). A product model and the parts of the assembly designed using SolidWorks are highlighted in figure 3.4

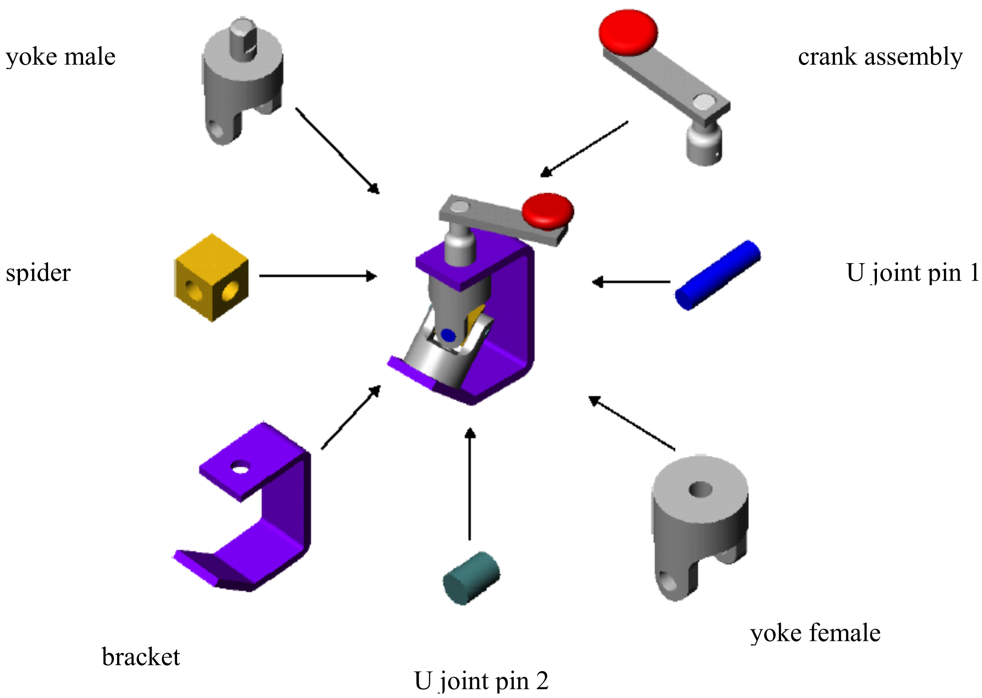

Figure 3.4. A universal joint assembly [SWk01]

- A CAD 3D-model consists of parts, assemblies, and drawings. Parts, assemblies, and drawings display the *same model in different documents*. Any changes made to the model in one document are propagated to the other documents containing the model (see figure 3.5).

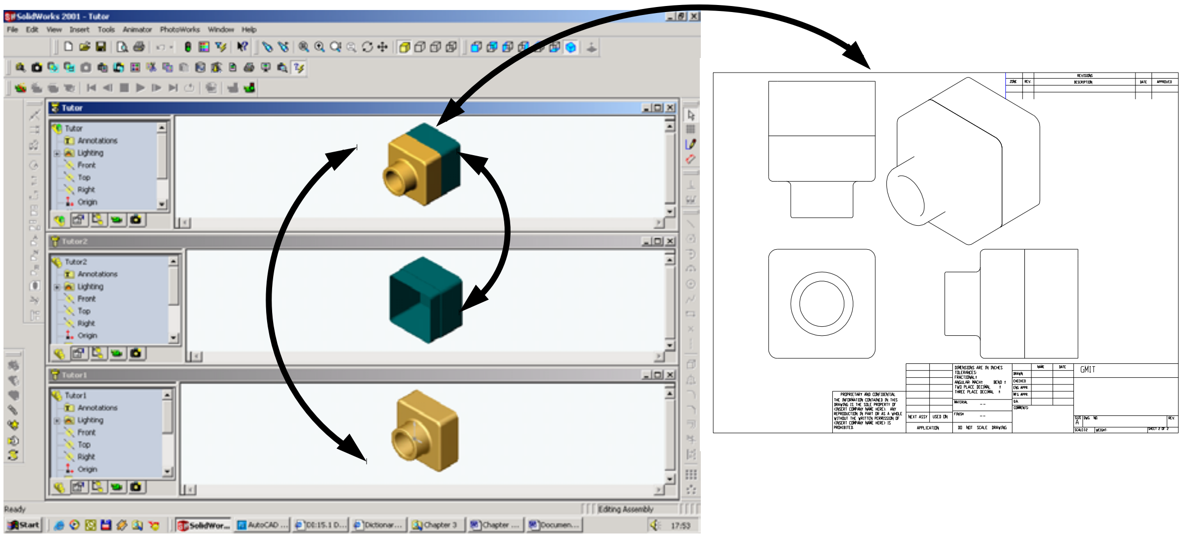

Figure 3.5. Changes made to the model in one document is propagated to other documents containing the model [SWk01]

Multiple-View Featuring Modelling

Current CAD/CAM technologies do not address the requirements of the integrated design engineering process completely. The CAD model is merely a geometric interpretation of the design [Shi00].

One of the most important ways of product modelling is now *feature modelling*. In *feature modelling*, product models contain more than geometric information only, such as the function of some part of the product for the end-user or the way some part of the product can be manufactured or assembled [CGG03]. Feature modelling is based on advanced geometric modelling.

Multiple-view feature modelling is a product development approach that combines concurrent engineering and feature modelling [Bro01]. *Concurrent engineering* aims at designing better products in less time, by using *Design for X* (DFX - where X stands for any product life cycle phase) and by enabling simultaneous activities in several product development phases [Bro01].

Concurrent engineering requires a product model containing information for all product life cycle phases [Bro97]. Solid modelling only deals with information about the geometry of a product. In a concurrent engineering environment *non-shape* information (*functional* information) is also involved. Feature modelling does deal with such non-shape information in addition to shape information; both are represented in *features* [Bro97]. Features can be used in several product life cycle activities. Each activity has its own *view* of a product, its own way of looking at it. Each view contains the features relevant to that specific activity.

Such a product model connects a CAD system with applications from down-stream product development phases. The architecture allows the CAD system and the down-stream applications to deposit a representation of their internal model that is relevant for other applications in a central master model, and also allows these applications to associate information to elements of this central model [Bro01]. In other words, the model supports propagation of all changes in the CAD model to the other applications, and propagation of minor changes from the applications back to the CAD system.

The multiple-view feature modelling system supports *four product development phases* [Bro01]:

- The first phase, in which the product architecture is determined by specifying components and their interfaces, is *conceptual design*. Interfaces between components are specified by means of degrees of freedom between the components.
- The second phase, in which the physical connections between the parts are determined, is *assembly design*. The connections are represented by connection features, such as dove-tail and pen-hole connection features.
- The third phase, in which the details of the geometry of parts are determined, is *part detail design*. Detail design features are form features; examples are a through hole and a protrusion.
- The fourth phase, in which the way each part is to be manufactured is determined, is *part manufacturing planning*. Manufacturing planning features are again form features, such as slot and hole.

The multiple-view feature modelling approach keeps the feature models of all views consistent, i.e. it ensures that all views represent the same product, based on the relations between these views.

3.2.2.3. STEP Technology for Data

STEP is a standard developed by the International Organization for Standardization (ISO). "STEP" is the unofficial name for the standard; the formal designation is ISO 10303 "*Product Data Representation and Exchange*" [ISO92].

STEP provides a basis for communicating product information at all stages in the product life cycle, covering all aspects of product description and manufacturing specifications – see figure 3.6. The fundamental components of the STEP are product information models and standards for sharing information corresponding to such models [Mor93].

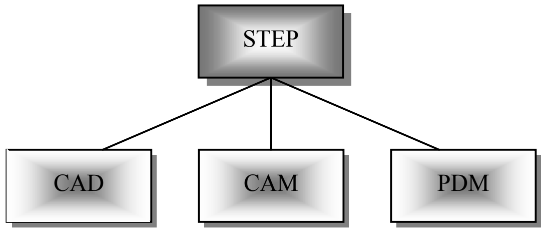

Figure 3.6. STEP covers all aspects of product description and manufacturing specifications [Gua97]

STEP can become part of the supporting information technology infrastructure for life cycle product data management. The key underlying the concept of STEP that allows it to play this role is the recognition of multiple, inter-related views of the total data about a product. Such views can be distinguished by [Fow95], [Gua97]:

- product type
- life cycle phase
- discipline.

STEP combines geometry and configuration controlled design data with information needed for analysis and composites. Analysis product definitions focus on [Gra00]:

- finite element models
- analysis controls
- analysis outputs.

A designer or engineer will generally be interested in a specific subset of the total data about a product – some of these will be reference data (produced by others and used as the basis for ongoing work), some will be created or modified as part of the design and engineering processes. STEP's role is in identifying and standardising the key data that pertains to these processes and to the data flows that occur within and between them. Such data flows can be [Fow95]:

- between similar systems, e.g. between two different 3D CAD systems
- between dissimilar systems, e.g. between a 3D CAD systems and a finite element analysis system
- across enterprise boundaries, e.g. between design and manufacturing functions, or between customer and supplier.

A summary of STEP is presented in figure 3.7.

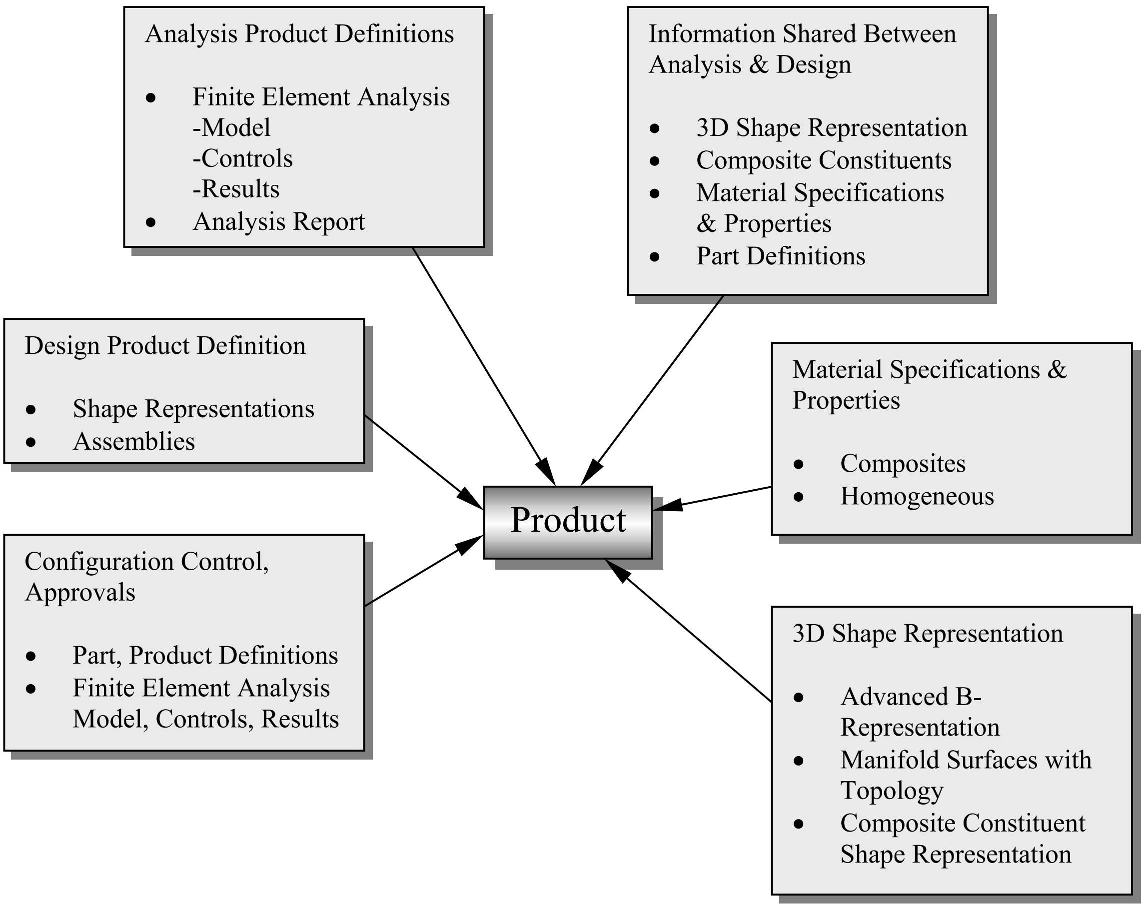

Figure 3.7. STEP representation [Gra00]

STEP Data Models

STEP uses the EXPRESS language and its associated implementation forms to create capabilities for the exchange and sharing of product data. This is accomplished through the standardisation of *data models*. The data models are defined at two levels [Fow95]:

- A *generic product data model* that supports the requirements of all product data applications
- *Specific product data models*, each fulfilling the requirements of a particular industrial application.

The *generic product data model* of STEP has a modular structure that supports extensibility and phased development [Fow95]. This includes basic elements such as the identification, classification or configuration of products [Fow97]. The generic model is published in several parts of the standard, known as *Integrated Resources*. From an architectural point of view, these documents define together a single data model.

STEP satisfies industry needs for product data communication through data models that are based in the common integrated resources but are adapted to meet specific needs. These data models are standardised as *Application Protocols*, which form application-specific *views* within the standard. An application protocol specifies how the STEP integrated resources are used to satisfy a particular need, and forms the basis for STEP implementation [Fow95]. As shown in figure 3.8, application protocols support particular perspectives on products and their supporting information, whereas integrated resources describe an abstract model of products.

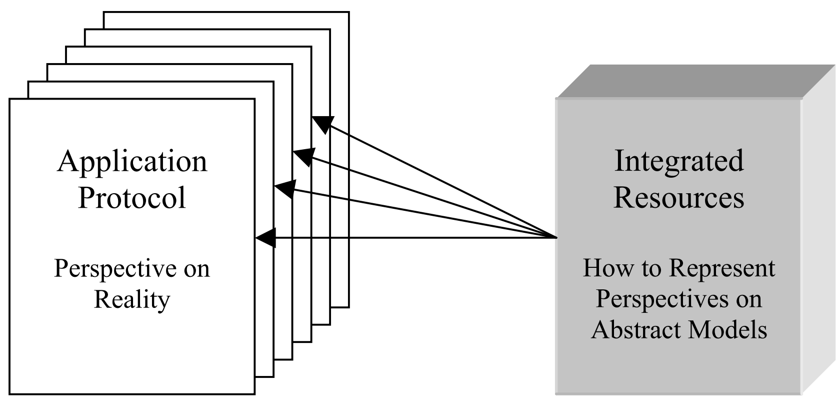

Figure 3.8. STEP Architecture Elements [Fow97]

The detailed structure and semantics of the STEP integrated resources are based on their fundamental *data architecture* – a high level structure that has been used to create and maintain the syntactic and semantic consistency of the model [Fow97].

The first aspect of the STEP data architecture is that it recognised three distinct, high level *views* or *potential uses* of product data. These are:

- how the product is classified or categorised
- how the product is presented to the market
- the technical description of the product for the purpose of design, engineering, manufacturing, operations, maintenance, etc.

Each of these concepts is supported by a major information unit within the STEP integrated resources. Figure 3.9 shows the three views on product data.

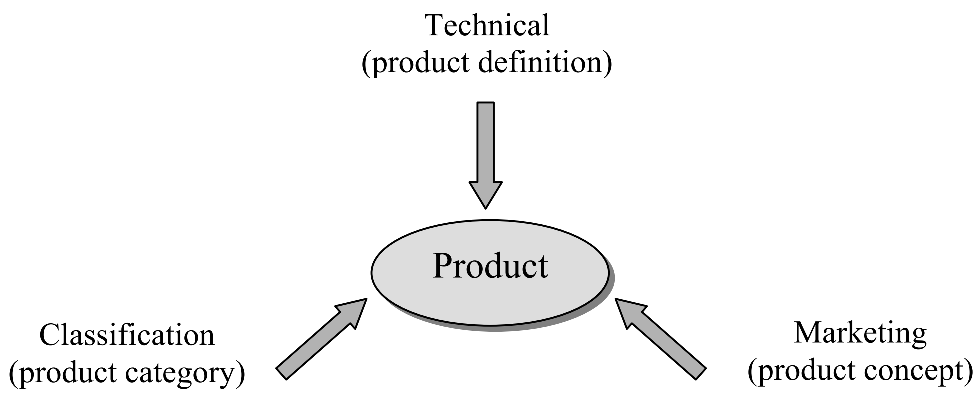

Figure 3.9. Views on product data [Fow97]

STEP and EXPRESS

EXPRESS (defined in ISO 10303-11) is a formal language used to describe information models of STEP. It provides comprehensive facilities for the definition of entities, attributes, and relationships, in the context of modular (multi-schema) data models.

EXPRESS's power is greatly enhanced by the fact that it is *computer interpretable*, i.e., data models written in EXPRESS can be checked using appropriate software tools, and can be transformed into data definition language (DDL) statements of many different programming and database languages [Fow95].

EXPRESS is an information modelling language, not a programming language. EXPRESS is 'object flavoured' [Den96] but not strictly object oriented (it does not encapsulate state with methods).

EXPRESS was originally developed to provide a formal, and computer processable means of defining the data necessary to describe a product throughout its lifecycle, from time of conception through its manufacture to its time of disposal. STEP uses EXPRESS as the formal specification of the required data and its relationships [Wil98].

The EXPRESS system comprises *three components* [Den96]:

- a core component that provides the behaviours of the EXPRESS object model and entity instance reading and writing routines using STEP file-based exchange form
- an EXPRESS parser that builds typed feature structures from the input EXPRESS (feature structures are elements of a logic on which unification, generalisation and specialisation are defined)
- a rule-based syntax transformation component that transforms the syntax tree of feature structures produced by the parser to a syntax tree of features structures in the target language (for example Lisp – List Processing).

EXPRESS models may be written in the style of Entity-Relationship, CODASYL, Relational, Object Oriented, or other kinds of data modelling [Wil98]. It may also be considered to be a Set Theoretic specification language, and some have even gone so far as to indicate that it might be classed as a higher order predicate logic language [Wil98].

3.3. END-OF-LIFE OPTIONS

Waste is a difficult problem society faces today. The products originating from renewable and non-renewable natural resources evolve into waste after their useful lives. *Waste* can be defined as redundant goods, by-products or residues that have no value and must be disposed of at a cost [Gun99]. A given quantity of waste is composed of different waste streams or fractions that have varying environmental impacts depending on their inherent hazardous characteristics [Pea85].

Governments, industries and the public have been very receptive and responsive to the waste problem. Therefore, manufacturers have started to show more interest in producing products that are environmentally friendly and which will be taken back at the end of their useful lives for reuse, recycling etc.

At the end of the product's life it can be disposed of, which means waste, but there are other options as well – product and materials recovery. Once materials enter the waste stream first priority should be given to reusing or remanufacturing them or to recycle them for the purpose of manufacturing new products. Disposal without any material or energy recovery is to be regarded as an option of last resort.

3.3.1. Recovery of Products and Materials

The recovery process is a combination of remanufacturing, reuse and recycling [Gun99]. Recovery processes can be categorised into *material recovery (recycling)* and *product recovery (remanufacturing)*. *Material recovery* mostly includes disassembly for separation and processing of materials (e.g. carrying out necessary chemical operations) of used products. The main purpose is to minimise the amount of disposal and maximise the amount of the materials returned back into the production cycle. *Product recovery* includes disassembly, cleaning, replacing or repairing bad components and reassembling. The recovered parts/products are used in repair, remanufacturing of other products and components and for sale to an outsider. A generic product life cycle waste is presented in figure 3.10.

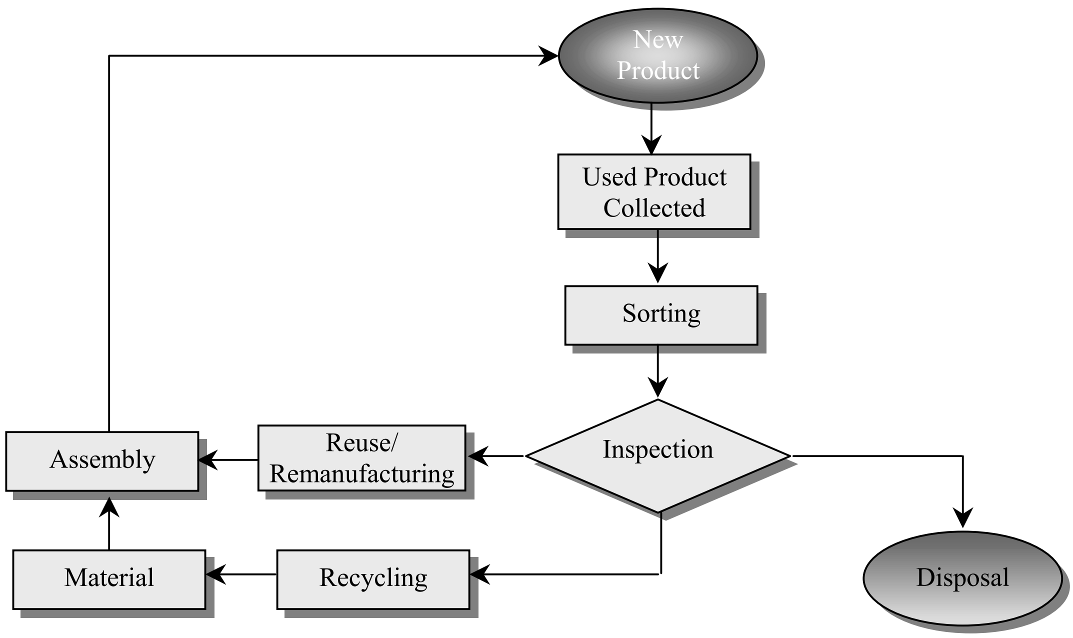

Figure 3.10. A generic product life cycle waste [Sin99, modified]

Material and product recovery is a fact nowadays. In the European Union for example, companies face new legislation that requires product take-back schemes, recycling and reuse at the end of life of their products.

3.3.1.1. Reuse

Reuse is defined as the use of a product or component part in its same form for the same use without remanufacturing [Gog98]. The reuse of product may be the reuse of the entire product or it may be the reuse of components of a product (*part reclamation*). Through extension of the product life cycle in this way all the material, human, energy and process resources are sustained through continued use of the full product functionality.

There are two approaches to reuse [Bet99]:

- Closed reuse processes – producer-led processes
- Open reuse processes – private commercially led processes.

Closed reuse processes are present when users consider the product as durable and long-lasting. The producers provide extensive after-sales services, sometimes including upgrading. A return occurs rather because of a change of needs than because of functional wear-out. Refurbished components as well as complete products are distributed through the same sales channels used for new products and even sold within the same market segments. Closed reuse processes also apply to re-consumables, e.g. reusable cameras. After use the product has still valuable parts and the replacement of some parts enables a user to consume it a second time. This process can repeat itself.

In *open reuse processes*, more than one class of users is involved, located at opposite ends of the take-back channel [Bet99]:

- Customers in search of the latest technology. These may seek remuneration for their old products to discount against their more expensive new product purchases, and to have the high volume of redundant equipment they generate managed
- Customers in need of cheap quality products, who may seek to buy refurbished equipment.

Reuse is highly profitable and commercially viable. It is certainly true that this cannot be said for all products which exist today or will exist in the future. The product type itself is only a factor in the nature and success of the recovery process.

3.3.1.2. Remanufacturing

Remanufacturing is an environmentally and economically sound way to achieve many of the goals of sustainable development. Remanufacturing focuses on value-added recovery [Gui00], rather than just materials recovery (recycling).

Remanufacturing is "*an industrial process in which worn-out products are restored to like-new condition. Through a series of industrial processes in a factory environment, a discarded product is completely disassembled. Useable parts are cleaned, re-furbished, and put into inventory. Then the new product is reassembled from the old and, where necessary, new parts to produce a fully equivalent – and sometimes superior – in performance and expected lifetime to the original new product*" [Gui00]. A typical unit flow in remanufacturing is shown in figure 3.11.

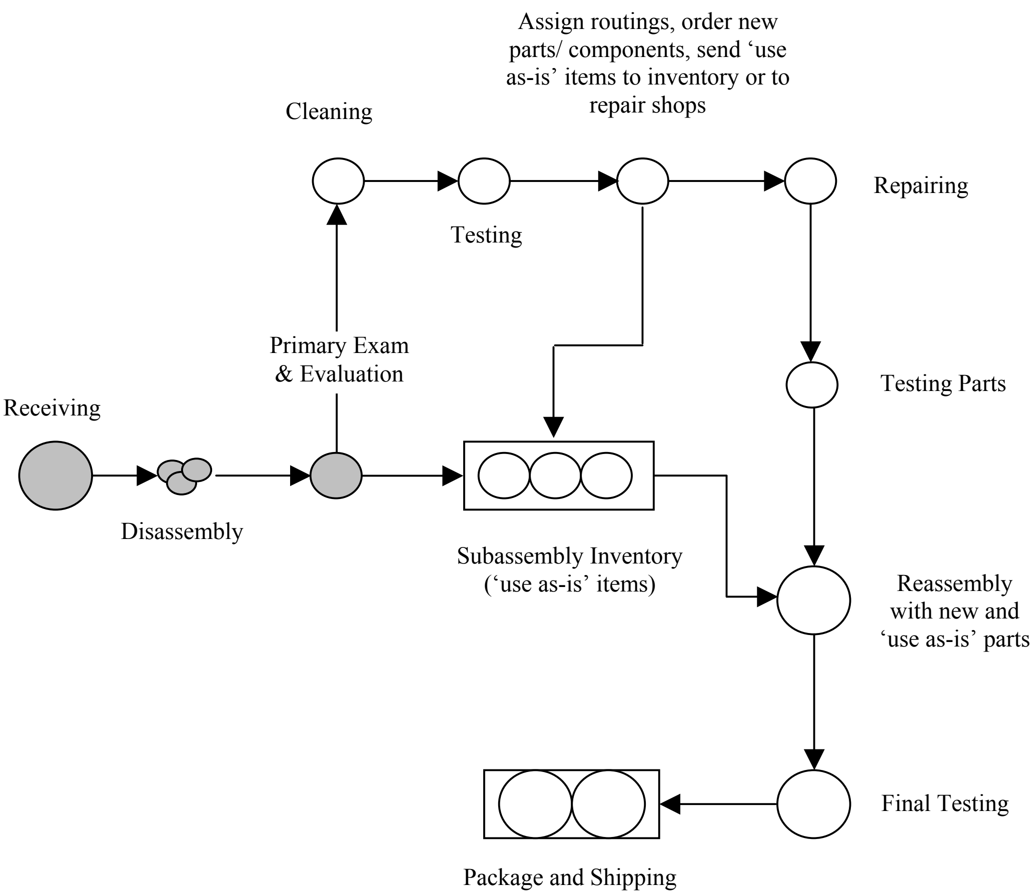

Figure 3.11. A typical unit flow in remanufacturing [Gun99]

Remanufacturing is distinctly different from repair operations, since products are disassembled completely and all parts are returned to like-new condition, which may include cosmetic operations. Remanufacturing is a form of waste avoidance since products are reused rather than being discarded. Remanufacturing also captures value-added remaining in the product in the forms of materials, energy and labour.

Lund has identified 75 separate product types that are routinely remanufactured, and has developed criteria for *remanufacturability* [Lun98]. The seven *criteria* are [Lun98]:

1. The product is a durable good
2. The product fails functionally
3. The product is standardised and the parts are interchangeable
4. The remaining value-added is high
5. The cost to obtain the failed product is low compared to the remaining value-added
6. The product technology is stable
7. The consumer is aware that remanufactured products are available.

Remanufacturing is a complicated process in terms of logistics. Seven major *characteristics* of the system make remanufacturing complicated [Gui00]: uncertainty in the timing and the quantity of returns, balancing returns with demands, disassembly, uncertainty in materials recovered, reverse logistics, materials matching requirements and routing uncertainty and processing time uncertainty.

3.3.1.3. Recycling

Recycling is performed to retrieve the material content of the end-of-life products. Recycling has proven to be an attractive business for many materials and industries, for example the consumer electronics industry. A typical computer contains gold, silver, palladium and platinum, and so does a telephone [Man94]. Besides the recovery of such highly valuable materials, other materials such as plastics or metals are being recovered due to environmental concerns.

In order to find a balance between the resources invested in a recycling process (i.e. time and money) and value gained from the recovered materials, economic analysis of recycling process is carried out. The objective, of course, is to continue the recovery process as long as the profitability is maintained [Gun99].

Figure 3.12 shows the main stages in a recycling process [Bet99]:

- Collection
- Sorting
- Disassembly
- Pre-processing – mechanical processing of products and subassemblies to produce different stream of mixed material fractions

- Specialist material processing – processing of one particular material stream to meet the quality specification for reuse by materials producers
- Materials production – production of finished or pure materials from reclaimed materials for use in new product manufacturing by producers.

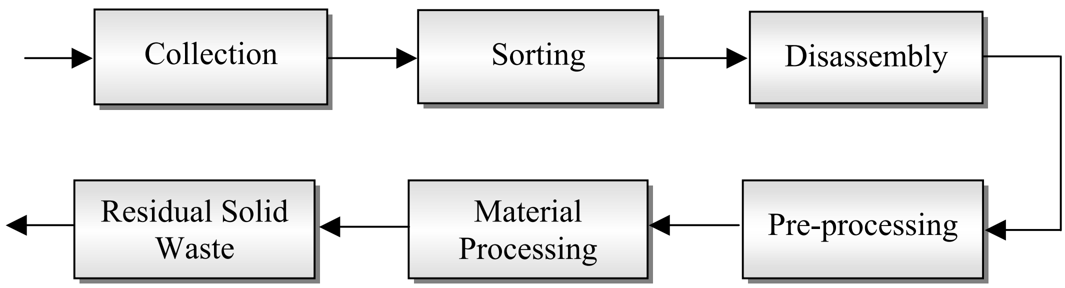

Figure 3.12. Stages of a recycling process [Bet99]

Recycling has various environmental impacts, both positive and negative. Some of these impacts are outlined below [Rhy95]:

- *Conservation of materials* – recoverability of materials is limited because of physical and economic constraints. *Physical limitations* arise from the fact that certain materials cannot be recycled after use (e.g. thermoset plastics). As for the economic constraints, if the potential revenue available to a secondary materials processor does not exceed the acquisition and processing costs, the economic viability of the recycling process breaks down.
- *Energy conservation* – for example 90% to 97% energy savings occur when aluminium is manufactured from secondary materials instead of virgin materials.
- *Pollution reduction* – lower levels of air pollution, water pollution or soil pollution may be attributable to recycling.
- *Reduction in mining wastes* when secondary materials are used for manufacturing glass and steel.
- *Large quantities of wastewater* through the plastic cleaning process.

3.3.2. Disposal at the End of Life of a Product

The ultimate end-of-life options are *incineration with energy recovery* or simply *disposal to landfill*.

3.3.2.1. Incineration with Energy Recovery

Incineration is the controlled burning of wastes at high temperatures in a facility designed for efficient and complete combustion [Rhy95]. The lack of available land for landfilling and the high cost of energy are two major incentives for including incineration as part of a solid waste management system. Most modern incinerators are designed for the recovery of energy.

Incineration is fundamentally a form of chemical processing, involving the rapid oxidation of materials. The combustion process involves several stages in which the waste is dried as it enters the furnace, the organic compounds are volatilised and the volatile compounds are ignited in the presence of oxygen.

Two common types of facilities used to burn unprocessed solid waste are field-erected mass burn incinerators and prefabricated modular incinerators [Rhy95]. They differ in design, construction, processing capacity, air pollution control requirements, service life and costs.

The burning of solid waste produces only about 25% as much energy, on a per weight basis, as that resulting from the burning of fossil fuels [Rhy95]. The primary energy products are *hot water*, *low-pressure steam*, *high-pressure steam* and *electricity*. The specific products generated depend upon the design of the facility, the fuel, and the requirements of the energy buyer. Steam and hot water are the easiest to generate, but transporting these products requires laying pipelines to the buyer's facility which involves a high cost. Electricity is generally more marketable than steam. Transportation is not limited to short distances as is the case for steam and the demand is likely to be less seasonal.

Inputs and Outputs of an Incineration Plant

The overall inputs and outputs to an incineration plant are presented in figure 3.13.

Municipal solid waste (MSW) and additional resources are *inputs* to the operation of incineration plants [EC00]. The additional resources consist both of renewable and non-renewable resources such as auxiliary materials, water, fossil fuels, and land. Auxiliary materials are used in the flue gas cleaning processes. The quantity of water used is relatively low and can be of secondary quality (not drinking water). Fossil fuels such as fuel oil or natural gas are used to start up and shut down incineration plants. The amounts used are relatively low. Electricity, produced from fossil fuels or originating from energy recovered at the plant itself, is additionally consumed during plant operation, particularly by the flue gas cleaning process. The amount of land required for an incineration plant, which is assumed to be independent of the process technology used, is relatively small compared to the plant capacity.

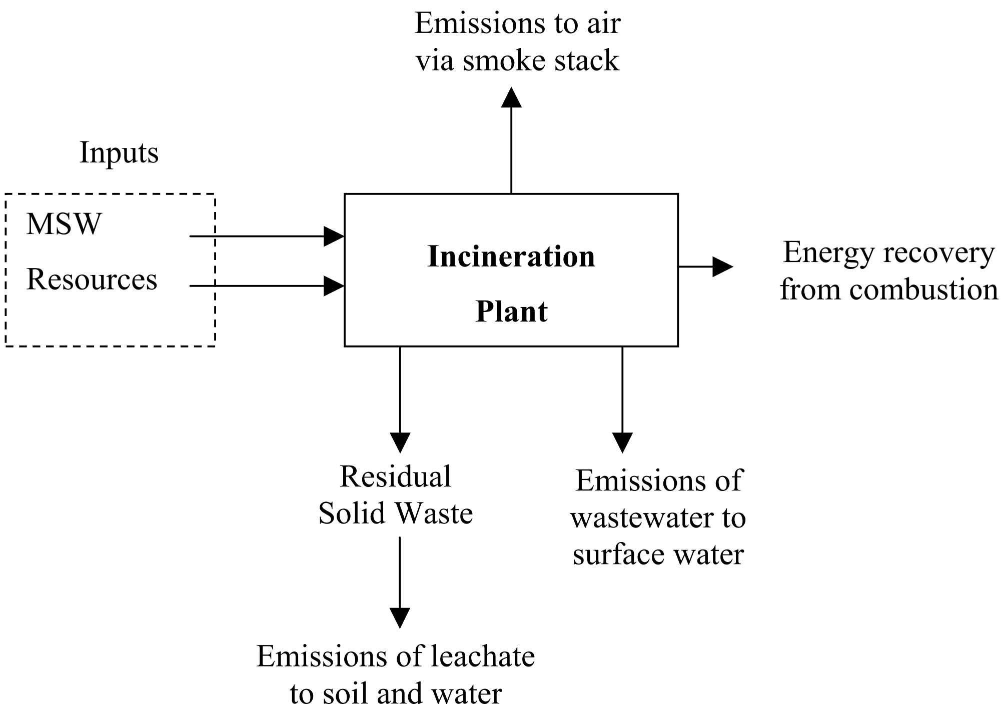

Figure 3.13. Representation of inputs and outputs to an incineration plant [EC00]

Outputs include emissions to air, water and soil, as well as the energy recovered during combustion [EC00]. Emissions to air include the flue gas from the incineration process. These emissions can be controlled using various treatment process that remove particulates and gases before the remaining flue gas is emitted to the air via the smokestack. Flue gas cleaning processes produce residues that are considered hazardous and need to be treated prior to disposal. The incineration process also generates residual solid waste requiring disposal and/or use. Contaminants in the residual solid waste can be leached and lead to emissions to soil and water.

3.3.2.2. Disposal to Landfill

Landfilling waste is a modern variation of the long-used practice of depositing waste in a dump site at the outskirts of a community. A modern sanitary landfill is an engineered site, selected, designed and operated in such a manner as to minimise environment impacts. Municipal waste is deposited in a confined area, spread in thin layers, compacted to the smallest practical volume and covered at the end of each working day [Rhy95].

A sanitary landfill is operated to minimise nuisance conditions arising from litter, dust, odours and fire, and the attraction of rats, flies, mosquitoes and birds. The standard method of operation consists of [Rhy95]:

1. Spreading waste in thin layers in a confined area
2. Compacting the waste to the smallest practical volume
3. Covering the waste daily with soil or another type of material.

Only a fraction of a landfill is developed at a time. These developed portions or phases can accept waste for a year or two after which the completed phase will be closed and another opened.

Inputs and Outputs of a Landfill Site

The overall inputs and outputs to a landfill site are presented in figure 3.14.

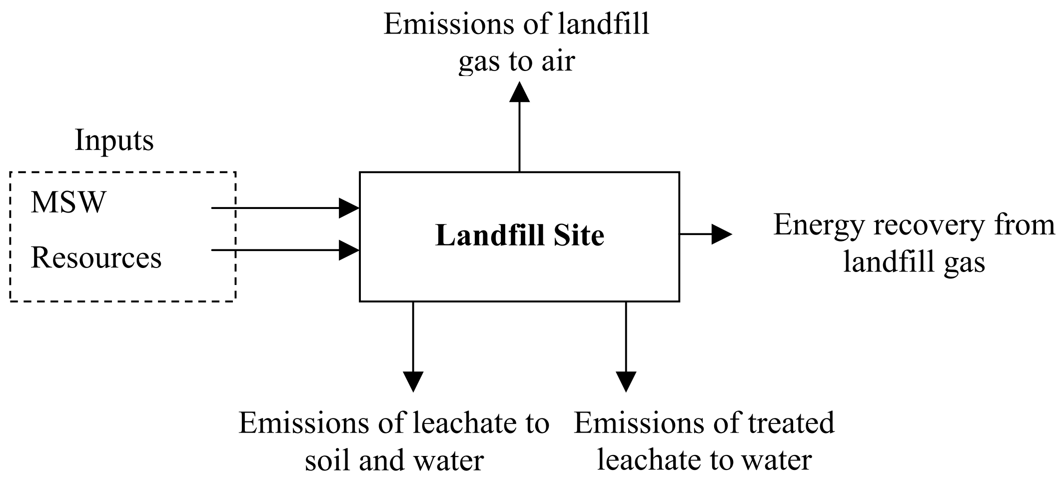

Figure 3.14. Representation of inputs and outputs to a landfill site [EC00]

Inputs: Municipal solid waste (MSW) and additional resources are needed to operate landfill sites. The additional resources consist both of renewable and non-renewable resources such as auxiliary materials, fossil fuels, and land [EC00]. At controlled landfill sites where leachate is collected, auxiliary materials are used to treat the leachate prior to recirculation in the landfill, or discharge either to a sewage treatment plant for tertiary treatment or directly to surface water. During the landfilling process, fossil fuels are consumed by vehicles working at the site, and electricity is required. Once the landfill is closed, energy is required during the active phase for monitoring activities. At modern landfills, energy is also expended to collect and treat leachate, and to collect and use or flare landfill gas. The amount of land taken up by a landfill is assumed to depend only on the site's waste capacity, i.e. the amount of waste that can be landfilled at the site.

Outputs from landfill sites include emissions to air, water and soil, as well as the energy recovered from landfill gas [EC00]. Landfill gas is emitted to air and leachate generated from the municipal solid waste can be emitted to soil and water. At landfill sites with gas collection systems, landfill gas is recovered and used to generate either heat, electricity or both. Where a landfill site has a leachate collection system, emissions to soil and water are reduced, and treated leachate is discharged to surface water.

In the European Union landfill of waste is controlled by the Landfill Directive adopted in April 1999 [Bur01]. The overall aim of the directive is to prevent, or reduce as far as possible, any negative impacts on human health or the environment due to the landfilling of waste. In particular, it is concerned with preventing pollution of surface and ground waters, pollution of soils and air pollution [Bur01].

3.4. CONCLUSIONS

As a consequence of both rapid depletion of raw materials and an increasing amount of different forms of waste (solid waste, air and water pollution etc.), two commonly accepted primary objectives have been gaining momentum:

- Create environmentally friendly products (green products)
- Develop techniques for product recovery and waste management.

Product recovery aims to minimise the amount of waste sent to landfills by recovering materials and parts from old or outdated products by means of recycling and remanufacturing (including reuse of parts and products). Product recovery has become an obligation to the environment and to society itself, enforced primarily by governmental regulations and customer perspective on environmental issues. For example, the proposed EU Directive on Waste Electrical and Electronic Equipment (WEEE Directive) lays down measures which aim, as a first priority, at the prevention of waste electrical and electronic equipment, and, in addition, at the reuse, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste [WEEE02].

Recovery of products is the last phase in the product life cycle and, as any other stage in the product life cycle, it needs product data. As the WEEE Directive states, producers must keep "*records on the mass of WEEE, their components, materials or substances when entering (input) and leaving (output) the treatment facility and/or when entering (input) the recovery or recycling facility*" [WEEE02]. Therefore, a product model that meets the requirements of processors is necessary.

It is easy to think that all the data associated with a product during its life, from conception, design, manufacture, use through to final disposal, could be stored in a single database. The reality is that this is not possible. Developing a single description of a product model which includes all possible data about a product would be difficult to achieve in practice and, even if possible, would be too large, complex and rigid. Therefore, a special product description for the end of life stage of the product life cycle is necessary.

Three product models have been presented in this chapter: BOM, CAD and STEP. BOM offers a list of components and materials of a product, data which is useful for the processors, but it does not offer all the information the processor might need in order to treat the EOL product (e.g. suitability for disassembly, for recycling, hazardous materials). A CAD model mainly gives a geometrical description of the product but that is not what the processor needs to know about the product he/she is going to treat at the end of life. As for the STEP model, it is very complex and it is suitable for a comprehensive PDM system. What the EOL product model needs would be only a small section of this comprising PDM system.

Therefore, a product model appropriate for the need of processors should be elaborated for the environmental and economic methodology for EOL products that is developed in this thesis.

CHAPTER 4. MULTI-CRITERIA ANALYSIS AND DECISION-MAKING FOR END-OF-LIFE PRODUCTS

4.1. INTRODUCTION

The decision-making process as it relates to determination of end-of-life option is based on several criteria, rather than an exclusive single criterion. The diversity of environmental impacts and the multitude of units they are expressed in, the natural resources depletion and the complexity involved in the economic valuation pose problems to monetisation of all these criteria [Tiw99]. That is why, for the complex environmental and economic decision-making processes, new techniques capable of giving solutions to satisfy both sustainability principles and economic efficiency must be considered.

Multi-criteria analysis methods can be very helpful in the environmental and economic decision-making process as they consider the results of monetary valuation, as well as ecological analysis, and the decision-makers' points of view. Several such methods, including powerful techniques routinely used in multiple-criteria decision-making – such as Analytical Hierarchy Process or PROMETHEE – will be presented in this chapter.

4.2. QUALITY FUNCTION DEPLOYMENT

Quality Function Development (QFD) was conceived in Japan by Yoji Akao in the late 1960s. QFD was born as a method or concept for new product development under the umbrella of Total Quality Control [Aka97]. Quality deployment is defined as a methodology that "*converts user demands into substitute quality characteristics, determines the design quality of the finished good, and systematically deploys this quality into component quality, individual part quality and process elements and their relationships*" [Aka97].

The QFD technique is usually used for solving problems associated with the development or improvement of any product or service. QFD emphasises active participation from the customer and helps integrate the engineering efforts of teams with skills from multiple disciplines.

4.2.1. The QFD Process

QFD is based on a matrix approach (a typical QFD chart – *House of Quality matrix* – is presented in figure 4.1). A series of charts is developed which maps the relationships between customer requirements and engineering characteristics, right through to production planning.

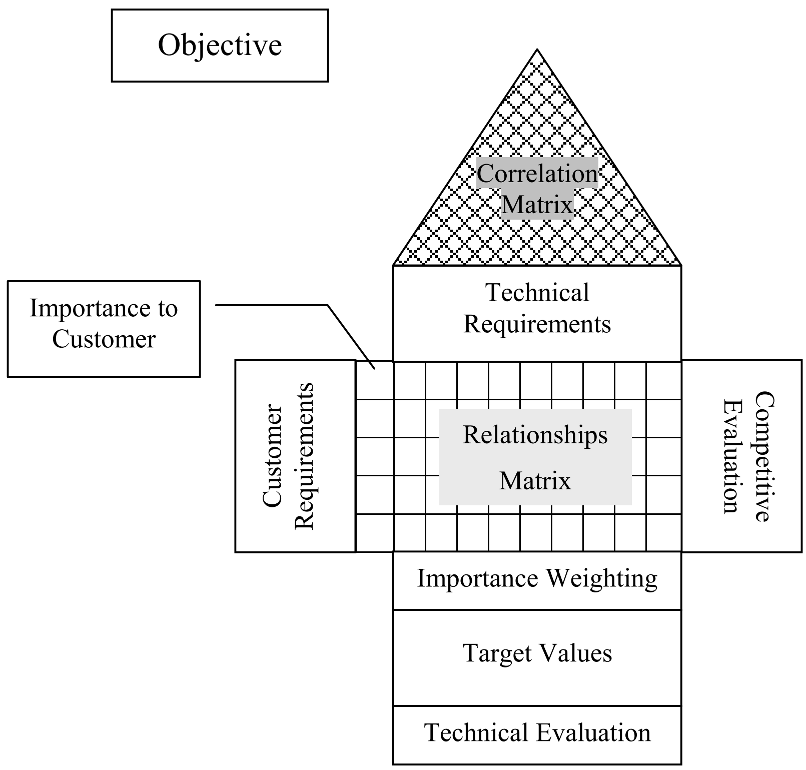

Figure 4.1. The House of Quality [Jag97], [MIT97]

The ***QFD process*** is described below [Jag97], [MIT97], [Kli02]:

Objective – describes the goal, problem or objective of the analysis. The customer plays an important role in defining the objective.

Customer requirements – determines the customer requirements for the product or service produced. It is the most important and time-consuming step in QFD. Customer requirements can be defined by interviews, brainstorming, feedback mechanisms and market research.

Importance to customer – prioritises customer requirements. Since trade-off decisions always exist, this step ensures that they favour customer needs and desires to the maximum extent and are not based only on what's convenient for the developer.

Competitive evaluation – is used to record the company's performance on particular customer requirements with respect to competitors, where such information is available.

Technical requirements – these are process characteristics that show performance parameters of the system.

Relationships matrix – shows the relationships between customer requirements and the technical requirements. It is possible to identify performance measures that, although they may seem important from the company's point of view, are not viewed as such by the customer.

Importance weighting – compares the strength of the customer requirements, the technical requirements and the customer importance information to identify technical requirements that are most important.

Target values – represent quantifiable goals for the technical requirements.

Technical evaluation – evaluates an organisation and its competitors' capability to meet the technical requirements.

Correlation matrix – explores the strength of the relationship between pairs of technical requirements. Weak correlations are traded off to find the best compromise and strong correlations are studied to prevent duplication of effort.

4.2.2. QFD and Environment

Some of the environmental activities in which QFD can be effectively used are *regulatory compliance, emission reduction, pollution and loss prevention programmes, construction or operating permit acquisition and equipment procurement* (equipment leaks).

The QFD methodology can be adapted for use in emission reduction as follows [Hal01]:

- Customer requirements are defined as *impact categories* that reflect environmental problems

- The technical requirements are expressed in terms of *substances that the process emitted* which need to be reduced
- The relationships matrix is described as the degree of contribution of a certain substance to a certain impact category (*impact potential*)
- The *weights of impact categories* are based on environmental experts' opinions
- The technical *correlation matrix* is not used because the correlation of the emitted substances have not been explored yet and need more research
- The *target specifications* are the results of the environmental benchmarking of emission values for the techniques being considered. They could be also emission limits for water, air and land as provided by the environmental agency
- The *design cost* is the cost of implementing the necessary emission reduction for a particular substance to meet the current environmental benchmarks or latest limits

The house of quality modified for emission reduction is called the ***house of environment/ecology*** because environmental requirements are being deployed instead of quality requirements. An example of the house of environment is presented in figure 4.2.

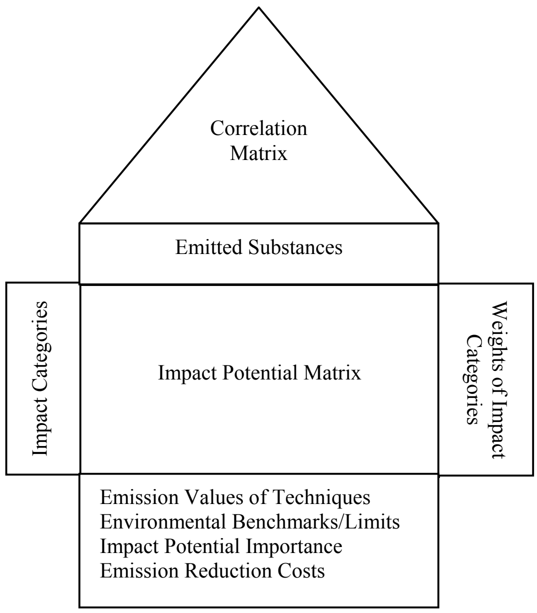

Figure 4.2. House of environment [Hal01]

4.2.3. QFD and Decision-Making for End-of-Life Products

The QFD method offers a complete analysis of a project. It is very useful for new projects evaluation. The modified QFD method – house of environment – could be used in the environmental decision-making for end-of-life products, but not for the economic part. The method has also the disadvantage that it is not intended for non-expert users as the weights of impact categories need an expert opinion.

4.3. Cost-Benefit Analysis

Cost-Benefit Analysis (CBA) estimates and totals up the equivalent money value of the benefits and costs to the community of projects to establish whether they are worthwhile [Mul02]. Generally, such an analysis appraises projects before they are undertaken. CBA attempts to evaluate all the marketed and un-marketed consequences of projects and to estimate the net social benefits [Mul02].

The ***procedure*** of cost-benefit analysis follows a few basic steps [Mul02], [Snl97]:

- Define the set of *objectives*
- State the *alternatives* that would meet the objectives
- Define the *decision criteria* and parameters, such as:
    - Period to be used for analysis
    - Discount rate
    - Categories of benefits and costs
- State the *constraints* that impinge on the project (technological, physical, environmental, financial and statutory)
- In respect of each chosen alternative:
    - Estimate the cost of taking that course of action
    - Estimate the benefits it would bring
    - Weigh up the costs and benefits by means of some quantitative indicator
    - Apply the criteria, calculate indicators
    - Carry out sensitivity tests (showing what would happen to the indicators of the parameters and assumptions were different)
- *Make the decision* based on the indicators calculated.

4.3.1. Quantifying and Valuing the Costs and Benefits

In order to reach a conclusion as to the desirability of a project, all aspects of the project, positive and negative, must be expressed in terms of a *common unit*. The most convenient unit is money. This means that all benefits and costs of a project should be measured in terms of their equivalent money value.

There are consequences of a decision, such as project's inputs and outputs, which have no market and do not give rise to financial payments to or from the relevant entity; these are called *externalities*. Examples are clean air, beautiful landscapes, environmental impacts – desirable and undesirable. In these cases, information on value can be obtained by a range of relatively recently developed methodologies such as *contingent valuation* (people are asked how much they are willing to pay to preserve or protect something that cannot be bought in a store) or *hedonic pricing* (a method of attaching prices to unpriced things by inferring what people are willing to pay from observation of their behaviour in other markets), but they are complicated and, even when well done, very approximate [Snl97].

Not only do the benefits and costs of a project have to be expressed in terms of equivalent money value, but they have to be expressed in terms of money of a particular time [Wat02]. The present value PV of a given amount FV (future value) accruing n years from now can be stated as:

$$PV = \frac{FV}{(1+i)^n} \qquad \text{[Mul02]}$$

The expression $\frac{1}{(1+i)^n}$ is known as the *discount factor*. The higher the discount rate (i) the lower the discount factor.

4.3.2. Cost-Benefit Analysis and Environment

Although many consider that cost-benefit analysis offers a way of achieving superior environmental results at a lower overall cost to society than other available approaches, this method sometimes produces inferior results in terms of both environmental protection and overall social welfare.

One problem with cost-benefit analysis in environment is that it seeks to translate all relevant considerations into monetary terms [Hez02]. The costs of protecting the environment through the use of pollution control devices and other approaches are measured in money units. This side of the cost-benefit analysis (the costs) is relatively straightforward in theory, although in practice it is not quite simple.

But more problematic is the other side of the cost-benefit analysis: the monetary valuation of benefits of nature. Since there are no natural prices for a healthy environment, cost-benefit analysis requires the creation of artificial ones. Artificial prices for environmental benefits are created by studying what people would be willing to pay for them. The methods of calculating these artificial prices do not confer accuracy and are based on individuals' private decisions as consumers, not on their public values as citizens [Hez02].

Costs and benefits of a policy frequently occur at different times. When the analysis spans a number of years, future costs and benefits are discounted in today's money. Cost-benefit analysis uses the present value of future benefits, it compares current costs not to the actual money value of future benefits, but to their present value. Discounting makes sense in comparing alternative financial investments, but it cannot reasonably be used to make a choice between preventing non-economic harms to present generations and preventing similar harms to future generations. In addition, discounting tends to trivialise long-term environmental risks, minimising the very real threat the society faces from potential catastrophes and irreversible environmental harms, such as those posed by global warming and nuclear waste.

4.3.3. Cost-Benefit Analysis and Decision-Making for End-of-Life Products

Cost-benefit analysis is a simple method useful for decision-making in many cases but it does not offer a hierarchy and it is difficult to find a common unit of measurement for all the criteria (especially the environmental criteria); it could be useful for the economic decision-making for end-of-life products, but not for the environmental part.

4.4. CROSS-IMPACT ANALYSIS

The cross-impact method was originally developed by Theodore Gordon and Olaf Helmer in 1966. The method resulted from a simple question: can forecasting be based on perceptions about how future events may interact? [Gor94]. Cross-impact analysis is a means of measuring the correlation between variables. It is most commonly used as a forecasting tool to identify how technological developments in one area will affect those in another, the strength of that influence and whether it makes the outcome more or less likely. The interrelationship between different events and developments is called *cross-impact* [Gor94].

4.4.1. Cross-Impact Analysis Procedure

The first step in a cross-impact analysis is to *define the events* to be included in the study. The inclusion of events that are not pertinent can complicate the analysis unnecessarily. Most studies include between 10 and 40 events (variables).

The next step is to build the *cross-impact matrix* comprising rows and columns of the events. A cross-impact matrix is a tool for systematic description of all potential modes of interaction between a given set of events (variables) and the assessment of the strength of these interactions [Schl97], [Cho03]. It ensures that none of the potential interrelations between the defined events will be omitted. For every single pair of them, the intensity of the impact that one has on the other is examined. Usually four intensities are used for assessing impacts:

0. no impact
1. weak impact
2. medium impact
3. strong impact.

An example of cross-impact matrix is presented in figure 4.3.

By cumulating row and column entries for each variable, its individual role in relation to the system is determined. The sum of rows (the active sum AS of a variable) is an indicator of how a variable acts on the system as a whole. The sum of columns (the passive sum PS) shows how it is affected by all other variables (P denoting Product and Q – quotient).

There are four types of variables [Schl97]:

- *active* – variables less affected by the rest of the system than they have impact on it (quotient > 1)
- *reactive* – variables more affected by the system than they affect it (quotient < 1)
- *critical* – variables affected by many other variables and have themselves many impacts (product > $(n-1)^2$)
- *inert* – variables less involved in the dynamics of the system (product < $(n-1)^2$).

The matrix will pinpoint the active levers where any intervention is effective and the reactive elements where no effort should be wasted. This analysis leads to a better understanding of the system's properties as a whole. It shows the decision-maker where to focus his/her efforts to achieve desired results.

Events (variables)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	AS	P=AS× PS
1 climatic extremes	-	1	1	2	0	0	1	0	0	2	0	0	1	0	**8**	**16**
2 affluent society	1	-	2	1	0	0	1	1	0	0	0	1	0	1	**8**	**64**
3 demographic structure	0	2	-	0	0	0	2	1	0	0	0	1	0	2	**8**	**24**
4 technological innovations	0	1	0	-	1	0	1	1	1	2	1	0	1	2	**11**	**132**
5 market liberalisation	0	0	0	2	-	3	2	3	2	2	1	2	3	2	**22**	**198**
6 electricity regulation	0	0	0	1	3	-	1	2	2	2	1	2	2	0	**16**	**240**
7 electricity demand	0	0	0	1	1	2	-	2	0	1	1	1	2	2	**13**	**208**
8 service quality	0	1	0	0	0	0	2	-	1	2	1	1	2	1	**11**	**209**
9 industry restructuring	0	0	0	1	1	2	1	2	-	2	2	2	3	0	**16**	**192**
10 flexibility of supply	0	0	0	1	1	2	2	2	1	-	2	1	1	2	**15**	**330**
11 transportation capacities	0	0	0	0	1	2	0	2	2	3	-	0	1	1	**12**	**156**
12 customer orientation	0	1	0	1	0	1	2	1	2	2	1	-	2	0	**13**	**182**
13 management of change	0	0	0	1	1	1	1	2	1	3	2	3	-	1	**16**	**304**
14 environmental hazards	1	2	0	1	0	2	0	0	0	1	1	0	1	-	**9**	**126**
	2	**8**	**3**	**12**	**9**	**15**	**16**	**19**	**12**	**22**	**13**	**14**	**19**	**14**	**PS**	
	400	**100**	**266**	**92**	**244**	**107**	**81**	**58**	**133**	**68**	**92**	**93**	**84**	**64**	**Qx100, Q= AS/ PS**	

Figure 4.3. Example of cross-impact matrix [Schl97]

4.4.2. Cross-Impact Analysis and Decision-Making for End-of-Life Products

The major benefit of using a cross-impact analysis is the ability to show how one situation impacts another; it shows interactions between events, situations. It could be useful for environmental decision-making, but results are quite difficult to understand.

4.5. ANALYTICAL HIERARCHY PROCESS

Solving a multi-criteria decision problem offers the decision-maker the best decision alternative. When finding the best choice of decision alternative, subject to a number of different criteria, the analytical hierarchy process (AHP) is a well-known and frequently used method [Bey02].

AHP solves a specific class of problems that involve prioritisation of potential alternate solutions through evaluation of a set of criteria elements [Asa94]. These elements may be divided into sub-elements and so on, thus forming a hierarchical decision tree.

AHP suits a wide range of applications; the method has been gaining popularity as a viable decision-support tool in a number of fields such as economics, politics, marketing, sociology and management.

4.5.1. AHP Procedure

The ***AHP procedure*** follows the following steps [Sin00], [Asa94]:

1. *Structuring the hierarchy of criteria and alternatives for evaluation*. A hierarchical structure is formed. The overall goal of the decision is at the top level of the hierarchy, detailed at the next level with the major criteria. Each criterion in turn is detailed to provide additional descendants. Once the decision structure is completely formed, all alternatives are assigned to each criterion at the lowest level.

2. *Assessing the decision-maker evaluations by pairwise comparisons*. Relative importance (or preference) for each criterion is assigned using the pairwise comparison method. Each criterion is compared against the other siblings, the pairwise comparisons using a nine-point scale:

   1 = Equal importance (preference)
   3 = Moderate importance of one over another
   5 = Strong importance (preference)
   7 = Very strong importance (preference)
   9 = Extreme importance (preference)
   2, 4, 6, 8 = Intermediate values between two adjacent judgements.

A square matrix is formed when every two criteria are compared. The matrix has the property that element $a_{ji} = \frac{1}{a_{ij}}$ (when a criterion has one of the above numbers assigned to it when compared to a second criterion, then the second criterion has the reciprocal value when compared to the first).

Relative importance for each alternative is rated in the same way as for criteria. All alternatives are judged against each criterion.

3. *Using the eigenvector method to obtain relative weights for criteria and alternatives*. The relative importances are given as a normalised eigenvector of the pairwise comparison matrix. The sum of relative importances of siblings always equals one.

4. *Synthesising comparisons to obtain the scores of the alternatives and rank the alternatives*. Absolute importances for all criteria and alternatives are calculated. The absolute importances are calculated by multiplying the relative importance of criterion/alternative by the absolute importance of the corresponding criterion at the previous level. For each alternative, all of its absolute importances are summed. This value is the score. Alternatives with greater scores are preferable to alternatives with less scores.

An example of a hierarchical structure that helps someone to select a satisfying college is given in figure 4.4.

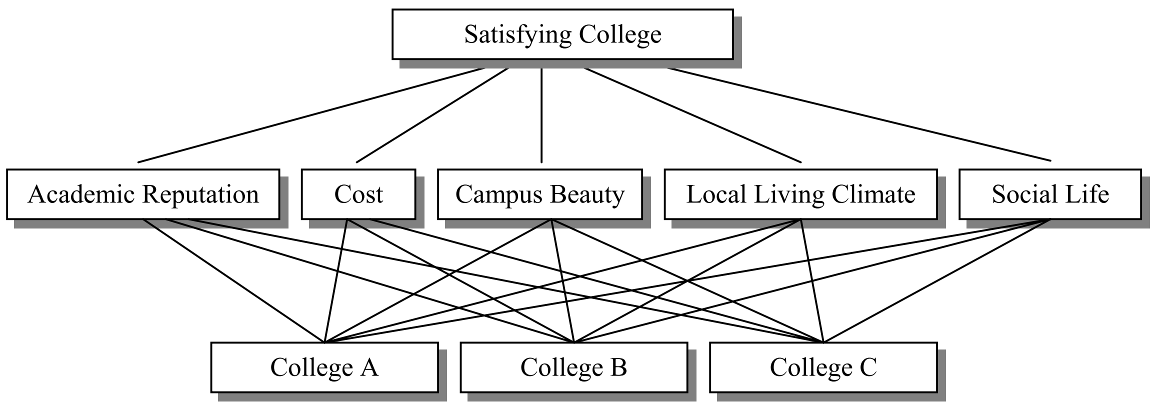

Figure 4.4. Hierarchical structure [Sch94]

4.5.2. AHP and Decision-Making for End-of-Life Products

The Analytical Hierarchy Process is a method for formalising decision-making where there are a limited number of choices but each has a number of attributes and it is difficult to formalise some of those attributes. The method offers a hierarchical structure but it has a high level of subjectivity. It is suitable for a number of 5-7 criteria on each level, otherwise it becomes too difficult to analyse. It could be successfully used in economic and environmental decision-making for EOL products where criteria are environmental and economic indicators, and alternatives – EOL options.

4.6. PROMETHEE

Most economical, industrial, financial or political decision problems are multi-criteria. The problem of the ranking of alternatives submitted to a multi-criteria evaluation is not an easy one, neither economically, nor mathematically. Usually there is no optimal solution, no alternative is the best one on each criterion. Compromise solutions have to be considered. Such a solution is *PROMETHEE (Preference Ranking Organisation METHod for Enrichment Evaluation)*, a well-known multi-criteria decision aid method for ranking a discrete set of alternatives [Dia98].

The method was proposed by J. P. Brans in 1982 and has been developed by taking into account all the necessary conditions required by multi-criteria analysis.

4.6.1. The PROMETHEE Procedure [Dia98], [Sal98], [Vai02], [Bra00]

The PROMETHEE method encompasses two phases: the construction of an *outranking relation* (aggregating the information about the alternatives and about the criteria) and the *exploitation of that relation* for decision-making.

Suppose the decision-maker is submitting his decision problem to a multi-criteria evaluation including k criteria $f_j()$, $j = 1, 2, \ldots, k$, and suppose the set of possible alternatives is finite and enumerated $A = \{a_i, i = 1, 2, \ldots, n\}$.

An evaluation table $\{f_j(a_i), j = 1, 2, \ldots, k; i = 1, 2, \ldots, n\}$ is then considered (see figure 4.5).

	$f_1()$	$f_2()$	...	$f_j()$	...	$f_k()$
a_1	$f_1(a_1)$	$f_2(a_1)$	...	$f_j(a_1)$	...	$f_k(a_1)$
a_2	$f_1(a_2)$	$f_2(a_2)$	...	$f_j(a_2)$	...	$f_k(a_2)$
...	...	...	...	...	...	...
a_i	$f_1(a_i)$	$f_2(a_i)$	...	$f_j(a_i)$	...	$f_k(a_i)$
...	...	...	...	...	...	...
a_n	$f_1(a_n)$	$f_2(a_n)$	...	$f_j(a_n)$	...	$f_k(a_n)$

Figure 4.5. Multi-criteria evaluation table [Bra00]

The PROMETHEE procedure requires additional information. This consists of:

- *Information between the criteria*: weights of relative importance of each criterion

$$w_j, j = 1,2,...,k; \qquad w_j \geq 0, \forall j; \sum_{j=1}^{k} w_j = 1$$

- *Information within the criteria*: for each criterion a preference function $P_j(a,b)$ giving the preference of decision a with regard to decision b, in function of the difference between the evaluations of a and b on that criterion.

  $P_j(a,b)$ can be supposed an increasing function such as:

$$\begin{cases} d_j(a,b) = f_j(a) - f_j(b) \\ P_j(a,b) = P_j[d_j(a,b)] \\ 0 \leq P_j(a,b) \leq 1 \\ P_j(a,b) = 0, \quad \textit{in case of no preference of a over b} \\ P_j(a,b) = 1, \quad \textit{in case of strict preference of a over b} \end{cases}$$

Brans proposes six different types of functions $P_j(a,b)$ whose shape is defined by at most two parameters (see figure 4.6).

The PROMETHEE procedure is then based on pairwise comparisons. For all ordered pairs of alternatives a *multicriteria preference index* π(,) is calculated. These indices may take any value in the [0,1] interval.

$$\pi(a,b) = \sum_{j=1}^{k} w_j P_j[d_j(a,b)] = \sum_{j=1}^{k} w_j P_j[f_j(a) - f_j(b)]$$

For each pair of alternatives *a* and *b*, $\pi(a,b)$ and $\pi(b,a)$ are computed to build an outranking relation.

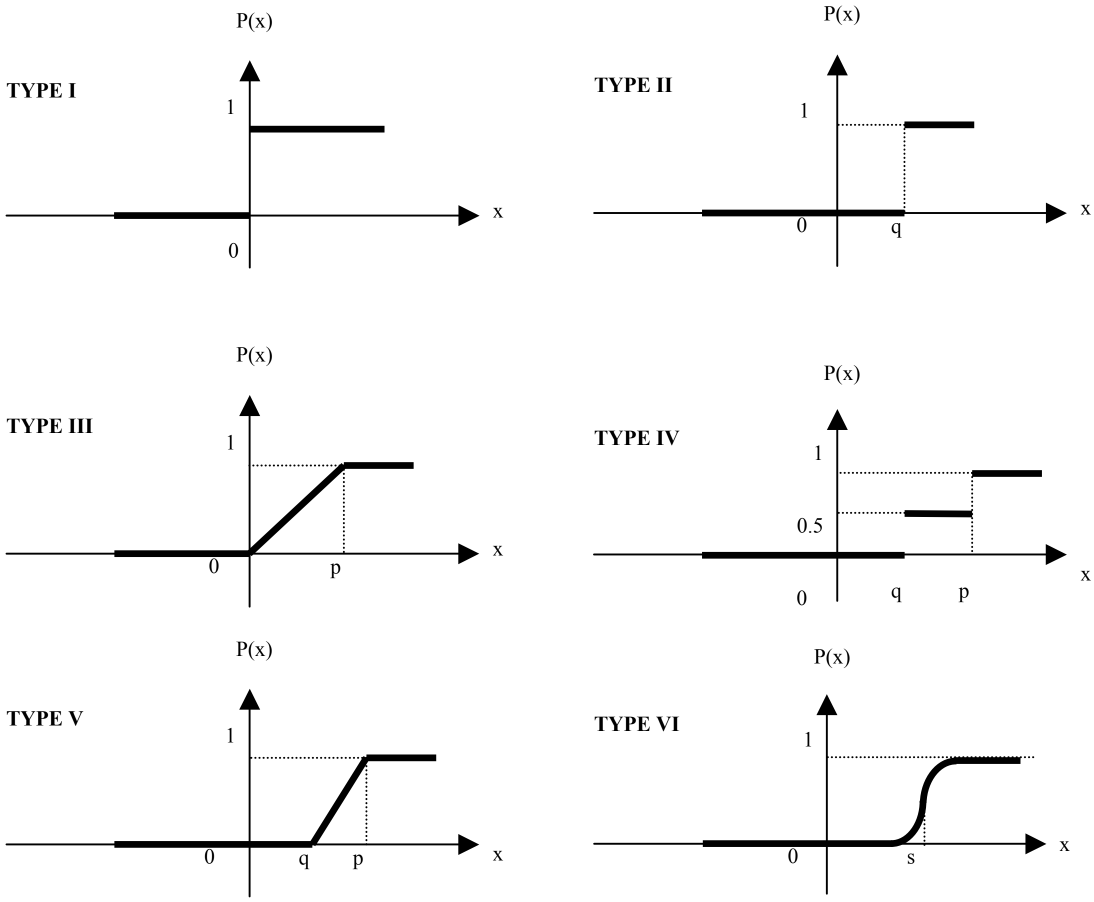

Figure 4.6. Six types of function $P_j(a,b)$ [Dia98]

For each alternative *a*, the leaving flow represents the outranking character of the alternative (the strength of the alternative):

$$\phi^{+}(a) = \frac{1}{n-1}\sum_{i=1}^{n}\pi(a,a_i)$$

The entering flow represents the outranked character of action *a* (the weakness of the alternative):

$$\phi^{-}(a) = \frac{1}{n-1}\sum_{i=1}^{n}\pi(a_i,a)$$

The PROMETHEE I method obtains a partial preorder (P, I, R), where P indicates strict preference, I indicates indifference and R stands for incomparability, from two different complete preorders, (P^+, I^+) and (P^-, I^-):

Considering a P^+ b if $\phi^+(a) > \phi^+(b)$

a I^+ b if $\phi^+(a) = \phi^+(b)$

a P^- b if $\phi^-(a) < \phi^-(b)$

a I^- b if $\phi^-(a) = \phi^-(b)$

then ***a* P *b*** if (a P^+ b and a P^- b) or (a P^+ b and a I^- b) or (a I^+ b and a P^- b)

a* I *b if (a I^+ b and a I^- b)

a* R *b if (not (a P b) and not (a I b))

The PROMETHEE II method produces a complete preorder (P, I) from the net flow $\phi(a) = \phi^+(a) - \phi^-(a)$:

a* P *b if $\phi(a) > \phi(b)$

a* I *b if $\phi(a) = \phi(b)$

4.6.2. PROMETHEE and Decision-Making for End-of-Life Products

PROMETHEE method is suitable for economic and environmental decision-making for EOL products. The alternatives can be the EOL scenarios and the criteria – the economic and environmental indicators. The inconvenience would be the need of experts opinion when choosing the type of preference function, therefore it is not suitable for non-expert users.

4.7. ELECTRE

Different versions of ELECTRE have been developed (I, II, III, IV and TRI); all are based on the same fundamental concepts (finding the most preferred alternative among a set of decision alternatives) but differ both operationally and according to the type of decision problem. ELECTRE I is designed for selection problems, ELECTRE TRI for assignment problems and ELECTRE II, III and IV for ranking problems [Buc99]. ELECTRE II is an old version, ELECTRE III is used when it is possible and desirable to quantify the relative importance of criteria and ELECTRE IV when this quantification is not possible [Buc99]. ELECTRE III will be discussed in this section.

4.7.1. ELECTRE III Methodology [Mie99], [Buc99]

A multiple-criteria decision-making problem is usually formulated by a set of alternatives A = (x_1, x_2, …, x_n) and a set of criteria (f_1, f_2, …, f_k). The criteria are real-valued functions defined on the set A so that $f_l(x_j)$ represents the performance of alternative x_j on the criterion f_l (see figure 4.7).

	$f_1()$	$f_2()$	…	$f_l()$	…	$f_k()$
x_1	$f_1(x_1)$	$f_2(x_1)$	…	$f_l(x_1)$	…	$f_k(x_1)$
x_2	$f_1(x_2)$	$f_2(x_2)$	…	$f_l(x_2)$	…	$f_k(x_2)$
…	…	…	…	…	…	…
x_j	$f_1(x_j)$	$f_2(x_j)$	…	$f_l(x_j)$	…	$f_k(x_j)$
…	…	…	…	…	…	…
x_n	$f_1(x_n)$	$f_2(x_n)$	…	$f_l(x_n)$	…	$f_k(x_n)$

Figure 4.7. Multi-criteria evaluation table

The method uses pseudo-criteria. A *pseudo-criterion* is a preference model including a double threshold for each criterion $f_l(x_j)$, $l = 1, 2, \ldots, k$:

- a *preference threshold* $p_l(f_l(x_j))$
- an *indifference threshold* $q_l(f_l(x_j))$

These thresholds may be constant, linear or affine functions of $f_l(x_j)$ in the form:

$$p_l(f_l(x_j)) = \alpha_{p,l} + \beta_{p,l} f_l(x_j)$$

and

$$q_l(f_l(x_j)) = \alpha_{q,l} + \beta_{q,l} f_l(x_j)$$

For every criterion $f_l(x_j)$ the double threshold model is:

x_i is **preferred** to x_j if $f_l(x_i) > f_l(x_j) + p_l(f_l(x_j))$

x_i is **weakly preferred** to x_j if $f_l(x_j) + q_l(f_l(x_j)) < f_l(x_i) \le f_l(x_j) + p_l(f_l(x_j))$

x_i is **indifferent** to x_j if $f_l(x_j) + q_l(f_l(x_j)) \geq f_l(x_i)$ and

$$f_l(x_i) + q_l(f_l(x_i)) \geq f_l(x_j)$$

The choice of thresholds affects whether a particular binary relation holds. While the choice of appropriate thresholds is not easy, in most realistic decision-making situations there are good reasons for choosing preference and indifference thresholds as $p_l(f_l(x_j)) > q_l(f_l(x_j)) > 0$, $\forall l = 1,...,k; \forall j = 1,...,n$

Using thresholds, the ELECTRE method seeks to build an outranking relation S. The value of $S(x_i,x_j)$ is defined based on concordance and discordance indices.

A *concordance index* $C(x_i,x_j)$ is computed for each pair of alternatives (x_i,x_j) by:

$$C(x_i, x_j) = \sum_{l=1}^{k} w_l c_l(x_i, x_j), \quad w_l = \text{weighting coefficients}$$

where $$\sum_{l=1}^{k} w_l = 1$$

and $$c_l(x_i, x_j) = \begin{cases} 1 & \text{if } f_l(x_i) + q_l(f_l(x_i)) \geq f_l(x_j) \\ 0 & \text{if } f_l(x_i) + p_l(f_l(x_i)) \leq f_l(x_j) \\ \dfrac{p_l(f_l(x_i)) - (f_l(x_j) - f_l(x_i))}{p_l(f_l(x_i)) - q_l(f_l(x_i))}, & \text{otherwise} \end{cases}$$

One more threshold, called a *veto threshold* $v_l(f_l(x_i))$ is needed for discordance indices. The veto threshold is constant, a linear or an affine function of $f_l(x_i)$, as well as the other thresholds.

A *discordance index* $d_l(x_i,x_j)$ is defined for each criterion f_l by:

$$d_l(x_i, x_j) = \begin{cases} 0 & \text{if } f_l(x_j) \leq f_l(x_i) + p_l(f_l(x_i)) \\ 1 & \text{if } f_l(x_j) \geq f_l(x_i) + v_l(f_l(x_i)) \\ \dfrac{f_l(x_j) - f_l(x_i) - p_l(f_l(x_i))}{v_l(f_l(x_i)) - p_l(f_l(x_i))}, & \text{otherwise} \end{cases}$$

where $v_l(f_l(x_i)) > p_l(f_l(x_i))$

For each pair of alternatives now a concordance and a discordance measure exist. The next step in the model is to combine these two measures to produce a measure of the degree of outranking.

Let us denote by $J(x_i,x_j)$ the set if criteria for which $d_l(x_i,x_j) > C(x_i,x_j)$. We will consider $J(x_i,x_j) = 0$ if $d_l(x_i,x_j) \le C(x_i,x_j), \forall l = 1,...,k$.

The *degree of outranking* $S(x_i,x_j)$ is defined by:

$$S(x_i,x_j) = \begin{cases} C(x_i,x_j) & \text{if } J(x_i,x_j) = 0 \\ C(x_i,x_j) \prod\limits_{l \in J(x_i,x_j)} \dfrac{1 - d_l(x_i,x_j)}{1 - C(x_i,x_j)} & , \quad \text{otherwise} \end{cases}$$

The ranking of the decision alternatives in ELECTRE III is normally carried out by a distillation procedure where the alternatives are ranked based on their qualification from the best to the worst (descending distillation chain) and from the worst to the best (ascending distillation chain). The final partial order of the alternatives is built based on these two complete preorders.

Let $\lambda = \max\limits_{x_i,x_j \in A} S(x_i,x_j)$. Consider a *discrimination threshold* $s(\lambda)$ and define a relation D such that:

$$D(x_i,x_j) = \begin{cases} 1 \;\; \text{if} \;\; S(x_i,x_j) > \lambda - s(\lambda) \\ 0 \;\; , \qquad \text{otherwise} \end{cases}$$

An equation proposed by Rogers and Bruen for assigning values for the discrimination threshold is [Rog97]:

$$s(\lambda) = 0.2 - 0.1\lambda$$

For each alternative x, a *qualification score* $Q(x)$ is computed as the number of alternatives which are outranked by x (number of alternatives x_j such that $D(x,x_j) = 1$) minus the number of alternatives which outrank x (number of alternatives x_j such that $D(x_j,x) = 1$).

In the descending procedure, the set of alternatives having the largest qualification score constitutes the first *distillate* and is denoted as D_1. If D_1 contains only one alternative, the previous procedure is performed in the set $A \backslash D_1$. Otherwise it is applied to D_1 and a distillate D_2 is obtained. If D_2 is a singleton, then the procedure is applied in $D_1 \backslash D_2$ if it is not empty otherwise the procedure is applied in D_2. This procedure is repeated until the distillate D_1 is completely explored. Then, the procedure starts exploring $A \backslash D_1$ in order to find a new distillate. The procedure is repeated until a complete preorder of the alternatives is obtained. This procedure is called the *descending distillation chain* because it starts with the alternatives having the highest qualification and ends with alternatives having the lowest qualification.

The ascending procedure is similar, except that the criterion of selecting the alternatives is based on the principle of the lowest qualification.

The result of ELECTRE III is a partial preorder of the alternatives based on the comparison of the two complete preorders obtained by means of the descending and the ascending distillation chains.

4.7.2. ELECTRE III and Decision-Making for End-of-Life Products

ELECTRE III is another method suitable for economic and environmental decision-making for EOL products. The alternatives can be the EOL scenarios and the criteria – the economic and environmental indicators. The inconvenience would be the element of subjectivity – the weightings – and the fact that expertise is needed when choosing the thresholds which are very important for the accuracy of the method.

4.8. CONCLUSIONS

The multi-criteria method for economic and environmental decision-making for end-of-life products must meet the following requirements:

- simplicity
- easy to understand by the user
- easy to use
- transferability into a software
- flexibility, suitability for different kinds of EOL options
- suitability for comparison of EOL options based on **both** economic and environmental indicators provided
- possibility to graphically represent the results.

Three of the methods presented in this chapter seem to perfectly meet these requirements: AHP, PROMETHEE and ELECTRE III. They all are suitable for EOL environmental and economic decision-making as they are dealing with alternatives – in our case the EOL options – and criteria – in our case the environmental and economic indicators. They are not too difficult to use and it is possible to transfer any of them into a software tool that could also represent the results graphically.

The AHP method is interactive so the user is likely to have confidence in it. However, the subjectivity in this method is obvious as the user, even if he is not an expert, compares and weights the alternatives and criteria.

The PROMETHEE and the ELECTRE III are quite similar and they both have been used in environmental decision-making successfully. They both need the opinion of experts for choosing the type of function (PROMETHEE) or the thresholds (ELECTREE), so there is less subjectivity when using these methods but they are not suitable for non-expert users. Some of the criteria the method chosen has to meet are the simplicity and ease to understand by the user. From this point of view PROMETHEE and ELECTRE seem to fail these criteria, as they might look very difficult and not at all interactive to users.

CHAPTER 5. ENVIRONMENTAL AND ECONOMIC DECISION SUPPORT METHODOLOGY FOR END-OF-LIFE PRODUCTS

5.1. INTRODUCTION

The literature review of chapter 2 revealed that there is no existing methodology to quantify both environmental and economic impacts of EOL products and to permit comparison between different possible EOL options. Therefore a new environmental and economic decision support methodology was developed to help producers make decisions for their products when they reach the last stage of the life cycle. The methodology, based on the EU WEEE Directive [WEEE02], is presented in this chapter.

There are many options for products at the end of their life (reuse/part reclamation, remanufacturing, recycling, incineration and landfill) and this methodology will enable producers and processors choose the best scenario in terms of impact on the environment and economical efficiency. *As the policy to date in Ireland is to practice incineration as little as possible, this option will not be considered*.

Having as starting point the methodologies for quantifying the environmental and the economic impacts presented in Chapter 2 (see chapter 2) and the possibility to apply them to end-of-life products, especially WEEE, the following environmental and economic decision support methodology is developed:

- Based on the principle stated in the Eco-indicator methodology – materials and processes should be defined "in such a way that they fit together like building blocks" [Goe00] – a detailed description of the products will be made in connection with the end-of-life processes. A suitable model for the product description will be chosen. Information about components and materials are key elements for the end-of-life processes.
- A detailed description of the end-of-life options is necessary. A flow chart comprising all processes will be made for each EOL option.

- Based on the LCA methodology, inventories of all environmental impacts in connection with each end-of-life option will be carried out for each type of product.
- Considering as a starting point the impact categories stated by the Eco-indicator methodology and the weighting factors (characterisation factors), environmental indicators that show the impact of end-of-life products on the environment will be chosen.
- Environmental indicators will be calculated for each type of product per EOL option.
- Economic indicators that show economic impact of end-of-life products will be chosen.
- For each type of product and end-of-life option economic indicators will be calculated using an appropriate methodology.
- As the methodology deals with environmental and economic indicators, it would be difficult to calculate a single number to comprise both impacts – environmental and economic. Therefore a multi-criteria analysis method will be used to obtain a hierarchy of the possible end-of-life options, considering both categories of criteria – environmental and economic.

In short, the methodology will comprise five steps:

1. product description
2. EOL options description
3. choice of environmental indicators and calculation for each type of product per EOL option
4. choice of economic indicators and calculation for each type of product per EOL option
5. choice of a multi-criteria analysis method and application for each type of product in order to get a hierarchy of the possible EOL options.

5.2. THE PRODUCT MODEL

Several product models have been investigated in chapter 3 (see chapter 3) and by analysing them the need for a new product model arose, a model that offers all the information processors might need in order to treat the EOL product.

The model developed in this methodology is applied to WEEE and offers a product representation capable of describing the structure of the whole family of products. The model defines all the components and the materials within the product composition structure. It is based on a tree diagram that shows all the levels that have to be considered in product definition in order to get accurate information. Level 1 represents the categories of products as defined by the WEEE Directive (see Appendix B for categories of electrical and electronic equipment covered by the WEEE Directive and products falling under these categories), level 2 - subcategories, level 3 – components, level 4 – sub-components, and level 5 - materials. The tree diagram is presented in figure 5.1.

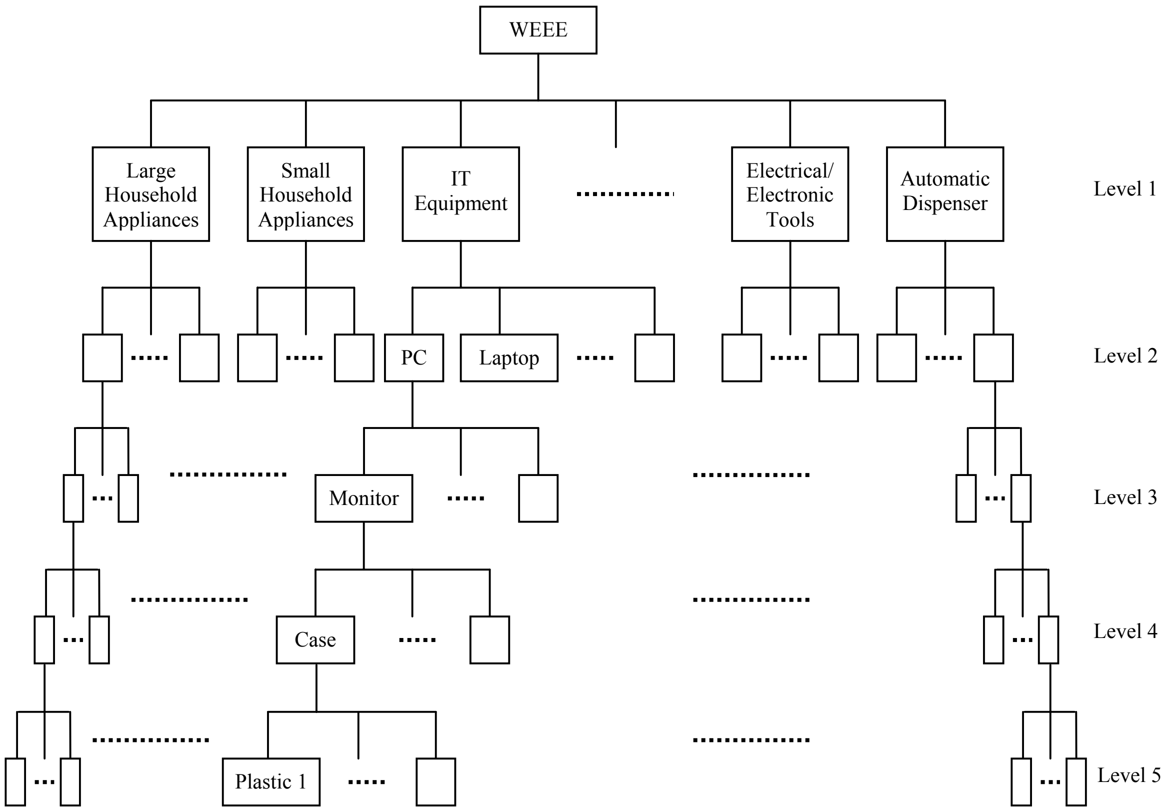

Figure 5.1. Five-level tree diagram model

The remanufacturing/recycling companies must know all the details regarding components and materials that constitue the product before deciding what processes it undergoes. Therefore, at each level in the product description tree additional information is provided:

- *Information about the product*
  - Weight (kg)
  - Volume (m^3)

  - Description (in terms of recyclability, repairability, remanufacturability, disassembly, etc)
  - Environmental category of product (hazardous/non-hazardous)
  - Value (price – from the producer point of view)
  - Second value (price on a second hand market – from the processor point of view).

- *Information about the component/sub-component*
  - Quantity (number of units)
  - Weight (kg)
  - Structure (other components = subcomponents)
  - Materials – see the materials additional information
  - Environmental category of component (hazardous/non-hazardous)
  - Value (price – from the OEM point of view)
  - Second value (price on a second hand market - from the remanufacturer point of view).

- *Information about the material*
  - Category (e.g. metals, plastics)
  - Type (e.g. PVC)
  - Environmental category of material (hazardous/non-hazardous)
  - Weight (kg)
  - Recyclability (recyclable or not)
  - Value.

It is important that materials be classified into hazardous/non-hazardous, as special care must be taken of the EOL products that contain hazardous substances. The WEEE Directive specifies that certain WEEE containing hazardous materials must be subject to pre-treatment and treatment before going to landfill or recovery [WEEE02].

5.3. THE END-OF-LIFE OPTIONS

The product model presented in the previous section enables producers to offer the processors (remanufacturer/recycler/landfill site) all the information they need to know in order to perform the required treatment. In order to calculate environmental and economic impact of a product it is also important to know what processes each product/component/sub-component/material undergoes. Therefore a decomposition of activities in processes is necessary so that a link product/component/subcomponent – process be created.

The description of products, as per the product model presented in the previous section, used in connection with the EOL processes is a key issue in the development of the environmental and economic decision support methodology for EOL products.

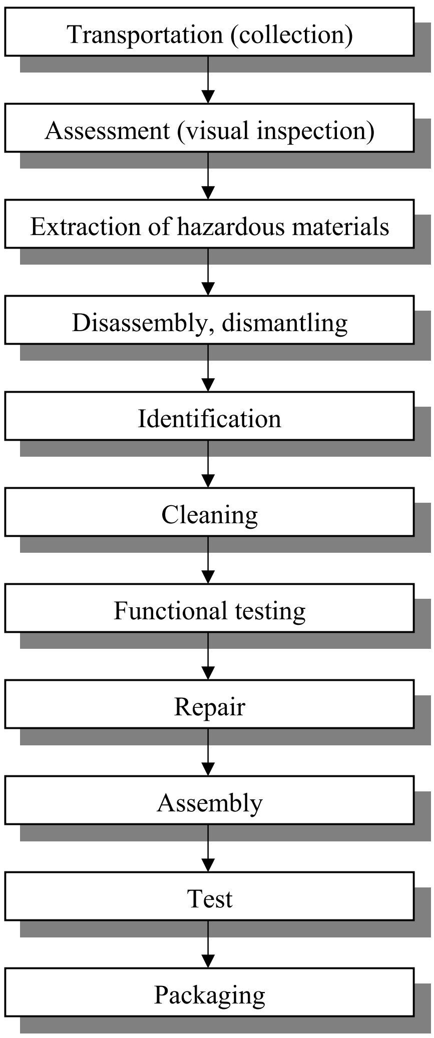

Figure 5.2. Possible sequence of processes for reuse/part reclamation

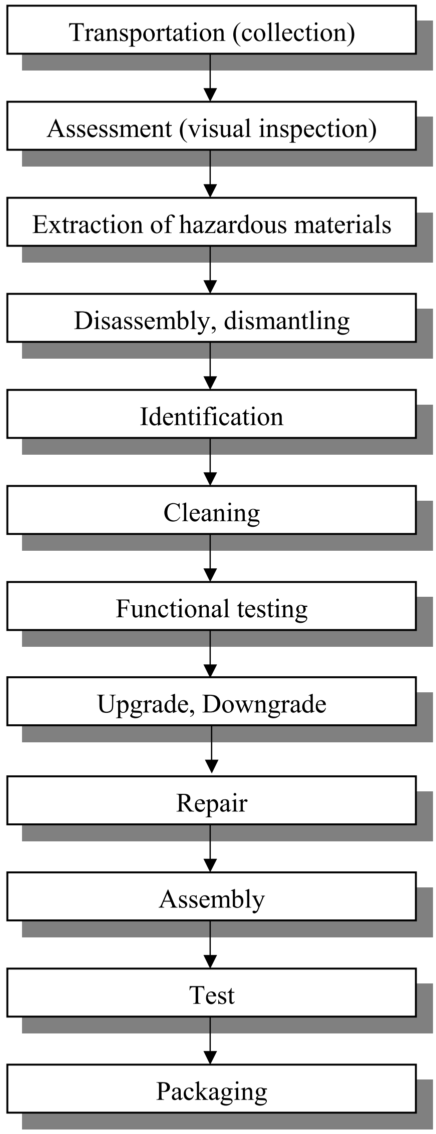

Figure 5.3. Possible sequence of processes for remanufacturing

Possible sequences of processes in each EOL activity are presented in the flowcharts in figures 5.2, 5.3, 5.4 and 5.5. As mentioned before, the EOL options considered in this methodology are reuse/part reclamation, remanufacturing, recycling and landfill (incineration is excluded).

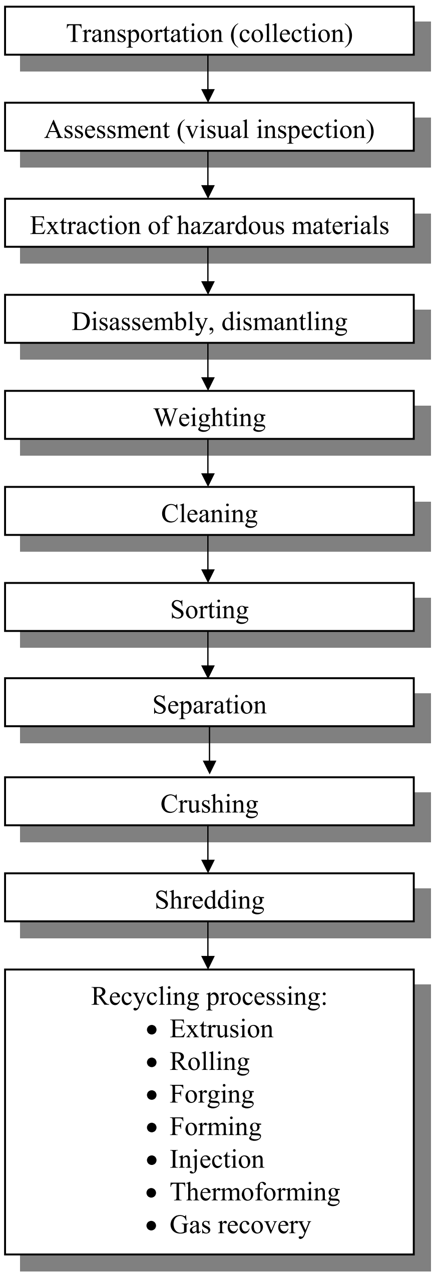

Figure 5.4. Possible sequence of processes for recycling

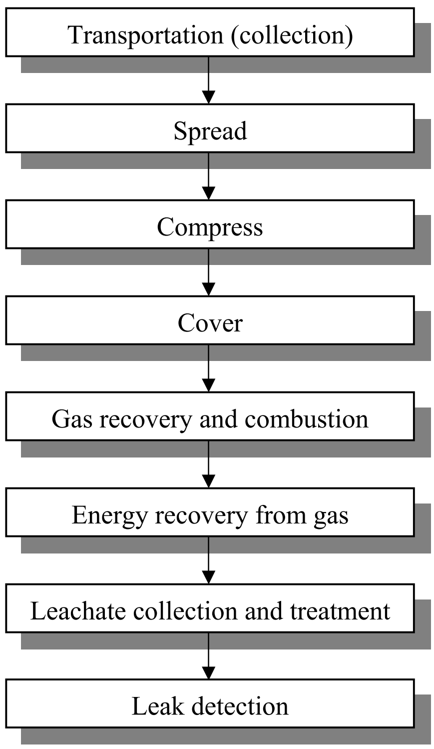

Figure 5.5. Possible sequence of processes for landfill

Once EOL activities have been decomposed into sub-processes, and a flow of processes for each product/component/sub-component is known, the calculation of different indicators necessary in the decision-making process may start.

5.4. The Environmental Indicators

The choice of environmental indicators for decision support for EOL products is based on the Eco-indicator 99 methodology described in chapter 2 (see section 2.2.3) and the requirements of the WEEE Directive [WEEE02]. Therefore we can talk about two categories of indicators: general environmental indicators and environmental indicators that show compliance/non-compliance with regulation. They are detailed as follows:

- ***General environmental indicators***:
  - *That show damage to resources*
    - Non-renewable primary energy input per product
    - Materials consumption per product
    - Water consumption per product
  - *That show damage to ecosystem*
    - GHG (greenhouse gas) emissions to air per product
    - ODS (ozone depleting substances) emissions to air per product
    - Acidification emissions to air per product
    - Water nutrient pollution per product
  - *That show damage to human health*
    - Hazardous substances eliminated into air per product
    - Hazardous substances eliminated into water per product
    - Carcinogenic substances emissions per product
- ***Environmental indicators that show compliance/non-compliance with regulation***:
  - *Percentage of hazardous materials per product*
  - *Percentage of waste reused/remanufactured/recycled/landfilled*
  - *Average percentage of product that is reused/remanufactured/recycled/ landfilled.*

These indicators are calculated for each EOL option per type of product, on a monthly and/or annual basis.

5.4.1. The Algorithm for General Environmental Indicators Calculation

In order to calculate the general environmental indicators an apportionment method is used, assuming that information about emissions can be obtained from processors *at the company level* and not at the process level. Another assumption made for this model is that one producer works with only one type of processor (remanufacturer, recycler, landfill site) according to a mutual agreement.

5.4.1.1. Preliminary Calculations

Before proceeding to the calculation of the general environmental indicators per product, some preliminary calculations must be made; these are based on data about emissions at the processor level and use the characterisation factors for each type of substance (see Appendix C). The preliminary values of indicators will be calculated with the formulae:

- *Materials consumption*

This indicator is a sum of weight of all materials purchased or obtained from other sources, including:

- raw materials for conversion
- other process materials (e.g. catalysts, solvents)
  (packaging for products, water consumption and materials used for energy purposes are excluded).

The unit for the materials consumption indicator is kg.

Formula: $Materials = \sum_{x} M_x$

where M_x = quantity of material of type x used by the processor during the month/year

- *Water consumption*

The water consumption indicator is a sum of all fresh water purchased from public supply, or obtained from surface or ground water sources (including water for cooling purposes).

Water consumption unit is cubic meter (m^3).

- *Non-renewable primary energy input, greenhouse gas emissions to air, ozone depleting substances emissions, acidification emissions, water nutrient pollution, hazardous substances eliminated into air/water, carcinogenic substances emissions*

For these indicators the formula used is:

Formula: $Indicator = \sum_x Indicator_x \times CF_x$

where $Indicator_x$ = quantity of emissions of type x emitted during the month/year that produce the same effect (indicator)

CF_x = conversion factor for emissions of type x

x = type of emission

For details for each type of indicator see Appendix D.

Once this step of the algorithm has been completed, all materials consumptions, water consumptions, and emissions at the processing company level are transferred into one of the general environmental indicators, according to the environmental impact each of them produces:

- Non-renewable primary energy input per processing company (kWh)
- Materials consumption per processing company (kg)
- Water consumption per processing company (m^3)
- GHG (greenhouse gas) emissions to air per processing company (kg CO_2 equivalent)
- ODS (ozone depleting substances) emissions to air per processing company (kg CFC-11 equivalent)
- Acidification emissions to air per processing company (kg SO_2 equivalent)
- Water nutrient pollution per processing company (kg phosphate equivalent)
- Hazardous substances eliminated into air per processing company (kg Pb equivalent)

- Hazardous substances eliminated into water per processing company (kg Pb equivalent)
- Carcinogenic substances emissions per processing company (kg PAH equivalent).

Now the process of allocation of these indicators to processes can start.

5.4.1.2. Allocation of General Indicators to Processes

After all the emissions have been converted into general indicators, these values are allocated to processes. It must be considered that a processor might have agreements with more than one producer, therefore he/she processes products made by different original manufacturers (OEMs).

Materials consumption is the only indicator that need not be allocated to processes as there should be records in the company for the materials consumption in each process.

For the rest of the indicators the allocation of emissions to processes is done using different characteristics such as machine running hours (MRH), direct labour hours (DLH), volume of product, weight of product or percentage of hazardous substances contained. An Emissions Allocation Rate (EAR) for each indicator is calculated as follows:

- *Non-renewable primary energy input*

Formula: $(EAR_{Enegy})_x = \dfrac{Energy}{\sum_x \sum_i MP_{ix} \times MRH_i} \times \sum_i MP_{ix} \times MRH_i$

where

$Energy$ = quantity of monthly/annual energy consumption per processor (calculated previous section)

MP_{ix} = power of machine i located in the cost centre (process) x

i = machine

x = process (cost centre)

MRH_i = machine running hours per month for machine i used in process (cost centre) x

Note: Energy consumption during transport is calculated separately based on the quantity of petrol used for transportation during the period.

- *Water consumption*

Formula: $$(EAR_{Water})_x = \frac{Water}{\sum_x \sum_j \sum_i NP_{ijx} \times V_{ij}} \times \sum_j \sum_i NP_{ijx} \times V_{ij}$$

where

$Water$ = quantity of monthly/annual water consumption per processor (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre)

V_{ij} = volume of product type i produced by producer j

- *Greenhouse gas emissions to air*

Formula: $$(EAR_{GHG})_x = \frac{GHG}{\sum_x \sum_i MP_{ix} \times MRH_i} \times \sum_i MP_{ix} \times MRH_i$$

where

GHG = quantity of monthly/annual GHG emissions per processor (calculated in previous section)

MP_{ix} = power of machine i located in the cost centre (process) x

i = machine

x = process (cost centre)

MRH_i = machine running hours per month for machine i used in process (cost centre) x

- *Ozone depleting substances emissions*

Formula: $$(EAR_{ODS})_x = \frac{ODS}{\sum_x \sum_j \sum_i NP_{ijx} \times W_{ij}} \times \sum_j \sum_i NP_{ijx} \times W_{ij}$$

where

ODS = quantity of monthly/annual ozone depleting substances emissions per processor (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre)

W_{ij} = weight of product type i produced by producer j

- *Acidification emissions*

Formula: $$(EAR_{Acidification})_x = \frac{Acidification}{\sum_x \sum_j \sum_i NP_{ijx} \times W_{ij}} \times \sum_j \sum_i NP_{ijx} \times W_{ij}$$

where

Acidification = quantity of monthly/annual acidification emissions per processor (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre)

W_{ij} = weight of product type i produced by producer j

- *Water nutrient pollution*

Formula: $$(EAR_{NutrientPollution})_x = \frac{NutrientPollution}{\sum_x \sum_j \sum_i NP_{ijx} \times W_{ij}} \times \sum_j \sum_i NP_{ijx} \times W_{ij}$$

where

Nutrient Pollution = quantity of monthly/annual nutrient substances emissions per processor (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre)

W_{ij} = weight of product type i produced by producer j

- *Hazardous substances eliminated to air*

Formula: $$(EAR_{Hazardous/air})_x = \frac{Hazardous/air}{\sum_x \sum_j \sum_i NP_{ijx} \times \%Haz_{ij}} \times \sum_j \sum_i NP_{ijx} \times \%Haz_{ij}$$

where

Hazardous/air = quantity of monthly/annual hazardous substances emissions to air per processor (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre)

$\%Haz_{ij}$ = percentage of hazardous materials in product type i produced by producer j

- *Hazardous substances eliminated to water*

Formula:

$$(EAR_{Hazardous/water})_x = \frac{Hazardous/water}{\sum_x \sum_j \sum_i NP_{ijx} \times \%Haz_{ij}} \times \sum_j \sum_i NP_{ijx} \times \%Haz_{ij}$$

where

Hazardous/water = quantity of monthly/annual hazardous substances emissions to water per processor (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre)

$\%Haz_{ij}$ = percentage of hazardous materials in product type i produced by producer j

- *Carcinogenic substances emissions*

Formula: $$(EAR_{Carcinogenic})_x = \frac{Carcinogenic}{\sum_x \sum_j \sum_i NP_{ijx} \times \%Haz_{ij}} \times \sum_j \sum_i NP_{ijx} \times \%Haz_{ij}$$

where

$Carcinogenic$ = quantity of monthly/annual carcinogenic substances emissions per processor (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre)

$\%Haz$ = percentage of hazardous materials in product type i produced by producer j

5.4.1.3. Allocation of General Indicators to Products

As mentioned before, for each product/component/sub-component it is known exactly what processes it undergoes. In the previous section general indicators per process were calculated, therefore it is now possible to calculate indicators per product. The formulae used are:

- *Non-renewable primary energy input*

For petrol for transportation:

Formula: $$En.Transp._{Prod.ij} = \frac{En.Transp.}{\sum_j \sum_i NP_{ij} \times V_{ij}} \times V_{ij}$$

where

$En.\ Transp.$ = quantity of energy consumed during transportation (petrol)

NP_{ij} = number of products of type i brand j (producer) transported

i = type of product

j = producer (brand)

V_{ij} = volume of product type i produced by producer j

For the energy consumed during other processes:

Formula: $$Energy_{\Pr od.ij} = \sum_x \left(\frac{(EAR_{Energy})_x}{\sum_j \sum_i NP_{ijx} \times MRH_{ijx}} \times MRH_{ijx} \right)$$

where

$(EAR_{Energy})_x$ = quantity of monthly/annual energy consumption per process (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre) that product i brand j undergoes

MRH_{ijx} = machine running hours per product of type i brand j per process (cost centre) x

Total:

$$TotalEn._{\Pr od.ij} = En.Transp._{\Pr od.ij} + Energy_{\Pr od.ij}$$

- *Materials consumption*

Formula: $$Materials_{\Pr od.ij} = \sum_x \left(\frac{Materials_x}{\sum_j \sum_i NP_{ijx}} \times NP_{ijx} \right)$$

where

$Materials_x$ = quantity of materials consumed during process x (calculated in previous section)

NP_{ijx} = number of products of type I brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre) that product i brand j undergoes

- *Water consumption, greenhouse gas emissions to air, ozone depleting substances emissions, acidification emissions, water nutrient pollution, hazardous substances eliminated into air/water, carcinogenic substances emissions*

For these indicators the formula used is (see Appendix D for details for each type of indicator):

Formula: $$Indicator_{\Pr od.ij} = \sum_{x}\left(\frac{(EAR_{Indicator})_x}{\sum_{j}\sum_{i} NP_{ijx} \times DLMRH_{ijx}} \times DLMRH_{ijx}\right)$$

where

$(EAR_{Indicator})_x$ = Emissions Allocation Rate per process (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre) that product i brand j undergoes

$DLMRH_{ijx}$ = direct labour hours or machine running hours per product of type i brand j per process (cost centre) x

For labour intensive processes the direct labour hours per product per process will be used (almost all the processes) and for machine intensive processes machine running hours per product per process will be used. The machine intensive processes are:

- Crushing
- Shredding
- Recycling processing
    - Extrusion
    - Rolling
    - Forging
    - Forming
    - Injection
    - Thermoforming
    - Gas recovery

5.4.2. The Algorithm for Calculation of Environmental Indicators that Show Compliance with Regulation

These are indicators suggested by the WEEE Directive [WEEE02] and help the producer see if he/she complies with the new legislation. The formulae for calculating these indicators are:

- *Percentage of hazardous materials per product*

Formula: $\frac{\sum_x HM_x}{PW} \times 100$

where

HM_x = weight of hazardous material of type x contained in the product for which calculation is made

PW = weight of the product for which calculation is made

x = type of hazardous material contained in product

- *Percentage of waste reused*

Formula: $\frac{WR}{WC} \times 100$

where

WR = quantity of product waste reused during the month/year (calculation based on data supplied by remanufacturer)

WC = quantity of product collected during the month/year (calculation based on data supplied by collector)

- *Percentage of waste remanufactured*

Formula: $\frac{WRem}{WC} \times 100$

where

$WRem$ = quantity of product waste remanufactured during the month/year (calculation based on data supplied by remanufacturer)

WC = quantity of product collected during the month/year (calculation based on data supplied by collector)

- *Percentage of waste recycled*

Formula: $\frac{WRec}{WC} \times 100$

where

$WRec$ = quantity of product waste recycled during the month/year (calculation based on data supplied by recycler)

WC = quantity of product collected during the month/year (calculation based on data supplied by collector)

- *Percentage of waste discarded to landfill*

Formula: $\frac{WL}{WC} \times 100$

where

WL = quantity of product waste discarded to landfill during the month/year (calculation based on data supplied by landfill site)

WC = quantity of product collected during the month/year (calculation based on data supplied by collector)

- *Average percentage of product that is reused*

Formula: $\frac{\sum_{i=1}^{n} PR_i}{n}$

where

PR_i = percentage of product i that is reused during the month/year (calculated based on data supplied by the producer and the remanufacturer)

$$PR_i = \frac{weight\ of\ product\ that\ is\ reused}{total\ weight\ of\ product}$$

n = number of products that are reused during the month/year (calculated based on data supplied by remanufacturer)

- *Average percentage of product that is remanufactured*

Formula: $\frac{\sum_{i=1}^{n} PRem_i}{n}$

where

$PRem_i$ = percentage of product i that is remanufactured during the month/year (calculated based on data supplied by the producer and the remanufacturer)

$$PRem_i = \frac{weight\ of\ product\ that\ is\ remanufactured}{total\ weight\ of\ product}$$

n = number of products that are remanufactured during the month/year (calculated based on data supplied by remanufacturer)

- *Average percentage of product that is recycled*

Formula: $\frac{\sum_{i=1}^{n} PRec_i}{n}$

where

$PRec_i$ = percentage of product i that is recycled during the month/year (calculated based on data supplied by the producer and the recycler)

$$PRec_i = \frac{weight\ of\ product\ that\ is\ recycled}{total\ weight\ of\ product}$$

n = number of products that are recycled during the month/year (calculated based on data supplied by recycler)

- *Average percentage of product that is discarded to landfill*

Formula: $\frac{\sum_{i=1}^{n} PL_i}{n}$

where

PL_i = percentage of product i that is discarded to landfill during the month/year (calculated based on data supplied by the producer and the processor – remanufacturer and recycler)

$$PL_i = \frac{weight\ of\ \ product\ that\ is\ discarded\ to\ ladfill}{total\ weight\ of\ \ product}$$

n = number of products that are discarded to landfill during the month/year (calculated based on data supplied by the processor – remanufacturer and recycler)

5.5. THE ECONOMIC INDICATORS

The WEEE Directive [WEEE02] states that producers have to bear the cost of recovery of end-of-life products; that is the reason why the most important economic factor for them is the processing cost. Therefore the methodology will consider only one economic indicator: the processing cost.

The processing cost is calculated per product for each EOL option using the absorption costing method (see section 2.3.2) which was chosen because it ensures that all overhead costs are absorbed by all products and it is not too much resources consuming and costly (in comparison with the ABC method for example – see section 2.3.3).

5.5.1. The Algorithm for Processing Cost Calculation

This section presents the steps followed in order to calculate the total processing cost per product for each EOL option:

- Calculation of direct materials cost per product
- Calculation of direct labour cost per product
- Calculation of overhead cost per product
- Calculation of total processing cost per product.

5.5.1.1. Direct Materials Cost per Product

For each type of product the direct materials cost will be calculated with the formula:

$$DM_i = \sum_x \left(\frac{DM_x}{\sum_i NP_{ix}} \times NP_{ix} \right)$$

where x = process

DM_x = direct materials cost per process x

NP_{ix} = number of products of type i processed during process x

i = type of product

5.5.1.2. Direct Labour Cost per Product

For each type of product the direct labour cost will be calculated with the formula:

$$DL_i = \sum_x DLH_{x\,\mathrm{Pr}\,od_i} \times LC_x$$

where x = process

DLH_{xProdi} = average direct labour hours per product i per process x

LC_x = average direct hourly labour cost per process x

5.5.1.3. Overhead Attachment to Products

In order to allocate indirect costs to products the overhead attachment procedure described in figure 2.11 (see chapter 2) is followed:

1. Allocation of overhead costs to cost centres

Let us denote the indirect costs incurred by a processing company as in table 5.1.

Table 5.1. Indirect costs incurred by the business

Cost item	**Total cost**
Rent of building	R
Insurance	I
Lighting and heating	L
Energy for machines	E
Indirect labour costs (supervisor's salary, etc)	S
Canteen costs	C
Depreciation and insurance of machinery	D

Each indirect cost is allocated to all the cost centres (processes) including the services cost centres (see table 2.1 for methods of allocation). The services cost centres considered are storage, maintenance and canteen.

Allocation of rent of building:

Formula: $\frac{A_x}{\sum_x A_x} \times R$

where: A_x = floor area where process x takes place

R = rent of building

Allocation of insurance:

Formula: $\frac{A_x}{\sum_x A_x} \times I$

where: A_x = floor area where process x takes place

I = insurance

Allocation of lighting and heating:

Formula: $\frac{A_x}{\sum_x A_x} \times L$

where: A_x = floor area where process x takes place

L = lighting and heating

Allocation of energy for machines:

Formula: $\frac{NM_x}{\sum_x NM_x} \times E$

where: NM_x = number of machines used for process x

E = energy for machines

Allocation of indirect labour cost:

Formula: $\frac{E_x}{\sum_x E_x} \times S$

where: E_x = number of employees that work on process x

S = indirect labour costs

Allocation of canteen costs:

Formula: $\frac{E_x}{\sum_x E_x} \times C$

where: E_x = number of employees that work on process x

C = canteen costs

Allocation of depreciation and insurance of machinery:

Formula: $\frac{VM_x}{\sum_x VM_x} \times D$

where: VM_x = value of machinery used for process x

D = depreciation and insurance of machinery

Total per cost centres (processes):

Formula:

$$T_{x_1} = \frac{A_x}{\sum_x A_x} \times R + \frac{A_x}{\sum_x A_x} \times I + \frac{A_x}{\sum_x A_x} \times L + \frac{NM_x}{\sum_x NM_x} \times E + \frac{E_x}{\sum_x E_x} \times S + \frac{E_x}{\sum_x E_x} \times C + \frac{VM_x}{\sum_x VM_x} \times D$$

where x = cost centre (process) including services centres

2. Allocation of cost of services to processes

Cost of each service centre is allocated to all the production cost centres (processes) (see table 2.2 for methods of allocation).

Allocation of storage costs:

Formula: $\frac{S_x}{\sum_x S_x} \times T_{S_1}$

where: S_x = value of stores requisition for process x

T_{S1} = total indirect costs per storage cost centre

Allocation of maintenance costs:

Formula: $\frac{NM_x}{\sum_x NM_x} \times T_{M_1}$

where: NM_x = number of machines used for process x

T_{M1} = total indirect costs per maintenance cost centre

Allocation of canteen costs:

Formula: $\frac{E_x}{\sum_x E_x} \times T_{Ca_1}$

where: E_x = number of employees that work on process x

T_{Ca1} = total indirect costs per canteen cost centre

Total transfer costs of services:

Formula: $T_{x_2} = \frac{S_x}{\sum_x S_x} \times T_{S_1} + \frac{NM_x}{\sum_x NM_x} \times T_{M_1} + \frac{E_x}{\sum_x E_x} \times T_{Ca_1}$

where x = production cost centre (process)

3. Total overhead cost per process

Formula: $T_x = T_{x_1} + T_{x_2}$

where x = production cost centre (process)

4. Overhead absorption rates

In order to calculate the overhead absorption rates, for labour intensive processes the direct labour hours per product per process are used (almost all the processes) and for machine intensive processes machine running hours per product per process are used. The machine intensive processes are:

- Crushing
- Shredding
- Recycling processing

- Extrusion
- Rolling
- Forging
- Forming
- Injection
- Thermoforming
- Gas recovery

If P_i is the number of items of product *i* processed in one month (where product *i* is a certain brand), then the overhead absorption rate (OAR) is calculated for each process:

$$OAR_x = \frac{T_x}{\sum_{i=1}^{n} P_i \times DLH_{x\Pr od_i}} \qquad \text{or} \qquad OAR_x = \frac{T_x}{\sum_{i=1}^{n} P_i \times MRH_{x\Pr od_i}}$$

where: x = process

T_x = total overhead cost per process

P_i = number of items of product *i* produced in one month

DLH_{xProdi} = average direct labour hours per process *x* per product *i*

MRH_{xProdi} = average machine running hours per process *x* per product *i*

5. Total Overhead Cost per Product

The total overhead cost for a product is calculated with the following formula:

$$TOC_{\Pr od_i} = \sum_x OAR_x \times DLH_{x\Pr od_i} + \sum_y OAR_y \times DLH_{y\Pr od_i}$$

where x = labour intensive process

y = machine intensive process

5.5.1.4. Total Processing Cost per Product

Finally, the total processing cost of a product is calculated:

$$TPC_{\Pr od_i} = DM_i + DL_i + TOC_{\Pr od_i}$$

where DM_i = direct materials costs per product *i*

DL_i = direct labour costs per product *i*

TOC_{Prodi} = total overhead per product i

5.6. THE DECISION SUPPORT

The challenge in this study was to construct a multi-criteria decision support model that includes relevant environmental and economic criteria and that can be applied to decision-making for end-of-life of electrical and electronic goods. The goal of the model is to choose the end-of-life option which satisfies best all the environmental and economic criteria, the potential solutions being reuse/part reclamation, remanufacturing, recycling and landfill. Incineration has not been considered as the policy in Ireland is to eliminate incineration as possible.

In the development of the methodology presented in this thesis the Analytical Hierarchy Process (AHP) – see section 4.5 – was chosen as this method is appropriate for multi-criteria modelling and decision-making, it provides a hierarchical framework for structuring the problem and it permits the direct involvement of the decision-maker in the process.

The AHP for environmental and economic decision-making for EOL products follows the following steps:

1. Structuring the hierarchy of criteria and alternatives for evaluation

The major criteria at the first level of the decision-tree are the environmental issues (damage to resources, damage to ecosystem, damage to human health and the compliance with regulations) and the economic issues. Damage to resources can be broken down to non-renewable primary energy input, materials consumption and water consumption; damage to ecosystem can be broken down to greenhouse effect, ozone layer depletion, acidification and water nutrient pollution; damage to human health can be broken down to hazardous substances emitted into air, hazardous substances emitted into water and emission of carcinogenic substances; compliance with regulations can be broken down to percentage of hazardous materials per product, percentage of waste that is reused/ remanufactured/recycled/incinerated/landfilled and average percentage of product that is reused/remanufactured/recycled/ incinerated/ landfilled; economic impact can be broken down to processing cost. This process of refining criteria is what forms a *decision tree*. Figure 5.6 shows the decision tree used by AHP to solve the end-of-life option problem.

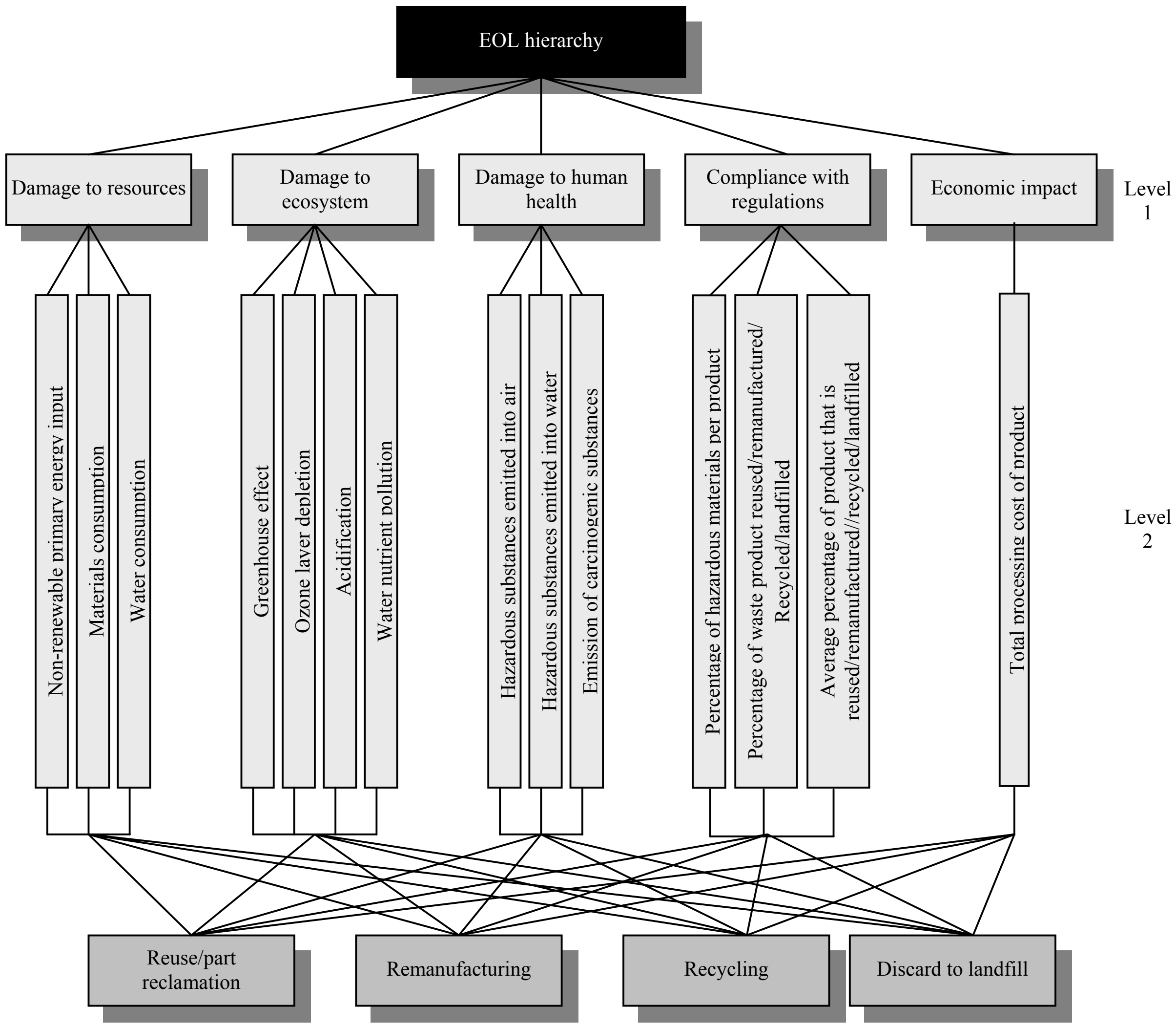

Figure 5.6. The hierarchical structure used by AHP in decision-making for end-of-life options for electrical and electronic products

2. Assessing the decision-maker evaluations by pairwise comparisons

Once the hierarchical structure is defined, *pairwise comparison judgements* may be made. Each criterion is compared to those that have the same parent node. Pairwise comparisons matrices are formed based on the scale presented in section 4.5.1. Table 5.2 shows a matrix of pairwise comparisons of the criteria at level 1 in the decision tree with respect to the overall objective: obtaining the best end-of-life option.

Table 5.2. Matrix of pairwise comparisons of the criteria at the first level in the decision tree with respect to the overall objective

	Damage to resources	Damage to ecosystem	Damage to human health	Compliance with regulations	Economic impact
Damage to resources	1	3	1/5	3	7
Damage to ecosystem	1/3	1	5	5	9
Damage to human health	5	1/5	1	1	3
Compliance with regulations	1/3	1/5	1	1	3
Economic impact	1/7	1/9	1/3	1/3	1

The diagonal values of any pairwise comparisons matrix are always 1 as each criterion is compared with itself and the lower triangular part of the matrix contains the reciprocal of the values in the upper triangular part $\left(a_{ji} = \frac{1}{a_{ij}} \right)$.

3. Using the eigenvector method to obtain relative weights for criteria and alternatives

Let us denote the pairwise comparisons matrix as $A=(a_{ij})$. If n criteria (C_1, C_2, …, C_n) at the same level are compared, then the relative weights are the normalised elements of the eigenvector $w=(w_1, w_2, \ldots, w_n)$ which verifies the equation:

$(\lambda_{max} I - A)\ w = 0$ where λ_{max} is the largest eigenvalue of A

In practice, to determine the relative weights the sum of each column is made. Then each number in the matrix is divided by the sum of the column it appears in. By averaging across each row, the final relative weight is obtained for each criterion.

Let us denote the relative weights derived from pairwise comparisons of the criteria at level 1 as:

w_i, where $\sum_{i=1}^{5} w_i = 1$

and $i = 1, 2, \ldots, 5$; i = criteria at level 1

The relative weights derived from pairwise comparisons of the criteria at level 2 corresponding to each criterion at level 1 are:

v_{ij}, where $\sum_{j=1}^{n} v_{ij} = 1$, $\forall\, i,\ i = 1, 2, \ldots, 5$

and i = criteria at level 1

$j = 1, 2, \ldots, n$

j = criteria at level 2 corresponding to criterion i at level 1

n = number of criteria at level 2 corresponding to criterion i at level 1

The relative weights derived from pairwise comparisons of the alternatives at the bottom level with respect to each criterion at level 2 are:

V_{kl}, where $\sum_{l=1}^{4} V_{kl} = 1$, $\forall\, k,\ k = 1, 2, \ldots, m$

and $l = 1, 2, 3, 4$; l = alternative

k = criteria at level 2

m = total number of criteria at level 2

4. Synthesising comparisons to obtain the scores of the alternatives and rank the alternatives

The absolute importances of criteria at level 2 corresponding to each criterion at level 1 are obtained with the formula:

$U_{ij} = w_i v_{ij}$, $\forall\, i,\ i = 1, 2, \ldots, 5$

$\forall\, j,\ j = 1, 2, \ldots, n$

where i = criterion at level 1

j = criterion at level 2

n = number of criteria at level 2 corresponding to criterion i at level 1

Let us denote the absolute importances of criteria at level 2 calculated before as:

W_k, where $k = 1, 2, \ldots, 14$

k = criterion at level 2

Then the scores of the alternatives (end-of-life options) are:

$S_l = \sum_{k=1}^{14} V_{kl} W_k$, $\forall\, l,\ l = 1, 2, 3, 4$

where l = alternative

k = criterion at level 2; $k = 1, 2, \ldots, 14$

The scores of the alternatives will give the hierarchy. The best end-of-life option (alternative) is the one with the highest score, max S_l.

5.7. CONCLUSIONS

Decision-making for end-of-life of products, especially electrical and electronic ones, is a difficult task. Many factors must be considered – environmental, economic – and so it becomes a multi-criteria decision problem.

This chapter has proposed a methodology that permits calculation of environmental and economic impact of EOL products based on an appropriate product model and EOL options description and, using the AHP, helps integrate all environmental and economic criteria in the decision-making process. Incorporating environmental considerations and constraints stated by legislation in the decision-making process along with the economic judgements alters the decision for end-of-life of products. The main advantage of the AHP from the decision-maker point of view is that he/she is directly involved in the process. The decision-maker evaluates each pair of items he/she assesses. The result of the assessment is based only on the judgement of the decision-maker.

CHAPTER 6. CONCLUSIONS

6.1. SUMMARY OF THE THESIS

One solution to the problem of increased production, consumption and disposal has focused on waste: its avoidance, its reduction, and its disposal. Legislative pressure is being applied to divert it from landfill and encourage recovery actions such as legislation at EU level pending in the area of waste electrical and electronic equipment (WEEE Directive).

Under increasing legislative pressure, business pressure to improve profitability, and public pressure arising from environmental awareness, producers are becoming aware of the necessity to take back their products at the end of their life for recovery. Therefore a decision must be made: to recover or not; and if recovered – which option is best? The decision is difficult to make as both sustainability principles and economic efficiency must be considered.

A literature review was carried out to investigate the existing methodologies that could support the decision-making for end-of-life products. The result: a deficit exists in relation to environmental and economic decision support for end-of-life products. A need for a methodology that considers clearly defined environmental indicators and economic indicators aroused. Therefore, some product models together with the possible end-of-life options were investigated and described and the potential for application to end-of-life products in order to facilitate calculation of environmental and economic indicators investigated. A need for a new product model was identified. Then, as the decision-making process for end-of-life products is complex and involves both environmental and economic indicators and the problem of monetisation appears, some multi-criteria decision methods were presented in chapter 4 and the potential for application to end-of-life products analysed.

Finally, a methodology was developed and presented in chapter 5 of the thesis. The methodology provides a scientific basis for environmental and economic impact assessment, and decision support for end-of-life products applied to waste electrical and electronic products. The methodology is based on a product model adequate to end-of-life use, a good description of end-of-life options in terms of processes, and it calculates environmental and economic indicators that, together with the Analytical Hierarchy Process (AHP), a multi-criteria analysis method, assist the decision-maker in the determination of the most appropriate end-of-life option for his/her products.

6.2. Conclusions And Recommendations For Future Work

Manufacturers have become aware of the necessity to recover their end-of-life products as the result of the legislative pressures, community pressures and business pressures.

However, a hierarchy of the possible end-of-life options based on both environmental and economic criteria was not available. A methodology to support the decision-making process in relation to determination of the most suitable end-of-life option for waste products is needed.

A methodology was developed based on a study of the current situation. It provides the producer with several important environmental indicators (including indicators that show compliance with legislation) and processing cost that shows a comprehensive picture of the environmental impact and the economic situation, and that can be used to assist the producer in the decision-making for his/her end-of-life products. A multi-criteria analysis method (Analytical Hierarchy Process – AHP) was proposed in this respect.

The algorithm for environmental indicators is based on the assumption that emissions are known at the processing company level and not at the process level. The methodology could be refined and more accurate results be obtained when emissions are captured at the process level.

Another assumption is that producers work with processors on an agreement basis so that one producer works with only one type of processor (one remanufacturer, one recycler, one landfill site). Legislation does not specify at the moment if there will be mutual agreements or collective schemes, but the methodology could be extended to be applied in any of the cases.

The method chosen for calculating costs is absorption costing. This permits total absorption of overhead costs but it is not very accurate. ABC (Activity-Based Costing) may be used in the future if more companies implement this method of costing.

The methodology is developed to assist producers in decision-making and also the processors (remanufacturers, recyclers). It can be extended to a national level and become a tool for the Environmental Protection Agency (EPA). The methodology then will enable the development of policy and regulation that takes account of environmental and economic considerations, that is sustainable, and facilitates resource recovery in a manner that makes economic, as well as environmental sense.

If the methodology is used by experts (EPA) then another multi-criteria method can be used to obtain the hierarchy of end-of-life options such as PROMETHEE or ELECTRE. The main reason why AHP was preferred to the other methods was the fact that the decision-maker is directly involved in the decision-making process and the result is based only on the judgement of the decision-maker, no expert opinion is involved.

The methodology developed in this thesis can be applied to waste electrical and electronic equipment. Although the electrical and electronic industry itself is very complex and diverse, the model could be extended to be applied to other types of waste as well. A more generic product model should be developed as well as more generic end-of-life options models.

The methodology needs data about the products and the emissions, data necessary in the algorithms for calculating different indicators. An information system should be developed to support gathering data and implementation of the methodology.

REFERENCES

References Chapter 1

[Col99] Colorni, Alberto; Laniado, Eliot & Muratori, Simona – *Decision Support Systems for Environmental Impact Assessment of Transport Infrastructures*, Transportation Research Part D: Transport & Environment, Vol. 4, Issue 1, 1999;

[COM93] *White Paper on Growth, Competitiveness, and Employment: The Challenges and Ways Forward into the 21st Century COM(93) 700 final*, the European Commission, Brussels, December 1993;

[Gog98] Goggin, Kate – *Modelling End-of-Life Product Recovery*, PhD Thesis, CIMRU Research Unit, NUI Galway, 1998;

[Spi97] Spicer, Andrew & Wang, H. Michael – *Environmental Design Industrial Template: A Software Tool for Analysis of Product Retirement*, Journal of Cleaner Production, Vol. 5, No. 3, 1997;

[Tiw99] Tiwari, D.N.; Loof, R. & Paudyal, G.N. – *Environmental-Economic Decision-Making in Lowland Irrigated Agriculture Using Multi-Criteria Analysis Techniques*, Agricultural Systems, Volume 60, Issue 2, 1999;

[UKG99] *Sustainability Counts*, Sustainable Development – the UK Government's Approach, 1999.

References Chapter 2

[Ase97] Asensio Camardiel, Patricia – *Performance Measurement Systems for Life Cycle Design (LCD)*, Report for GACE Project, CIMRU-NUIG, 1997;

[Ase99] Asensio Camardiel, Patricia – *An Integrated Approach to Product Design for Environment (DFE)* – Masters Thesis, CIMRU-NUIG, 1999;

[Bir96] Birkin, Frank – *Environmental Management Accounting*, 1996;

[Bou02] Boustead Consulting Limited web site: http://www.boustead-consulting.co.uk;

[Can96] Canter, W. Larry – *Environmental Impact Asssessment*, Irwin/McGraw-Hill, USA, 1996;

[Cas88] Cassimatis, Peter - *A Concise Introduction to Engineering Economics*, Unwin Hyman Inc., USA, 1988;

[CES03] Centre for Environment and Society, University of Essex, 2003: http://www2.essex.ac.uk/ces/ResearchProgrammes/externalities/Externwhatareextns.htm;

[Cla95] Clarke, J. Peter – *Accounting Information for Managers*, Oak Tree Press, Dublin, 1995;

[Dit95] Ditz, Daryl; Ranganathan & Banks, R. Darryl – *Green Ledgers: Case Studies in Corporate Environmental Accounting*, World Resources Institute, 1995;

[DoD95] Department of Defense – *ABC Guidebook*, 1995; http://c3i.osd.mil/bprcd/0201i.htm;

[Dru96] Drury, Colin – *Management and Cost Accounting*, International Thomson Business Press, UK, 1996;

[Emb02] Emblemsvag, Jan – *Activity-Based Costing*; http://www.emblemsvag.com;

[FEETM] *Forum for Economics and Environment Training Manual*, Module 6 – Macro-Economic Policies, Policy Analysis and the Environment: http://www.econ4env.co.za/training/MODULE6a.pdf;

[Fry98] Fry, L. Fred; Stoner, R. Charles & Hattwick, E. Richard - *Business - An Integrative Framework*, Irwin McGrawhill, USA, 1998;

[Gil95] Gilpin, Alan – *Environmental Impact Assessment (EIA): Cutting Edge for the Twenty-First Century*, Press Syndicate of the University of Cambridge, 1995;

[Gla94] Glasson, John; Therivel, Riki & Chadwick, Andrew – *Introduction to Environmental Impact Assessment: Principles and Procedures, Process, Practice and Prospects*, UCL Press Ltd., University College London, 1994;

[Goe00] Goedkoop, Mark; Effting, Suzanne & Collignon, Marcel – *The Eco-indicator 99, A Damage Oriented Method for Life Cycle Impact Assessment: Manual for Designers*, PRé Consultants, 2000;

[Goe96] Goedkoop, Mark – *The Eco-indicator 95: Final Report*, PRé Consultants, 1996;

[Goe97] Goedkoop, Mark – *The Eco-indicator 97 Explained – working document*, PRé Consultants, 1997;

[Gui01] Guinée, B. Jeroen et al. – *Life Cycle Assessment – An Operational Guide to the ISO Standards, Final Report*, Ministry of Housing, Spatial Planning and the Environment (VROM) and Centre of Environmental Science – Leiden University (CML), May 2001;

[Ham96] Hamilton, Kirk & Lutz, Ernst – *Green National Accounts: Policy Uses and Empirical Experience*, Pollution and Environmental Economics Division, World Bank, 1996;

[Hec99] Hecht, E. Joy – *Environmental Accounting – Where We Are Now, Where We Are Heading*, Resources, Issue 135, 1999;

[Hor87] Horngren, T. Charles & Foster, George – *Cost Accounting – A Managerial Emphasis*, Prentice-Hall Inc., USA, 1987;

[IFS03] Biz/ed/Institute for Fiscal Studies Virtual Economy, 2003: http://www.bized.ac.uk/virtual/economy/library/glossary/glossarydf.htm#extcost;

[Inn98] Innes, John & Mitchell, Falconer – *A Practical Guide to Activity-Based Costing*, Kogan Page Ltd., London, 1998;

[ISO97] *ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework*, International Standard Organisation, 1997;

[ISO98] *ISO 14041: Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis*, International Standard Organisation, 1998;

[ISO99] *ISO 14042: Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment*, International Standard Organisation, 1999;

[Lec99] Lecouls, Henri – ISO 14043: *Environmental Management ·Life Cycle Assessment · Life Cycle Interpretation*, Int. J. LCA, No. 4(5) 245, 1999;

[Mar00] Marsmann, Manfred – *The ISO 14040 Family*, Int. J. LCA, No. 5 (6), 2000;

[O'Su90] O'Sullivan, Michael – *Environmental Impact Assessment*, Resource & Environmental Management Unit, University College Cork, Ireland, 1990;

[Pro02] Proctor, Ray – *Managerial Accounting for Business Decisions*, Pearson Education Ltd., UK, 2002;

[Rey73] Reynolds, G. Lloyd - *Microeconomics - Analysis and Policy*, Irwin-Dorsey Limited, Georgetown, Ontario, 1973;

[Roo95] Rooney, M. Sinead – *Environmental Economics, A Survey with Evidence of Application of Economic Instruments in Environmental Policy*, Masters Degree in Arts to the Economics Department, University College Galway, 1995;

[SET93] *Guidelines for Life-Cycle Assessment: A 'Code of Practice'*, SETAC, Brussels, 1993;

[SET98] *SETAC – Evolution and Development of the Conceptual Framework and Methodology of Life-Cycle Impact Assessment, Addendum to Life-Cycle Impact Assessment: The State of the Art*, Barnthouse et al., 1998;

[Tur97] Turney, B. B. Peter – *Activity Based Costing – The Performance Breakthrough*, Kogan Page Ltd., London, 1997;

[UN03a] *About the System of National Accounts*, United Nations, Department of Economic and Social Affairs, Statistics Division, 2003: http://unstats.un.org/unsd/sna1993/introduction.asp;

[UN03b] *About the System of National Accounts*, United Nations, Department of Economic and Social Affairs, Statistics Division, 2003: http://unstats.un.org/unsd/environment/issue9.htm;

[UNS00] United Nations Environment Programme & Society of Environment Toxicology and Chemistry, *The Life Cycle Initiative – UNEP/SETAC co-operation on Best Available Practice in Life Cycle Assessment (LCA)*, 2000;

[Wat94] Wathern, Peter – *Environmental Impact Assessment: Theory and Practice,* Biddles Ltd., UK, 1994;

[WEEE02] *Draft proposal for the EU Directive on Waste Electrical and Electronic Equipment*, European Parliament, Brussels, 2002;

[Wil75] Wilson, R.M.S - *Cost Control Handbook*, Gower Press Ltd, UK, 1975;

[Zob02] Zobel, T. et al – *Identification and Assessment of Environmental Aspects in an EMS Context: an Approach to a New Reproducible Method Based on LCA Methodology*, Journal of Cleaner Production, No. 10, 2002.

References Chapter 3

[Bet99] Bettac, E.; K. Maas, P. Beullens, and R. Bopp – *RELOOP: Reverse Logistics Chain Optimization in a Multi-User Trading Environment*, Conference Record IEEE International Symposium on Electronics & the Environment, Danvers, Massachusetts, USA, 42-47, 1999;

[Bro01] Bronsvoort, F. Willem, Bidarra, Rafael & Noort, Alex – *Semantic and Multiple-View Feature Modelling: Towards More Meaningful Product Modelling*, Geometric Modelling: Theoretical and Computational Basis towards Advanced CAD Applications, Kimura F (Ed.), Kluwer Academic Publishers, Dordrecht, 2001;

[Bro97] Bronsvoort, F. Willem et al. – *Multiple-View Feature Modelling and Conversion*, Geometric Modelling: Theory and Practice – The State of the Art, Strasser W., Klein R. and Rau R. (eds), Springer, Berlin, 1997;

[Bur01] Burnley, Stephen – *The Impact of the European Landfill Directive on Waste Management in the United Kingdom*, Resources, Conservation and Recycling, Vol. 32, 2001;

[CCL97] *Bill of Materials Role in Manufacturing*, Cybor Communications Limited, 1997: http://www.cybor.co.nz/news/bill.html;

[CET01] Concurrent Engineering Team (CETEAM): http://www.ceteam.com/knowledge-based_engineering.htm;

[CGG03] Computer Graphics and CAD/CAM Group – *Geometric and Feature Modelling*: http://www.cg.its.tudelft.nl/wwwcc/, 2003;

[Che00] Cheesman, John & Daniels, John – *UML Components, A Simple Process for Specifying Component-Based Software*, Addison-Wesley Publishing, 2000;

[Cim01] Product Data Management and Computer-Aided Software Engineering CimData: http://pdm.project.ericsson.se/cimdata/pdm_case/pdm_case.htm;

[Cla97] Clancy, Jon – *Engineering Bill of Materials*, CIRAS News, Vol. 32, No. 1, 1997;

[DED01] Design Engineer on a Disk, Hugh Jack, 1993-2001: http://claymore.engineer.gvsu.edu;

[Den96] Denno, Peter - *Dynamic Objects and Meta-level Programming of an EXPRESS Language Environment*, Dynamic Objects Workshop, Object World, Boston, 1996;

[EC00] European Comission, DG Environment, 2000 – *A Study on the Economic Valuation of Environmental Externalities from Landfill Disposal and Incineration of Waste*: http://europa.eu.int/comm/environment/enveco/waste/cowi_ext_from_landfill.pdf;

[EIA94] *EIA/IS 632, Interim Standard: Systems Engineering,* Electronic Industries Alliance, 1994;

[Fow95] Fowler, Julian – *STEP: The Standard for the Exchange of Product Model Data*, The Workshop on Systems Engineering, European Space Agency, 1995;

[Fow97] Fowler, Julian & Boyle, Alan – *From Product to Product Knowledge Modelling in STEP*, PDT Solutions, 1997;

[Gog98] Goggin, Kate – *Modelling End-of-Life Product Recovery*, PhD Thesis, CIMRU Research Unit, NUI Galway, 1998;

[GPS00] *Bill of Materials Sample Report,* Great Plains Software Inc, 2000;

[Gra00] Graves, Gerry – *ISO 10303-209 The International Standard for Exchanging and Sharing Engineering Analysis Data*, PDES Inc., 2000: http://ea.aticorp.org/ap209/engineering.html;

[Gua97] Guarino, Nicola; Borgo, Stefano & Masolo, Claudio – *Logical Modelling of Product Knowledge: Towards a Well-Founded Semantics for STEP*, European Conference on Product Data Technology, Sophia Antipolis, France, 1997;

[Gui00] Guide Jr., V.R. Daniel – *Production Planning and Control for Remanufacturing: Industry Practice and Research Needs*, Journal of Operations Management, Vol. 18, Issue 4, 2000;

[Gun99] Gungor, Askiner & Gupta, M. Surenda – *Issues in Environmentally Conscious Manufacturing and Product Recovery: A Survey*, Computer & Industrial Engineering, No. 36, 1999;

[Hub88] Hubka, V. and Eder, W. E. – *Theory of Technical Systems,* Springer-Verlag, Berlin, 1988;

[IEEE95] *IEEE 1220-1994 – IEEE Trial-Use Standard for Application and Management of the Systems Engineering Process*, IEEE Computer Society, Institute of Electrical and Electronics Engineers, 1995;

[Isa00] Isaksson, Ola & al. – *Trends in Product Modelling – An ENDREA Perspective*, Proceedings Product Models, Linköping, Sweden, 2000;

[ISO92] *ISO 10303: Product Data Representation and Exchange*, International organisation for Standardisation, 1992;

[Lun98] Lund, R. – *Remanufacturing: An American Resource*, Proceeding of the Fifth International Congress Environmentally Conscious Design and Manufacturing, Rochester, NY, USA, 1998;

[Mal97] Malmqvist, Johan and Schachinger, Peter – *Towards an Implementation of the Chromosome Model - Focusing the Design Specification*, International Conference on Engineering Design, ICED 97, Tampere, Finland, 1997;

[Man94] Mann, Ray & Biddle, B. Michael – *Recipe for Recycling*, IEEE Spectrum, Vol. 31, No. 8, 1994;

[Mor93] *Overview of the STEP and the STEP Standard Data Access Interface,* Position Paper for Workshop on Application Integration Architectures, Texas Instruments, 1993;

[Pea85] Peavy, S. Howard; Rowe, R. Donald & Tchobanoglous, George – *Environmental Engineering*, McGraw-Hill Book Co, Singapore, 1985;

[Rhy95] Rhyner, R. Charles; Schwartz, J. Leander; Wenger, B. Robert & Kohrell, G. Mary – *Waste Management and Resource Recovery*, CRC Press, USA, 1995;

[She98] Sheard, S. A. and Lake, J. G. – *Systems Engineering Standards and Models Compared*, Proceedings of the 8th International Symposium on Systems Engineering (INCOSE), Vancouver, Canada, 1998;

[Shi00] Shikarpur, Deepak – *Knowledge-Based Engineering for Effective eManufacturing*, Express Computer, Indican Express Group, 2000;

[Sin99] Sindjou, Guy Bear - *Effect of Waste on End of Product Life Cycle*, Special Scientific Report #99-19, 1999 Summer Institute, National Science Foundation's (NSF) Tokyo Office, 1999;

[Spi97] Spicer, Andrew & Wang, H. Michael – *Environmental Design Industrial Template: A Software Tool for Analysis of Product Retirement*, Journal of Cleaner Production, Vol. 5, No. 3, 1997;

[SWk01] *SolidWorks 2001 Getting Started*, SolidWorks Corporation, USA, 1995-2001;

[WEEE02] *Draft proposal for the EU Directive on Waste Electrical and Electronic Equipment*, European Parliament, Brussels, 2002;

[Wil98] Wilson, R. Peter – *STEP and EXPRESS*, Workshop on Distributed Information, Computation and Process Management for Scientific and Engineering Environments, May 1998.

References Chapter 4

[Aka97] Akao, Yoji – *QFD: Past, Present and Future*, International Symposium on QFD, Linköping, 1997;

[Asa94] Asahi, T.; Turo, D. & Shneiderman, B. – *Technical Research Report: Using Treemaps to Visualise the Analytic Hierarchy Process*, Institute for Systems Research, 1994;

[Bey02] Beynon, Malcolm – *DS/AHP Method: A Mathematical Analysis, Including an Understanding of Uncertainty*, European Journal of Operational Research, Volume 140, 2002;

[Bra00] Brans, J. Pierre – *Ethics and Decision*, Centre for Statistics and Operational Research, Brussels, Belgium, 2000;

[Buc99] Buchanan, John; Sheppard, Philip & Vanderpooten, Daniel – *Project Ranking Using ELECTRE III*, Northern Generation, Electricity Corporation of New Zealand, New Zealand, 1999;

[Cho03] Cho, Keun-Tae & Kwon, Cheol-Shin – *Hierarchies with Dependence of Technological Alternatives: A Cross-Impact Hierarchy Process*, European Journal of Operational Research, 2003;

[Dia98] Dias, C. Luis; Costa, P. João & Clímaco, N. João – *A Parallel Implementation of the PROMETHEE Method*, European Journal of Operational Research, Volume 102, 1998;

[Gor94] Gordon, Jay Theodore – *Cross-Impact Method*, AC/UNU Millennium Project, 1994;

[Hal01] Halog, Anthony; Schultmann, Frank & Rentz, Otto – *Using Quality Function Deployment for Technique Selection for Optimum Environmental Performance Improvement*, Journal of Cleaner Production, Volume 9, Issue 5, 2001;

[Hez02] Heinzerling, Lisa & Ackerman, Frank – *Cost-Benefit Analysis of Environmental Protection*, The Georgetown Environmental Law and Policy Institute, Georgetown University,Washington, 2002;

[Jag97] Jagdev, H.; Bradley, P. & Molloy, O. – *A QFD Based Performance Measurement Tool*, Computers in Industry, Volume 33, 1997;

[Kli02] Kliewer, Chris et al. – *Quality Function Deployment*, QFD Report, University of Calgary, Alberta, Canada, 2002;

[Mie99] Miettinen, Kaisa & Salminen, Pekka – *Decision-Aid for Discrete Multiple Criteria Decision Making Problems with Imprecise Data*, European Journal of Operational Research, Volume 119, 1999;

[MIT97] MITRE Corporation – *QFD: A Structured Problem Solving Technique*, SEPO TechNote No. 7, R1, 1997;

[Mul02] Mulreany, Michael – *Cost-Benefit Analysis Readings*, Institute of Public Administration, Dublin, 2002;

[Sal98] Salmien, Pekka; Hokkanen, Joonas & Lahdelma, Risto – *Comparing Multicriteria Methods in the Context of Environmental Problems*, European Journal of Operational Research, Volume 104, 1998;

[Sch94] Schmoldt, L. Daniel; Peterson, L. David & Smith, L. Robert – *The Analytic Hierarchy Process and Participatory Decisionmaking*, Decision Support – 2001, Volume 1, 17th Annual Geographic Information Seminar and the Resource Technology '94 Symposium, Ontario, 1994;

[Schl97] Schlange, E. Lutz & Jüttner, Uta – *Helping Managers to Identify the Key Strategic Issues*, Long Range Planning, Volume 30, No. 5, 1997;

[Sin00] Sinuany-Stern, Zilla et al. – *An AHP/DEA Methodology for Ranking Decision Making Units*, International Transactions in Operational Research, Vol. 7, Issue 2, 2000;

[Snl97] Snell, Michael – *Cost-Benefit Analysis for Engineers and Planners*, Thomas Telford Publications, London, 1997;

[Tiw99] Tiwari, D.N.; Loof, R. & Paudyal, G.N. – *Environmental-Economic Decision-Making in Lowland Irrigated Agriculture Using Multi-Criteria Analysis Techniques*, Agricultural Systems, Volume 60, Issue 2, 1999;

[Vai02] Vaillancourt, Kathleen & Waaub, Jean-Philippe – *Environmental Site Evaluation of Waste Management Facilities Embedded into EUGÈNE Model: A Multicriteria Approach*, European Journal of Operational Research, Volume 139, 2002;

[Wat02] Watkins, Thayer – *Introduction to Cost Benefit Analysis*, course notes, San Jose State University Economics Department, 2002.

References Chapter 5

[Ase97] Asensio Camardiel, Patricia – *Performance Measurement Systems for Life Cycle Design (LCD)*, Report for GACE Project, CIMRU-NUIG, 1997;

[Goe00] Goedkoop, Mark; Effting, Suzanne & Collignon, Marcel – *The Eco-indicator 99, A Damage Oriented Method for Life Cycle Impact Assessment: Manual for Designers*, PRé Consultants, 2000;

[Goe96] Goedkoop, Mark – *The Eco-indicator 95: Final Report*, PRé Consultants, 1996;

[Han99] Hannah, John & Hillier, M. J. – *Mechanical Engineering Science*, Addison Wesley Longman Ltd., England, 1999;

[Mul01] Müller, Kaspar & dr. Sturm, Andreas – *Standardized Eco-Efficiency Indicators*, Ellipson, Switzerland, January 2001;

[WEEE02] *Draft Proposal for the EU Directive on Waste Electrical and Electronic Equipment*, European Parliament, Brussels, 2002.

BIBLIOGRAPHY

1. *About the System of National Accounts*, United Nations, Department of Economic and Social Affairs, Statistics Division, 2003: http://unstats.un.org/unsd/sna1993/introduction.asp;
2. *About the System of National Accounts*, United Nations, Department of Economic and Social Affairs, Statistics Division, 2003: http://unstats.un.org/unsd/environment/issue9.htm;
3. Akao, Yoji – *QFD: Past, Present and Future*, International Symposium on QFD, Linköping, 1997;
4. Asahi, T.; Turo, D. & Shneiderman, B. – *Technical Research Report: Using Treemaps to Visualise the Analytic Hierarchy Process*, Institute for Systems Research, 1994;
5. Asensio Camardiel, Patricia – *An Integrated Approach to Product Design for Environment (DFE)* – Masters Thesis, CIMRU-NUIG, 1999;
6. Asensio Camardiel, Patricia – *Performance Measurement Systems for Life Cycle Design (LCD)*, Report for GACE Project, CIMRU-NUIG, 1997;
7. Bartelmus, Peter & van Tongeren, Jan – *Environmental Accounting: An Operational Perspective*, 1994: http://www.un.org/Depts/unsd/enviro/wp1.pdf;
8. Bellmann, Klaus & Khare, Anshuman – *A Systems Dinamic Perspective on the Development of Recycling Strategy for End-of-Life Vehicles*, Technovation, Vol. 21, 2001;
9. Bettac, E.; K. Maas, P. Beullens, and R. Bopp – *RELOOP: Reverse Logistics Chain Optimization in a Multi-User Trading Environment*, Conference Record IEEE International Symposium on Electronics & the Environment, Danvers, Massachusetts, USA, 42-47, 1999;
10. Beynon, Malcolm – *DS/AHP Method: A Mathematical Analysis, Including an Understanding of Uncertainty*, European Journal of Operational Research, Volume 140, 2002;

11. Bidgoli, Hossein – *Decision Support Systems: Principles & Practice*, West Publishing Company, USA, 1989;
12. *Bill of Materials Role in Manufacturing*, Cybor Communications Limited, 1997: http://www.cybor.co.nz/news/bill.html;
13. *Bill of Materials Sample Report,* Great Plains Software Inc, 2000;
14. *Bill of Materials Walkthrough*: http://www.inmet.com/ecce/models/current/walkthroughs/bom_walkthrough.html;
15. Bimpler, David & Kirkland, John – *Capturing Images in a Net: Perceptual Modelling of Product Descriptors Using Sorting Data*, Marketing Bulletin, 1998;
16. Birkin, Frank – *Environmental Management Accounting*, 1996;
17. Biz/ed/Institute for Fiscal Studies Virtual Economy, 2003: http://www.bized.ac.uk/virtual/economy/library/glossary/glossarydf.htm#extcost;
18. Bloom, M. Howard – *What is STEP and How Is It Used?*: http://www.mel.nist.gov/msidlibrary/doc/bloom92.pdf;
19. Boustead Consulting Limited web site: http://www.boustead-consulting.co.uk;
20. Brans, J. Pierre – *Ethics and Decision*, Centre for Statistics and Operational Research, Brussels, Belgium, 2000;
21. Brans, Jean-Pierre & Mareschal, Bertrand – *How to Decide with PROMETHEE*: http://homepages.ulb.ac.be/~bmaresc/PromWeb.htm;
22. Bronsvoort, F. Willem et al. – *Multiple-View Feature Modelling and Conversion*, Geometric Modelling: Theory and Practice – The State of the Art, Strasser W., Klein R. and Rau R. (eds), Springer, Berlin, 1997;
23. Bronsvoort, F. Willem, Bidarra, Rafael & Noort, Alex – *Semantic and Multiple-View Feature Modelling: Towards More Meaningful Product Modelling*, Geometric Modelling: Theoretical and Computational Basis towards Advanced CAD Applications, Kimura F (Ed.), Kluwer Academic Publishers, Dordrecht, 2001;
24. Buchanan, John; Sheppard, Philip & Vanderpooten, Daniel – *Project Ranking Using ELECTRE III*, Northern Generation, Electricity Corporation of New Zealand, New Zealand, 1999;
25. Burnley, Stephen – *The Impact of the European Landfill Directive on Waste Management in the United Kingdom*, Resources, Conservation and Recycling, Vol. 32, 2001;

26. Canter, W. Larry – *Environmental Impact Asssessment*, Irwin/McGraw-Hill, USA, 1996;
27. Cassimatis, Peter - *A Concise Introduction to Engineering Economics*, Unwin Hyman Inc., USA, 1988;
28. Centre for Environment and Society, University of Essex, 2003: http://www2.essex.ac.uk/ces/ResearchProgrammes/externalities/Externwhatareextns.htm;
29. Cheesman, John & Daniels, John – *UML Components, A Simple Process for Specifying Component-Based Software*, Addison-Wesley Publishing, 2000;
30. Cho, Keun-Tae & Kwon, Cheol-Shin – *Hierarchies with Dependence of Technological Alternatives: A Cross-Impact Hierarchy Process*, European Journal of Operational Research, 2003;
31. Clancy, Jon – *Engineering Bill of Materials*, CIRAS News, Vol. 32, No. 1, 1997;
32. Clarke, J. Peter – *Accounting Information for Managers*, Oak Tree Press, Dublin, 1995;
33. Clegg A J and Williams D J – *The Strategeic and Competitive Implications of Recycling and Design for Dissassembly in the Electronics Industry*, Keynote, Proceedings of 2nd IEEE International Symposium of Electronics and the Environment, San Francisco, 1994;
34. Colorni, Alberto; Laniado, Eliot & Muratori, Simona - *Decision Support Systems for Environmental Impact Assessment of Transport Infrastructures*, Transportation Research Part D: Transport & Environment, Volume 4, Issue 1, 1999;
35. Computer Graphics and CAD/CAM Group – *Geometric and Feature Modelling*: http://www.cg.its.tudelft.nl/wwwcc/, 2003;
36. Concurrent Engineering Team (CETEAM): http://www.ceteam.com/knowledge-based_engineering.htm;
37. CPM – *Brief Introduction to ISO/TS 14048 Data Documentation Format Prepared by CPM*, Centre for Environmental Assessment of Product and Material Systems, Chalmers University of Technology, Gothenburg, Sweden, 2001;
38. Craig, P. Paul – *Energy Limits on Recycling*, Ecological Economics, Vol. 36, 2001;
39. DeGarmo, E. Paul; Sullivan, G. William & Canada, R. John – *Engineering Economy*, Macmillan Publishing Company, USA, 1984;

40. Denno, Peter - *Dynamic Objects and Meta-level Programming of an EXPRESS Language Environment*, Dynamic Objects Workshop, Object World, Boston, 1996;
41. Department of Defense – *ABC Guidebook*, 1995; http://c3i.osd.mil/bprcd/0201i.htm;
42. Design Engineer on a Disk, Hugh Jack, 1993-2001: http://claymore.engineer.gvsu.edu;
43. *Diagnosis of Company Status in Product Data Modelling*: http://www.iai.csic.es/netcim/action11.htm;
44. Dias, C. Luis; Costa, P. João & Clímaco, N. João – *A Parallel Implementation of the PROMETHEE Method*, European Journal of Operational Research, Volume 102, 1998;
45. Ditz, Daryl; Ranganathan & Banks, R. Darryl – *Green Ledgers: Case Studies in Corporate Environmental Accounting*, World Resources Institute, 1995;
46. Doody, S. Francis - *Introduction to the Use of Economic Indicators*, Random House, New York, 1965;
47. *Draft proposal for the EU Directive on Waste Electrical and Electronic Equipment*, European Parliament, Brussels, 2002;
48. Drury, Colin – *Management and Cost Accounting*, International Thomson Business Press, UK, 1996;
49. Dubreuil, Alain – *Analysis of the Eco-indicator 95 Model*, CANMET, Department of Natural Resources, Canada;
50. *EIA/IS 632, Interim Standard: Systems Engineering,* Electronic Industries Alliance, 1994;
51. Emblemsvag, Jan – *Activity-Based Costing*; http://www.emblemsvag.com;
52. *Environmental Impact Assessment*, internet: http://www.leidenuniv.nlinterfaccmlchainettooleia.htm;
53. European Comission, DG Environment, 2000 – *A Study on the Economic Valuation of Environmental Externalities from Landfill Disposal and Incineration of Waste*: http://europa.eu.int/comm/environment/enveco/waste/cowi_ext_from_landfill.pdf;
54. *Forum for Economics and Environment Training Manual*, Module 6 – Macro-Economic Policies, Policy Analysis and the Environment: http://www.econ4env.co.za/training/MODULE6a.pdf;
55. Fowler, Julian – *STEP: The Standard for the Exchange of Product Model Data*, The Workshop on Systems Engineering, European Space Agency, 1995;

56. Fowler, Julian & Boyle, Alan – *From Product to Product Knowledge Modelling in STEP*, PDT Solutions, 1997;
57. Fry, L. Fred; Stoner, R. Charles & Hattwick, E. Richard - *Business - An Integrative Framework*, Irwin McGrawhill, USA, 1998;
58. Gilpin, Alan – *Environmental Impact Assessment (EIA): Cutting Edge for the Twenty-First Century*, Press Syndicate of the University of Cambridge, 1995;
59. Glad, Ernest & Becker, Hugh – *Activity Based Costing and Management*, John Wiley & Sons Inc., England, 1996;
60. Glasson, John; Therivel, Riki & Chadwick, Andrew – *Introduction to Environmental Impact Assessment: Principles and Procedures, Process, Practice and Prospects*, UCL Press Ltd., University College London, 1994;
61. Goedkoop, Mark – *The Eco-indicator 95: Final Report*, PRé Consultants, 1996;
62. Goedkoop, Mark – *The Eco-indicator 97 Explained – working document*, PRé Consultants, 1997;
63. Goedkoop, Mark; Demmers, Marjolein & Collignon, Marcel – *The Eco-indicator 95 Manual for Designers*, PRé Consultants, 1996;
64. Goedkoop, Mark; Effting, Suzanne & Collignon, Marcel – *The Eco-indicator 99, A Damage Oriented Method for Life Cycle Impact Assessment: Manual for Designers*, PRé Consultants, 2000;
65. Goff, S. Walter – *Management Accounting for Managers*, MacDonald & Evans Ltd., UK, 1975;
66. Goggin, Kate – *Modelling End-of-Life Product Recovery*, PhD Thesis, CIMRU Research Unit, NUI Galway, 1998;
67. Gordon, Jay Theodore – *Cross-Impact Method*, AC/UNU Millennium Project, 1994;
68. Graves, Gerry – *ISO 10303-209 The International Standard for Exchanging and Sharing Engineering Analysis Data*, PDES Inc., 2000: http://ea.aticorp.org/ap209/engineering.html;
69. Grigg, V. L. Sacha & Read, D. Adam – *A Discussion on the Various Methods of Application for Landfill Tax Credit Funding for Environmental and Community Projects*, Resources, Conservation and Recycling, Vol. 32, 2001;
70. Guarino, Nicola; Borgo, Stefano & Masolo, Claudio – *Logical Modelling of Product Knowledge: Towards a Well-Founded Semantics for STEP*, European Conference on Product Data Technology, Sophia Antipolis, France, 1997;

71. Guide Jr., V.R. Daniel – *Production Planning and Control for Remanufacturing: Industry Practice and Research Needs*, Journal of Operations Management, Vol. 18, Issue 4, 2000;
72. *Guidelines for Life-Cycle Assessment: A 'Code of Practice'*, SETAC, Brussels, 1993;
73. Guinée, B. Jeroen et al. – *Life Cycle Assessment – An Operational Guide to the ISO Standards, Final Report*, Ministry of Housing, Spatial Planning and the Environment (VROM) and Centre of Environmental Science – Leiden University (CML), May 2001;
74. Gungor, Askiner & Gupta, M. Surenda – *Issues in Environmentally Conscious Manufacturing and Product Recovery: A Survey*, Computer & Industrial Engineering, No. 36, 1999;
75. Halog, Anthony; Schultmann, Frank & Rentz, Otto – *Using Quality Function Deployment for Technique Selection for Optimum Environmental Performance Improvement*, Journal of Cleaner Production, Volume 9, Issue 5, 2001;
76. Hamilton, Kirk & Lutz, Ernst – *Green National Accounts: Policy Uses and Empirical Experience*, Pollution and Environmental Economics Division, World Bank, 1996;
77. Hecht, E. Joy – *Environmental Accounting – Where We Are Now, Where We Are Heading*, Resources, Issue 135, 1999;
78. Heinzerling, Lisa & Ackerman, Frank – *Cost-Benefit Analysis of Environmental Protection*, The Georgetown Environmental Law and Policy Institute, Georgetown University,Washington, 2002;
79. Heitger, E. Lester & Matulich, Serge – *Managerial Accounting*, McGraw-Hill Book Company, USA, 1987;
80. Helmkamp, G. John – *Managerial Accounting*, John Wiley & Sons, USA, 1990;
81. Homburg, Carsten – *Hierarchical Multi-Objective Decision Making*, European Journal of Operational Research, Volume 105, 1998;
82. Horngren, T. Charles & Foster, George – *Cost Accounting – A Managerial Emphasis*, Prentice-Hall Inc., USA, 1987;
83. Hubka, V. and Eder, W. E. – *Theory of Technical Systems,* Springer-Verlag, Berlin, 1988;
84. *IEEE 1220-1994 – IEEE Trial-Use Standard for Application and Management of the Systems Engineering Process*, IEEE Computer Society, Institute of Electrical and Electronics Engineers, 1995;

85. Innes, John & Mitchell, Falconer – *A Practical Guide to Activity-Based Costing*, Kogan Page Ltd., London, 1998;
86. Isaksson, Ola & al. – *Trends in Product Modelling – An ENDREA Perspective*, Proceedings Product Models, Linköping, Sweden, 2000;
87. *ISO 10303: Product Data Representation and Exchange*, International organisation for Standardisation, 1992;
88. *ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework*, International Standard Organisation, 1997;
89. *ISO 14041: Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis*, International Standard Organisation, 1998;
90. *ISO 14042: Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment*, International Standard Organisation, 1999;
91. *ISO Standards, Final Report, Ministry of Housing, Spatial Planning and the Environment (VROM) and Centre of Environmental Science* – Leiden University (CML), May 2001;
92. Jagdev, H.; Bradley, P. & Molloy, O. – *A QFD Based Performance Measurement Tool*, Computers in Industry, Volume 33, 1997;
93. Johnson, G.V. et al. – *Guidance Tools for Use in Nuclear Material Management Decision Making*, WM'02 Conference, Feb. 24-28, Tucson, AZ, 2002;
94. Kalameja, J Alan – *The AutoCAD 2000 Tutor for Engineering Graphics*, Thomson Learning ™, Canada, 2000;
95. Kliewer, Chris et al. – *Quality Function Deployment*, QFD Report, University of Calgary, Alberta, Canada, 2002;
96. Lecouls, Henri – *ISO 14043: Environmental Management ·Life Cycle Assessment · Life Cycle Interpretation*, Int. J. LCA, No. 4 (5), 1999;
97. *Lecture Notes on Environmental Impact Assessment*, Glen Paoletto, internet: http://www.gdrc.orguemeialecture-notes.html;
98. Lucey, T. – *Costing*, Letts Education, London, 1996;
99. Lund, R. – *Remanufacturing: An American Resource*, Proceeding of the Fifth International Congress Environmentally Conscious Design and Manufacturing, Rochester, NY, USA, 1998;
100. Madigan, David – *Construction Product Modelling: Implications for the ACI Whole Life-Cycle Assessment Work*, University of Bath, U.K., 1997;

101. Malmqvist, Johan and Schachinger, Peter – *Towards an Implementation of the Chromosome Model - Focusing the Design Specification*, International Conference on Engineering Design, ICED 97, Tampere, Finland, 1997;
102. Mann, Ray & Biddle, B. Michael – *Recipe for Recycling*, IEEE Spectrum, Vol. 31, No. 8, 1994;
103. *Manufacturing Cost Assessment – Bill of Materials*: http://www.eren.doe.gov/buildings/codes_standards/reports/cwtsd/Appendix_D_mfr_Cost_Assessment.pdf;
104. Marsmann, Manfred – *The ISO 14040 Family*, Int. J. LCA, No. 5 (6), 2000;
105. Menad, N. – *Cathode Ray Tube Recycling*, Resources, Conservation and Recycling, Vol. 26, 1999;
106. Miettinen, Kaisa & Salminen, Pekka – *Decision-Aid for Discrete Multiple Criteria Decision Making Problems with Imprecise Data*, European Journal of Operational Research, Volume 119, 1999;
107. MITRE Corporation – *QFD: A Structured Problem Solving Technique*, SEPO TechNote No. 7, R1, 1997;
108. Morris, R. John & Read, D. Adam – *The UK Landfill Tax and the Landfill Tax Credit Scheme: Operational Weaknesses*, Resources, Conservation and Recycling, Vol. 32, 2001;
109. Müller, Kaspar & dr. Sturm, Andreas – *Standardized Eco-Efficiency Indicators*, Ellipson, Switzerland, January 2001;
110. Mulreany, Michael – *Cost-Benefit Analysis Readings*, Institute of Public Administration, Dublin, 2002;
111. Nakamura, Shinichiro – *An Interindustry Approach to Analysing Economic and Environmental Effects of the Recycling of Waste*, Ecological Economics, Volume 28, Issue 1, January 1999;
112. O'Sullivan, Michael – *Environmental Impact Assessment*, Resource & Environmental Management Unit, University College Cork, Ireland, 1990;
113. *Overview of the STEP and the STEP Standard Data Access Interface,* Position Paper for Workshop on Application Integration Architectures, Texas Instruments, 1993;
114. Palmer, T. Noel - *Essential Economics*, ETA Publications Ltd, 1978;
115. Peavy, S. Howard; Rowe, R. Donald & Tchobanoglous, George – *Environmental Engineering*, McGraw-Hill Book Co, Singapore, 1985;

116. Penev, Kiril & de Ron, Ad – *Disassembly and Recycling of Electronic Consumer Products: An Overview*, Technovation, Vol. 15, No. 6, 1995;
117. Proctor, Ray – *Managerial Accounting for Business Decisions*, Pearson Education Ltd., UK, 2002;
118. Product Data Management and Computer-Aided Software Engineering CimData: http://pdm.project.ericsson.se/cimdata/pdm_case/pdm_case.htm;
119. *Ranking by Classical Logic (ELECTRE)*: http://www.unesco.org/webworld/idams/advguide/Chapt3_5_1.htm;
120. Reynolds, G. Lloyd - *Microeconomics - Analysis and Policy*, Irwin-Dorsey Limited, Georgetown, Ontario, 1973;
121. Rhyner, R. Charles; Schwartz, J. Leander; Wenger, B. Robert & Kohrell, G. Mary – *Waste Management and Resource Recovery*, CRC Press, USA, 1995;
122. Riggs, L. James – *Engineering Economics*, McGraw-Hill Book Company, USA, 1977;
123. Robertson, James – *Eco-Taxes*, The New Internationalist, No. 278, April 1996;
124. Rogers, M. & Bruen, M. – *Threshold values for noise, air and water impact criteria within the ELECTRE model*, the 46th Meeting of the European Working Group on Multicriteria Aid for Decisions, Paris, 1997;
125. Rogers, Martin & Bruen, Michael – *A New System for Weighting Environmental Criteria for Use within ELECTRE III*, European Journal of Operational Research, Volume 107, 1998;
126. Rooney, M. Sinead – *Environmental Economics, A Survey with Evidence of Application of Economic Instruments in Environmental Policy*, Masters Degree in Arts to the Economics Department, University College Galway, 1995;
127. Ryding, Sven-Olof – *ISO 14042: Environmental Management·Life Cycle Assessment · Life Cycle Impact Assessment*, Int. J. LCA, No. 4 (5), 1999;
128. Salmien, Pekka; Hokkanen, Joonas & Lahdelma, Risto – *Comparing Multicriteria Methods in the Context of Environmental Problems*, European Journal of Operational Research, Volume 104, 1998;
129. Sarkis, Joseph – *A Comparative Analysis of DEA as a Discrete Alternative Multiple Criteria Decision Tool*, European Journal of Operational Research, Volume 123, 2000;

130. Schlange, E. Lutz & Jüttner, Uta – *Helping Managers to Identify the Key Strategic Issues*, Long Range Planning, Volume 30, No. 5, 1997;
131. Schmoldt, L. Daniel; Peterson, L. David & Smith, L. Robert – *The Analytic Hierarchy Process and Participatory Decisionmaking*, Decision Support – 2001, Volume 1, 17th Annual Geographic Information Seminar and the Resource Technology '94 Symposium, Ontario, 1994;
132. SETAC – *Evolution and Development of the Conceptual Framework and Methodology of Life-Cycle Impact Assessment,* addendum to *Life-Cycle Impact Assessment: The State of the Art*, Barnthouse et al., 1998;
133. SETAC Europe – *Evaluation and Reporting Guidelines for Life Cycle Assessment Case-Studies, Final Report*, 1997;
134. Sheard, S. A. and Lake, J. G. – *Systems Engineering Standards and Models Compared*, Proceedings of the 8th International Symposium on Systems Engineering (INCOSE), Vancouver, Canada, 1998;
135. Shikarpur, Deepak – *Knowledge-Based Engineering for Effective eManufacturing*, Express Computer, Indican Express Group, 2000;
136. Sindjou, Guy Bear - *Effect of Waste on End of Product Life Cycle*, Special Scientific Report #99-19, 1999 Summer Institute, National Science Foundation's (NSF) Tokyo Office, 1999;
137. Sinuany-Stern, Zilla et al. – *An AHP/DEA Methodology for Ranking Decision Making Units*, International Transactions in Operational Research, Vol. 7, Issue 2, 2000;
138. Snell, Michael – *Cost-Benefit Analysis for Engineers and Planners*, Thomas Telford Publications, London, 1997;
139. *SolidWorks 2001 Getting Started*, SolidWorks Corporation, USA, 1995-2001;
140. Spicer, Andrew & Wang, H. Michael – *Environmental Design Industrial Template: A Software Tool for Analysis of Product Retirement*, Journal of Cleaner Production, Vol. 5, No. 3, 1997;
141. Stevels, A.L.N.; Ram, A.A.P. & Deckers, E. – *Take-back of Discarded Consumer Electronic Products from the Perspective of the Producer. Conditions for Success*, Journal of Cleaner Production, Volume 7, Issue 5, 1999;
142. *Sustainability Counts*, Sustainable Development – the UK Government's Approach, 1999;

143. *The Basics of QFD*: http://www.iti-oh.com/cppd/qfd/qfd_basics.htm;

144. Tilman, Joe – *How to Create a Bill of Materials Using TurboCAD's Database*, August 2001;

145. Tilton, E. John – *The Future of Recycling*, Resources Policy, Vol. 25, 1999;

146. Tiwari, D.N.; Loof, R. & Paudyal, G.N. – *Environmental-Economic Decision-Making in Lowland Irrigated Agriculture Using Multi-Criteria Analysis Techniques*, Agricultural Systems, Volume 60, Issue 2, 1999;

147. Tukker, Arnold – *Life Cycle Assessment as a Tool in Environmental Impact Assessment*, Environmental Impact Assessment Review, No. 20, 2000;

148. Turban, Efraim & Aronson, E. Jay – *Decision Support Systems and Intelligent Systems*, Prentice-Hall International Inc., USA, 1998;

149. Turk, Ziga – *Semantic Representation of Product Modelling Data*, International Conference on the Management of Information Technology for Construction, Singapore, 1993;

150. Turney, B. B. Peter – *Activity Based Costing – The Performance Breakthrough*, Kogan Page Ltd., London, 1997;

151. United Nations Environment Programme & Society of Environment Toxicology and Chemistry, *The Life Cycle Initiative – UNEP/SETAC co-operation on Best Available Practice in Life Cycle Assessment (LCA)*, 2000;

152. US Coast Guard's Marine Safety and Environmental Protection – *Risk-Based Decision-Making Guidelines, Vol. 3: Procedures for Assessing Risk*, USA, 2002;

153. Vaillancourt, Kathleen & Waaub, Jean-Philippe – *Environmental Site Evaluation of Waste Management Facilities Embedded into EUGÈNE Model: A Multicriteria Approach*, European Journal of Operational Research, Volume 139, 2002;

154. Wathern, Peter – *Environmental Impact Assessment: Theory and Practice,* Biddles Ltd., UK, 1994;

155. Watkins, Thayer – *Introduction to Cost Benefit Analysis*, course notes, San Jose State University Economics Department, 2002;

156. *What is LCA?* Internet: http://144.213.211.8080/ecomat/LCA/whatis/about.htm;

157. *White Paper on Growth, Competitiveness, and Employment: The Challenges and Ways Forward into the 21st Century COM(93) 700 final*, the European Commission, Brussels, December 1993;

158. Wilson, R. Peter – *STEP and EXPRESS*, Workshop on Distributed Information, Computation and Process Management for Scientific and Engineering Environments, May 1998;

159. Wilson, R.M.S - *Cost Control Handbook*, Gower Press Ltd, UK, 1975;

160. Yücel, Adnan &Hunter, A. Keith – *Recommended Practices for AP 209*, USA, 1999;

161. Zobel, T. et al – *Identification and Assessment of Environmental Aspects in an EMS Context: an Approach to a New Reproducible Method Based on LCA Methodology*, Journal of Cleaner Production, No. 10, 2002.

APPENDIX A

Table A1. A preliminary set of indicators developed by the EIA methodology [Can96]

Biophysical environmental indicators:

1. CO_2 emissions
2. greenhouse gas emissions
3. SO_x emissions
4. NO_x emissions
5. use of water resources
6. river quality
7. wastewater treatment
8. land use changes
9. protected areas
10. use of nitrogenous fertilisers
11. use of forest resources
12. trade in tropical wood
13. threatened species
14. fish catches
15. waste generation
16. municipal waste
17. industrial accidents
18. public opinion

Social and economic environment indicators:

19. growth of economic activity
20. energy intensity
21. energy supply
22. industrial production
23. transport trends
24. private fuel consumption
25. population

APPENDIX B

Categories of electrical and electronic equipment covered by the WEEE Directive (Annex IA of the Directive) [WEEE02]

1. Large household appliances
2. Small household appliances
3. IT & telecommunication equipment
4. Consumer equipment
5. Lighting equipment
6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools)
7. Toys, leisure and sports equipment
8. Medical devices (with the exception of all implanted and infected products)
9. Monitoring and control instruments
10. Automatic dispensers

Products falling under the categories set out in Annex IA of the Directive [WEEE02]

1. Large household appliances

- Large cooling appliances
- Refrigerators
- Freezers
- Other large appliances used for refrigeration, conservation and storage of food
- Washing machines
- Clothes dryers
- Dish washing machines
- Cooking
- Electric stoves
- Electric hot plates

- Microwaves
- Other large appliances used for cooking and other processing of food
- Electric heating appliances
- Electric radiators
- Other large appliances for heating rooms, beds, seating furniture
- Electric fans
- Air conditioner appliances
- Other fanning, exhaust ventilation and conditioning equipment

2. Small household appliances

- Vacuum cleaners
- Carpet sweepers
- Other appliances for cleaning
- Appliances used for sewing, knitting, weaving and other processing for textiles
- Irons and other appliances for ironing, mangling and other care of clothing
- Toasters
- Fryers
- Grinders, coffee machines and equipment for opening or sealing containers or packages
- Electric knives
- Appliances for hair-cutting, hair drying, tooth brushing, shaving, massage and other body care appliances
- Clocks, watches and equipment for the purpose of measuring, indicating or registering time
- Scales

3. IT & telecommunication equipment

- Centralised data processing:
  - Mainframes
  - Minicomputers
  - Printer units
- Personal computing:

  - o Personal computers (CPU, mouse, screen and keyboard included)
  - o Lap-top computers (CPU, mouse, screen and keyboard included)
- Note-book computers
- Note-pad computers
- Printers
- Copying equipment
- Electrical and electronic typewriters
- Pocket and desk calculators

  and other products and equipment for the collection, storage, processing, presentation or communication of information by electronic means
- User terminals and systems
- Facsimile
- Telex
- Telephones
- Pay telephones
- Cordless telephones
- Cellular telephones
- Answering systems

  and other products or equipment of transmitting sound, images or other information by telecommunication

4. Consumer equipment

- Radio sets
- Television sets
- Videocameras
- Video recorders
- Hi-fi recorders
- Audio amplifiers
- Musical instruments

  and other products or equipment for the purpose of recording or reproducing sound or images, including signals or other technologies for the distribution of sound and image than by telecommunications

5. Lighting equipment

- Luminaires for fluorescent lamps with the exception of luminaires in households
- Straight fluorescent lamps
- Compact fluorescent lamps
- High intensity discharge lamps, including pressure sodium lamps and metal halide lamps
- Low pressure sodium lamps
- Other lighting or equipment for the purpose of spreading or controlling light with the exception of filament bulbs

6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools)

- Drills
- Saws
- Sewing machines
- Equipment for turning, milling, sanding, grinding, sawing, cutting, shearing, drilling, making holes, punching, folding, bending or similar processing of wood, metal and other materials
- Tools for riveting, nailing or screwing or removing rivets, nails, screws or similar uses
- Tools for welding, soldering or similar use
- Equipment for spraying, spreading, dispersing or other treatment of liquid or gaseous substances by other means
- Tools for mowing or other gardening activities

7. Toys, leisure and sports equipment

- Electric trains or car racing sets
- Hand-held video game consoles
- Video games
- Computers for biking, diving, running, rowing, etc.
- Sports equipment with electric or electronic components
- Coin slot machines

8. Medical devices (with the exception of all implanted and infected products)

- Radiotherapy equipment
- Cardiology
- Dialysis
- Pulmonary ventilators
- Nuclear medicine
- Laboratory equipment for in-vitro diagnosis
- Analysers
- Freezers
- Fertilization tests
- Other appliances for detecting, preventing, monitoring, treating, alleviating illness, injury or disability

9. Monitoring and control instruments

- Smoke detector
- Heating regulators
- Thermostats
- Measuring, weighing or adjusting appliances for household or as laboratory equipment
- Other monitoring and control instruments used in industrial installations (e.g. in control panels)

10. Automatic dispensers

- Automatic dispensers for hot drinks
- Automatic dispensers for hot or cold bottles or cans
- Automatic dispensers for solid products
- Automatic dispensers for money
- All appliances which deliver automatically all kind of products.

APPENDIX C

Conversion Factors for Environmental Impact Calculations

Table C1. Conversion factors for non-renewable primary energy input and CO_2-emissions [Mul01]

Energy purchased by an enterprise [1kWh]	Corresponding non-renewable primary energy input [kWh]	Corresponding CO_2-emissions based on primary energy input [kg]
Petrol (Oil)	1.30	0.095
Natural gas	1.27	0.069
Wood/biomass	0.07	0.0033
Coal	1.20	0.133
Electricity	3.07	0.14

Table C2. Calorific values of fuels [Han99]

Fuel	Calorific values [MJ/kg]
Coal	35
Wood	20
Petrol	45
Natural gas	38

Table C3. Characterisation factors for global warming emissions [Goe96], [Mul01]

Substance	Global Warming Potential [kg CO_2 equivalent per kg substance]
Carbon Dioxide (CO_2)	1
Methane (CH_4)	11
Nitrous Oxide (N_2O)	270
Sulphur Hexafluoride (SF_6)	23900
1,1,1-trichloroethane	100
CFC (hard)	7100
CFC (soft)	1600
CFC-11 (trichlorofluoromethane, Freon 11)	3400

CFC-113 (trichlorotrifluoroethane, Freon 113)	4500
CFC-114 (dichlorotetrafluoroethane, Freon 114)	7000
CFC-115 (chloropentafluoroethane, Freon 115)	7000
CFC-12 (dichlorodifluoromethane, Freon 12)	7100
CFC-13 (chlorotrifluoromethane, Freon 13)	13000
Dichloromethane	15
Trichloromethane	25
Tetrachloromethane	1300
Trifluoromethane (HFC-23)	11700
Difluoromethane (HFC-32)	650
Methyl fluoride (HFC-41)	150
1,1,1,2,2,3,4,5,5,5-decafluoropentane (HFC-43-10mee20.8)	1300
Pentafluoroethane (HFC-125)	3400
1,1,2,2-tetrafluoro-1,2-diiodoethane (HFC-134)	1000
1,1,1,2-tetrafluoroethane (HFC-134a)	1200
1,1-difluoroethane (HFC-152a)	150
1,1,2-trifluoroethane (HFC-143)	300
1,1,1-trifluoroethane (HFC-143a)	3800
1,1,1,2,3,3,3-heptafluoropropane (HFC-227ea)	2900
1,1,1,3,3,3-hexafluoropropane (HFC-236fa)	6300
1,1,2,2,3-pentafluoropropane (HFC-245ca)	560
Carbon tetrafluoride (perfluoromethane)	6500
Hexafluoroethane/Freon 116 (perfluoroethane)	9200
Octafluoropropane (perfluoropropane)	7000
Decafluorobutane (perfluorobutane)	7000
Cyclooctafluorobutane (perfluorocyclobutane)	8700
Dodecafluoro-pentane (perfluoropentane)	7500
Tetradecafluorohexane (perfluorohexane)	7400
HALON-1211 (bromochlorodifluormethane)	4900
HALON-1301 (bromotrifluoromethane)	4900
HCFC-123 (2,2-dichloro-1,1,1-	90

trifluoroethane)	
HCFC-124 (2-chloro-1,1,1,2-tetrafluorethane)	440
HCFC-141b (HCFC-141b d 1,1-dichloro-1-fluoroethane)	580
HCFC-142b (1-chloro-1,1-difluoroethane)	1800
HCFC-22 (chlorodifluoromethane)	1600

Table C4. Characterisation factors for ozone depleting emissions [Goe96]

Substance	ODP [kg CFC-11 equivalent per kg substance]
1,1,1-trichloroethane (methyl chloroform, vinyl trichloride)	0.12
CFC (hard)	1
CFC (soft)	0.055
CFC-11 (trichlorofluoromethane, Freon 11)	1
CFC-113 (trichlorotrifluoroethane, Freon 113)	1.07
CFC-114 (dichlorotetrafluoroethane, Freon 114)	0.8
CFC-115 (chloropentafluoroethane, Freon 115)	0.5
CFC-12 (dichlorodifluoromethane, Freon 12)	1
CFC-13 (chlorotrifluoromethane, Freon 13)	1
Halon 1201 (bromodifluoromethane)	1.4
Halon 1202 (dibromodifluoromethane)	1.25
Halon 1211 (bromochlorodifluoromethane)	4
Halon 1301 (bromotrifluoromethane)	16
Halon 2311	0.14
Halon 2401	0.25
Halon 2402 (1,2-dibromo-1,1,2,2-tetrafluoroethane)	7
HCFC-123 (2,2-dichloro-1,1,1-trifluoroethane)	0.02
HCFC-124 (2-chloro-1,1,1,2-tetrafluorethane)	0.022
HCFC-141b (HCFC-141b d 1,1-dichloro-1-fluoroethane)	0.11
HCFC-142b (1-chloro-1,1-difluoroethane)	0.065
HCFC-22 (chlorodifluoromethane)	0.055
HCFC-225ca (3,3-dichloro-1,1,1,2,2-pentafluoropropane)	0.025
HCFC-225cb (1,3-dichloro-1,1,2,2,3-pentafluoropropane)	0.033

Bromomethane (methyl bromide)	0.6
Tetrachloromethane (carbon tetrachloride)	1.08

Table C5. Characterisation factors for acidification emissions [Goe96]

Substance	Acidification Potential [kg SO_2 equivalent per kg substance]
Ammonia (NH_3)	1.88
Hydrochloric acid (HCl)	0.88
Hydrofluoric acid (HF)	1.6
Nitric oxide (NO)	1.07
Nitrogen dioxide (NO_2)	0.7
Nitrogen oxides (NO_x)	0.7
Sulphur dioxide (SO_2)	1
Sulphur oxides (SO_x)	1
Sulfuric trioxide (SO_3)	0.8
Nitric acid (HNO_3)	0.51
Sulfuric acid (H_2SO_4)	0.65
Phosphoric acid (H_3O_4P)	0.98
Hydrogen sulfide (H_2S)	1.88

Table C6. Characterisation factors for nutrient pollution [Ase97]

Substance	Weight Factor [kg phosphate equivalent per kg substance]
Phosphate (PO_4^{-3}) - water	1
Chemical oxygen demand (COD) - water	0.022
Ammonia (NH_3) - water	0.33
Ammonium ion (NH_4^+)- water	0.33
Total nitrogen (N_{tot}) - water	0.42
Total phosphorus (P_{tot}) - water	3.06
Nitrate (NO_3^-) - water	0.1

Table C7. Characterisation factors for hazardous substances [Goe96]

Substance	Weight Factor [kg Pb equivalent per kg substance]
Cadmium oxide – CdO (air)	50
Cadmium – Cd (air)	50
Mercury –Hg (air)	1
Manganese – Mn (air)	1
Lead – Pb (air)	1
Arsenic – As (air)	1

Boron – B (water)	0.03
Barium – Ba (water)	0.14
Cadmium – Cd (water)	3
Chromium – Cr (water)	0.2
Copper – Cu (water)	0.005
Mercury – Hg (water)	10
Manganese – Mn (water)	0.02
Molybdenum – Mo (water)	0.14
Nickel – Ni (water)	0.5
Lead – Pb (water)	1
Antimony – Sb (water)	2

Table C8. Characterisation factors for carcinogenic substances [Goe96]

Substance	Weight Factor [kg PAH equivalent per kg substance]
PAH (benzoapyrene)	1
Arsenic – As	0.044
Benzene – C_6H_6	0.000011
Chromium – Cr (6+)	0.44
C_xH_y aromatic	0.000011
Ethylbenzene	0.000011
Fluoranthene	1
Nickel – Ni	0.44
Tar	0.000011

APPENDIX D

The Algorithm for General Environmental Indicators Calculation

Preliminary Calculations

- *Non-renewable primary energy input*

Formula: $Energy = \sum_x E_x \times ECF_x$

where

E_x = quantity of energy of type x purchased by the processor during the month/year

ECF_x = energy conversion factor for energy of type x

x = type of energy purchased (electricity, coal, etc.)

For conversion factors see table C1 Appendix C. The unit for this indicator is kWh.

Note: The methodology permits calculation of energy no matter what measure unit is used by the processor who provides data. It can be converted automatically into energy units based on the calorific values of fuels (see table C2 Appendix C).

- *Greenhouse gas emissions to air*

Formula: $GHG = \sum_x GHG_x \times CF_x$

where

GHG_x = quantity of greenhouse gas of type x emitted during the month/year

CF_x = GHG conversion factor for greenhouse gas of type x

x = type of GHG

For conversion factors see tables C1 and C3 Appendix C. The unit for this indicator is kg CO_2 equivalent.

- *Ozone depleting substances emissions*

Formula: $ODS = \sum_{x} ODS_x \times CF_x$

where

ODS_x = quantity of ozone depleting substance of type x emitted during the month/year

CF_x = ODS conversion factor for ozone depleting substance of type x

x = type of ODS

For conversion factors see table C4 - Appendix C. The unit for this indicator is kg CFC-11 equivalent.

- *Acidification emissions*

Formula: $Acidification = \sum_{x} AE_x \times CF_x$

where

AE_x = quantity of acidification emissions of type x emitted during the month/year

CF_x = acidification potential for substance of type x

x = type of acidification emissions

For conversion factors see table C5 - Appendix C. The unit for this indicator is kg SO_2 equivalent.

- *Water nutrient pollution*

Formula: $Nutrientpollution = \sum_{x} WN_x \times CF_x$

where

WN_x = quantity of substance of type x eliminated into water during the month/year that produces eutrophication (nutrient pollution)

CF_x = nutrient pollution conversion factor for substance of type x

x = type of nutrient pollutant

For conversion factors see table C6 - Appendix C. The unit for this indicator is kg phosphate equivalent.

- *Hazardous substances eliminated into air*

Formula: $Hazardous/air = \sum_x HSA_x \times CF_x$

where

HSA_x = quantity of hazardous substance of type x eliminated into air during the month/year

CF_x = hazardous substance eliminated into air conversion factor for substance of type x

x = type of hazardous substance eliminated into air

For conversion factors see table C7 - Appendix C. The unit for this indicator is kg Pb equivalent.

- *Hazardous substances eliminated into water*

Formula: $Hazardous/water = \sum_x HSW_x \times CF_x$

where

HSW_x = quantity of hazardous substance of type x eliminated into water during the month/year

CF_x = hazardous substance eliminated into water conversion factor for substance of type x

x = type of hazardous substance eliminated into water

For conversion factors see table C7 - Appendix C. The unit for this indicator is kg Pb equivalent.

- *Carcinogenic substances emissions*

Formula: $Carcinogenic = \sum_x CS_x \times CF_x$

where

CS_x = quantity of carcinogenic substance of type x emitted during the month/year

CF_x = carcinogenic substance conversion factor for substance of type x

x = type of carcinogenic substance

For conversion factors see table C8 - Appendix C. The unit for this indicator is kg PAH equivalent.

Allocation of General Indicators to Products

- *Water consumption*

Formula: $$Water_{\Pr od.ij} = \sum_x \left(\frac{(EAR_{Water})_x}{\sum_j \sum_i NP_{ijx} \times DLH_{ijx}} \times DLH_{ijx} \right)$$

where

$(EAR_{Water})_x$ = Water consumption Allocation Rate per process (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product j = producer (brand)

x = process (cost centre) that product i brand j undergoes

DLH_{ijx} = direct labour hours per product of type i brand j per process (cost centre) x

- *Greenhouse gas emissions to air*

Formula: $$GHG_{\Pr od.ij} = \sum_x \left(\frac{(EAR_{GHG})_x}{\sum_j \sum_i NP_{ijx} \times MRH_{ijx}} \times MRH_{ijx} \right)$$

where

$(EAR_{GHG})_x$ = GHG Emissions Allocation Rate per process (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre) that product i brand j undergoes

MRH_{ijx} = machine running hours per product of type i brand j per process (cost centre) x

- *Ozone depleting substances emissions*

Formula: $ODS_{\Pr od.ij} = \sum_x \left(\frac{(EAR_{ODS})_x}{\sum_j \sum_i NP_{ijx} \times DLMRH_{ijx}} \times DLMRH_{ijx} \right)$

where

$(EAR_{ODS})_x$ = ODS Emissions Allocation Rate per process (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre) that product i brand j undergoes

$DLMRH_{ijx}$ = direct labour hours or machine running hours per product of type i brand j per process (cost centre) x

- *Acidification emissions*

Formula: $Acidification_{\Pr od.ij} = \sum_x \left(\frac{(EAR_{Acidification})_x}{\sum_j \sum_i NP_{ijx} \times DLMRH_{ijx}} \times DLMRH_{ijx} \right)$

where

$(EAR_{Acidification})_x$ = Acidification Emissions Allocation Rate per process (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost

j = producer (brand)

x = process (cost centre) that product i brand j undergoes

$DLMRH_{ijx}$ = direct labour hours or machine running hours per product of type i brand j per process (cost centre) x

- *Water nutrient pollution*

Formula: $NutrientPollution_{\Pr od.ij} = \sum_x \left(\frac{(EAR_{NutrientPollution})_x}{\sum_j \sum_i NP_{ijx} \times DLMRH_{ijx}} \times DLMRH_{ijx} \right)$

where

$(EAR_{NutrientPollution})_x$ = Water Nutrient Emissions Allocation Rate per process (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost

j = producer (brand)

x = process (cost centre) that product i brand j undergoes

$DLMRH_{ijx}$ = direct labour hours or machine running hours per product of type i brand j per process (cost centre) x

- *Hazardous substances eliminated into air*

Formula: $$Hazardous/air_{Prod.ij} = \sum_x \left(\frac{(EAR_{Hazardous/air})_x}{\sum_j \sum_i NP_{ijx} \times DLMRH_{ijx}} \times DLMRH_{ijx} \right)$$

where

$(EAR_{Hazardous/air})_x$ = Hazardous Emissions to Air Allocation Rate per process (calculated in previous section)

NP_{ijx} = number of products of type i brand j (producer) processed in the cost centre (process) x

i = type of product

j = producer (brand)

x = process (cost centre) that product i brand j undergoes

$DLMRH_{ijx}$ = direct labour hours or machine running hours per product of type i brand j per process (cost centre) x

- *Hazardous substances eliminated into water*

Formula:

$$Hazardous/water_{Prod.ij} = \sum_x \left(\frac{(EAR_{Hazardous/water})_x}{\sum_j \sum_i NP_{ijx} \times DLMRH_{ijx}} \times DLMRH_{ijx} \right)$$

where

$(EAR_{Hazardous/water})_x$ = Hazardous Emissions to Water Allocation Rate per process (calculated in previous section)

NP_{ijx} = number of products of type *i* brand *j* (producer) processed in the cost centre (process) *x*

i = type of product

j = producer (brand)

x = process (cost centre) that product *i* brand *j* undergoes

$DLMRH_{ijx}$ = direct labour hours or machine running hours per product of type *i* brand *j* per process (cost centre) *x*

- *Carcinogenic substances emissions*

Formula: $$Carcinogenic_{\Pr od.ij} = \sum_x \left(\frac{(EAR_{Carcinogenic})_x}{\sum_j \sum_i NP_{ijx} \times DLMRH_{ijx}} \times DLMRH_{ijx} \right)$$

where

$(EAR_{Carcinogenic})_x$ = Carcinogenic Substances Emissions Allocation Rate per process (calculated in previous section)

NP_{ijx} = number of products of type *i* brand *j* (producer) processed in the cost centre (process) *x*

i = type of product

j = producer (brand)

x = process (cost centre) that product *i* brand *j* undergoes

$DLMRH_{ijx}$ = direct labour hours or machine running hours per product of type *i* brand *j* per process (cost centre) *x*