

ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF POTABLE WATER PRODUCTION

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Submitted in fulfillment of the academic requirements for the degree of Master of Science in Engineering in the School of Chemical Engineering, University of Natal

Durban
December 2001

ABSTRACT

This study investigates and compares the environmental burdens of two different methods for producing potable water by using the environmental life cycle assessment (LCA). The first method, for the production of potable water, is used by Umgeni Water at their Wiggins Waterworks and it involves conventional processes. The second method is based on a South African membrane technology and currently it is used in three pilot plants around the country.

The life cycle concept gives the means to understand the environmental impacts associated with a product, process or activity by considering all life-cycle stages, from *cradle-to-grave*. Formal methodologies for conducting such studies have been developed and in this project the methodological framework endorsed by the International Organisation for Standardisation (ISO) 14040 series of standards has been used.

By using this methodology and by tracing all processes involved in the production of potable water, it was found that the main contribution towards the environmental burdens of potable water is due to electricity generation. This conclusion is valid for both methods investigated, and as a result the recommendations focus on increasing the energy efficiency of waterworks in order to increase their overall environmental performance.

I dedicate this work to my mother Paraschiva and to my father Petru, may he rest in peace.

Motto

“Man shapes himself through decisions that shape his environment”

(Rene Dubos)

PREFACE

Since my undergraduate years I have had a keen interest in the development and application of environmental tools for industry and business, and I saw this pioneering study as a challenge to contribute to such developments. I hope this thesis will offer some guidance and will be a good reference on how an environmental management tool, the environmental life cycle assessment is applied in the local context.

The research work for this thesis was carried out in the University of Natal's School of Chemical Engineering, Pollution Research Group, under the supervision of Professor Christopher Buckley and it was funded by the Water Research Commission of South Africa.

This thesis is my own work, unless otherwise indicated in the text.

ACKNOWLEDGEMENTS

I want to thank all the people who helped me in this research by giving some of their precious time, information and advice.

Special thanks go to my supervisor Professor Christopher Buckley for his advice and encouragement, to Professor Henrik Wenzel and Professor Michael Overcash for sharing data and their expertise and to my husband Holger Friedrich for his proofreading, discussions and patience.

The financial support of this research from the Water Research Commission of South Africa and from the University of Natal is gratefully acknowledged.

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LIST OF ABBREVIATIONS

APME	Association of Plastic Manufacturers in Europe
BS	British Standard
BUWAL	Bundesamt fuer Umwelt, Wald und Landschaft, Switzerland
CFC	Chlorofluorocarbons
CML	Center for Environmental Science, University of Leiden, The Netherlands
DAF	Dissolved Air Flotation
DCB	1, 4 Dichlorobenzene
DE	Germany
EDIP	Environmental Design of Industrial Products
EF	Equivalency Factors
EIA	Environmental Impact Assessment
EMAS	Eco-Management and Audit Scheme (EU)
EPA	Environmental Protection Agency (USA)
EPS	Environmental Priority System
EU	European Union
HTH	Calcium Hypochlorite
IKP	Institut fuer Kunststoffkunde und Kunststoffprueffung, University of Stuttgart
IPCC	Intergovernmental Panel on Climatic Change
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LC ₅₀	Lethal Concentration for 50% of the organisms in a test
NASA	National Aeronautics and Space Administration (USA)
NEP	Nordic Environmental Sound Product Development
NGO	Non-governmental Organisation
NOAA	National Oceanic and Atmospheric Administration (USA)
NOEC	No Observed Effect Concentration
OD	Outer Diameter
PE	Polyethylene
PEMS	Pira's Environmental Management System
PLA	Product Line Analysis
POCP	Photochemical Ozone Creation Potential

polyDADMAC	Poly-diallyldimethylammonium Chloride
PVC	Polyvinyl Chloride
REPA	Resource and Environmental Profile Analysis
RER	Country Code for Europe in the SPOLD System
SA	South Africa
SABS	South African Bureau of Standards
SETAC	Society of Environmental Toxicology and Chemistry
SPOLD	Society for the Promotion of Life Cycle Assessment Development
THM	Trihalogenated Methane
UCT	University of Cape Town
UKDoE	United Kingdom Department of Environment
UNEP	United Nation Environmental Programme
USA	United States of America
USES	Uniform System for the Evaluation of Substances
VOC	Volatile Organic Compounds
WCED	World Commission on Environment and Development (UN)
WMO	World Meteorological Organisation

CHAPTER 1

INTRODUCTION

This chapter addresses three issues believed to be important in introducing this research. Firstly, it contains an introduction to the study, secondly it states clearly the aims and objectives of this research and thirdly it gives an overview of this thesis with regard to structure and presentation.

1.1 Introduction to the Study

In South Africa potable water is one of the most valuable resources and as a result much work has gone into establishing and achieving environmental quality in the process of obtaining this water. Each of the individual processes used in the production of potable water has associated environmental burdens. To provide a holistic perspective on these burdens, as well as to identify areas where further improvement is possible, an environmental decision-making tool - the life-cycle assessment (LCA) - has been introduced. The life cycle concept gives the means to understand, manage and reduce the environmental impacts associated with a product, process or activity by considering all life-cycle stages, from *cradle-to-grave*. The LCA methodology enables the calculation of environmental burdens in a systematic and scientific way, allowing comparisons on environmental grounds. It also allows the identification of areas where environmental improvement is achievable and where it will give the best results.

This study compares the environmental burdens resulting from two different methods used in the production of potable water. The first one is the *conventional method* and is currently employed at Wiggins Waterworks, a waterworks of Umgeni Water situated in Durban, South Africa. The main processes involved are preozonation, addition of chemicals, flocculation, sedimentation, filtration, ozonation, chlorination and storage. The second method is based on the use of a South African *membrane filtration* technology, and the following processes are involved: prefiltration, membrane filtration, chlorination (different to the previous method) and storage. There are three pilot plants employing this membrane technology in South Africa. For the conventional method this LCA study identifies the main contributions to the overall burdens, focusing on areas for improvement. For the membrane method of producing potable water, this LCA study, besides identifying the main environmental contributions, may guide further development of the technology in order to improve its environmental performance.

The environmental impact categories, on which the environmental performance of the two methods of producing potable water are compared, include global, regional and local impacts.

The impact categories are enumerated as follows: global warming, stratospheric ozone depletion, photochemical ozone formation, acidification, nutrient enrichment, ecotoxicity and human toxicity. An inventory of all inputs and outputs for the production of potable water by the two methods was prepared. This was followed by a quantification of the contributions by the two methods to each of the environmental impact categories. The inputs from processes involved in the production of water include energy inputs and raw material inputs. The outputs include products, by-products and emissions to air, water and soil. To relate the different life spans of the various inputs (e.g. tanks, pumps, pipes) for the production of potable water as well as to allow comparison between the two methods, a functional unit is used. For this study the functional unit is the production of one kilolitre (kL) of water to the quality specified by Umgeni Water for potable water.

Formal LCA methodologies (as presented in the ISO 14040 series of standards) guided this study and these methodologies produce a score for each environmental theme. The methodologies involved and the results obtained are presented in detail and the environmental performances for each of the impact categories are compared for the two methods. Areas of intervention for environmental improvement have been detected and measures for improvement are recommended.

1.2 The Objectives and Aims of the Study

The overall objective of this study is to generate information on the environmental life cycle of water treatment processes used in the production of potable water. This study also intends to identify the improvement potentials for these processes and to compare the environmental burdens of conventional water treatment processes with those of a treatment method involving membranes. As a result, the specific aims of the study are defined as follows:

- to calculate the full life cycle environmental consequences of selected treatment processes and methods and to present them to decision-makers involved in this field,
- to highlight areas for improvement of the environmental performance of the selected water treatment methods, and
- to alert the water industry to the benefits of using full life cycle assessment in the selection of processes and methods.

Therefore the specific objectives of the study are:

- to conduct life cycle assessments for one conventional and one membrane water treatment method, and
- to compare the environmental burdens associated with each process.

1.3 The Structure and Presentation of the Thesis

This thesis is presented in a style designed to allow a logical understanding of the study and to minimise repetition. This was necessary because in structuring this thesis two sets of rules had to be taken into consideration. The first set is related to the academic presentation requirements and the second one to the requirements set by the standardised (ISO 14040) life cycle assessment methodology.

Following the introduction, **Chapter 2** gives the background to environmental life cycle assessment. It presents the paradigm in which it emerged, followed by the definition, history, components, applications and limitations of environmental life cycle assessments.

Chapter 3 provides the background information for the two methods of producing potable water used in this study. Technical data about individual processes making up these methods are included in this chapter.

Chapter 4 highlights the different stages of this study and the methodologies associated with each stage. Assumptions and limitations are also presented as well as problems encountered in the research process.

Chapter 5 presents the research results and provides an analysis of these results for each of the two methods investigated. A comparison of the results from the two methods is also presented.

Chapter 6 is the concluding chapter and summarises the findings of this research and attempts to provide recommendations to improve the environmental performance for the production of potable water.

There are 15 appendices accompanying this thesis and they provide supporting information.

CHAPTER 2

BACKGROUND TO ENVIRONMENTAL LIFE-CYCLE ASSESSMENT (LCA)

*Industry has the power to enhance or degrade the environment; it inevitably does both
(Our Common Future, 1987)*

It was in the early 1960's when environmental concerns became a matter of public interest and strong environmental movements and ideologies were born. Since then, issues like air pollution, water contamination, toxic wastes, oil spills, acid rain, global warming, the ozone hole, desertification, deforestation and soil erosion have attracted the attention of environmentalists, researchers, policy makers and the public.

This chapter introduces some of the environmental initiatives and concepts developed in response to the environmental problems enumerated above and emphasises the environmental tools developed for industry. In particular, it presents the environmental life-cycle assessment as a management tool with its definitions, history, methodological framework, applications and limitations.

2.1 Impacts on the Environment due to Industry

Industrial growth is seen as the engine for economic development and an important component for the economic welfare of society, by providing employment and creating wealth. Industrial growth is interlinked with growing consumerism and growing populations, and it was demonstrated that besides other human activities, industry and business have a share in causing or exacerbating some of the environmental problems enumerated above. Industry contributes to environmental degradation through the inputs and the outputs resulting from its functioning (Park and Labys, 1998). The manufacturing of goods implies the extraction and exploitation of natural resources, used as inputs in various processes. A variety of raw materials are used such as minerals, water, wood, fossil fuels etc., and the depletion of these resources can cause serious environmental problems. Industry is one of the biggest consumers of energy and energy generation is associated with environmental issues like air pollution, global warming and acid rain. On the output side, industrial processes generate, besides useful products and by-products, emissions (gaseous, liquid and solid) to air, water bodies and soil. These emissions cause air pollution, soil pollution, pollution of surface and underground water and can create serious public hazards. In addition, aspects such as industrial safety, risk of accidents, exposure to toxic substances and risk in the workplace have to be considered in all industrial processes (Park and Labys, 1998).

There is a direct relationship between the growth of the global economy and the consumption of resources and the production and release of pollutants. In the last hundred years the world's industrial production has increased more than 100-fold and for the same period the rate of global consumption of fossil fuels has increased by a factor of 50 (Graedel and Allenby, 1995). Global carbon dioxide emissions due to fossil fuel burning, cement production and gas flaring increased from 500 million tons at the beginning of the century to about 6 000 million tons in 1994 (Graedel and Allenby, 1995). Over 100 000 synthetic industrially produced chemicals have been registered over the last few decades in the European Union alone, and very little is known about their behaviour in the environment (Wenzel et al., 1997). These are a few statistics illustrating the magnitude and the relatively short time over which industrial activities have gained momentum.

2.2 Environmental Initiatives and Concepts

In response to the environmental problems presented above, there have been numerous initiatives to slow environmental degradation and to shift economic activity towards a more sustainable pattern.

2.2.1 The Concept of Sustainable Development

The term sustainable development originated in the 1970s and it has become widely accepted in both developed and developing countries. It is generally seen as the new paradigm that should direct further development and industrial growth. Ideas around sustainable development emerged first at the United Nations Conference on the Human Environment (Stockholm, 1972). These ideas were further crystallized throughout the 1970s and 1980s in a series of international initiatives, like the World Conservation Strategy and the United Nations World Commission on Environment and Development (WCED). The commission's report *Our Common Future* (also called the Brundtland report) presents the most widely accepted definition of sustainable development: *development which meets the needs of the present generation without compromising the ability of future generations to meet their own needs* (Our Common Future, 1987). In 1992 another United Nations initiative, the Rio Summit, focussed on the goals of sustainable development and through its subsequent treaties directed the implementation of the concept in practice. In particular, Agenda 21 provides a list of activities that should be followed if sustainable development is to be implemented.

Agenda 21 sets a series of objectives for industry to follow. These objectives are:

- *Promoting cleaner production – governments, business and industry including transnational corporations should aim to increase the efficiency of resource utilisation, including increasing the reuse and recycling of residues, and to reduce the quantity of waste discharge per unit of economic output*
- *Promoting responsible entrepreneurship through:*
 1. *encouraging the concept of stewardship in the management and utilisation of natural resources by entrepreneurs*
 2. *increasing the number of entrepreneurs engaged in enterprises that subscribe to and implement sustainable development policies (Earth Summit '92, Agenda 21, 1992)*

In order to help and direct the implementation of the concept of sustainability, these general objectives have been made more specific through a series of initiatives which developed different environmental tools for industry to use in their day to day functioning.

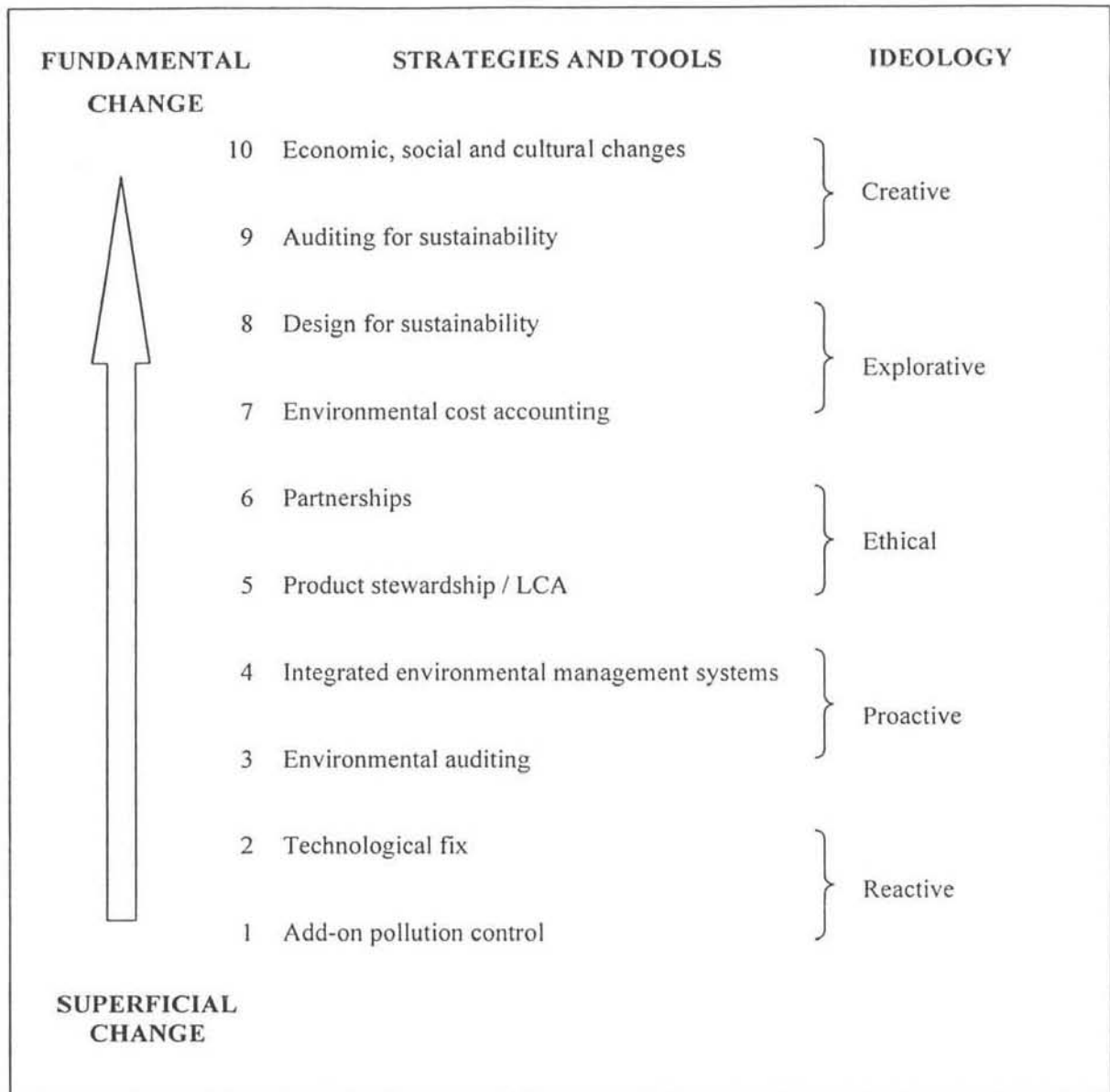
2.2.2 The Practical Implementation of the Concept of Sustainable Development

Cleaner production is one of the core concepts in implementing sustainable development for industry and business. The United Nations Environmental Programme (UNEP) defines cleaner production as:

the continuous application of an integrated preventative environmental strategy applied to processes and services to increase overall efficiency and reduce risks to humans and the environment.

- *Production processes: conserving raw materials and energy, eliminating toxic raw materials, and reducing the quantity and toxicity of all emissions and wastes.*
- *Product: reducing negative impacts along the life cycle of a product, from raw materials extraction to its ultimate disposal.*
- *Services: incorporating environmental concerns into designing and delivering services (UNEP Website).*

With regard to the implementation of the concept of sustainability in practice, Welford (1995) presents a scale and a *spectrum of greening* applicable to industry and business. **Figure 2.1** shows an adaptation of this spectrum. With regard to the ideologies and strategies presented by Welford in his spectrum, the first six strategies (part of reactive, proactive and ethical ideologies) currently dominate. The last four strategies (explorative and creative) have still to be defined and are presented as future developments.



Source: modified after Welford (1995)

Figure 2.1: Welford's Spectrum of Greening

In order to improve the environmental performance of industry as a whole and of individual companies in particular, many new environmental tools have been developed in accordance with the ideologies and strategies presented. Some of these environmental tools like environmental management systems, environmental auditing and life-cycle assessments are mentioned in Welford's *spectrum of greening*, however, others like environmental impact assessment and risk assessment are left out on his scale.

Table 2.1 presents a few details about the environmental tools developed and used by companies to achieve environmental improvement. Some of these tools (i.e. environmental impact assessments) are mandatory in South Africa. Other environmental tools are not mandatory but are widely used due to the perceived benefits for a company. Examples of such tools are environmental auditing and environmental management systems.

Table 2.1: Environmental Tools Used by Companies

Environmental Tool	Short Description	Mandatory in South Africa
Environmental Auditing (ISO 9000 and BS 7750)	Creates awareness of environmental problems by highlighting direct environmental impacts.	No
Environmental Impact Assessment (EIA)	Highlights environmental problems associated with a particular development, project or site. Presents mitigation options. There are guidelines on conducting EIAs.	Yes
Environmental Management Systems (ISO 14000, BS 7755 and EMAS)	Involves four steps: reviewing performance, setting improvement targets, acting to meet targets and auditing to check if targets have been achieved. It should improve the environmental performance of a company with each cycle.	No
Environmental Life Cycle Assessment	Determines environmental burdens associated with a product, process or activity over its entire life cycle.	No
Specific Hazard or Risk Assessment	Determines the probability of any regular or accidental negative impact at a specific site, during a specific time period and due to specific causes.	No
Substance Flow Analysis	Answers questions related to one resource or substance in an industrial system (process, factory, etc.) by using a materials balance analysis.	No
Social Assessment	Highlights social aspects associated with a particular development, location or environmental problem. Fosters dialog with surrounding communities and interested and affected parties.	Yes, as part of an EIA

From these tools, the environmental life cycle assessment is the only one which allows for a cradle-to-grave approach. This approach is important in the industrial context because industrial activities and processes are not separated from the environment and from each other. They are interlinked in an elaborate web. A collection of operations that together perform a given function (like the manufacture of a specific product) forms a system and LCA is the only environmental tool which is capable of considering all the components of this system from an environmental point of view (Curran, 1996).

2.3 The Environmental Life Cycle Assessment as a Holistic Environmental Tool

Most products and activities require a variety of production, distribution, use and disposal activities. Each of these activities will require certain raw materials and produce certain emissions which will have specific impacts and effects on the environment. The life cycle assessment (LCA) is an environmental tool dealing with the complex interaction between the environment and a product or activity, taking into account all the impacts due to the use of raw materials and all the emissions produced.

2.3.1 Definition of Environmental Life Cycle Assessment

A LCA is a tool in which environmental burdens associated with a product, system or activity are documented and evaluated. It is considered the *only environmental assessment tool which avoids positive ratings for measurements which only consists in the shifting of burdens* (Kloepfer, 1997). A detailed LCA is a complex process and in the literature there are many definitions capturing one or more of its theoretical or methodological aspects. One of the most comprehensive definitions of LCA is proposed by Lindfors et al. (1995):

LCA is a process to evaluate the environmental burdens associated with a product system, or activity by identifying and quantitatively describing the energy and materials used, and wastes released to the environment, and to assess the impacts of those energy and material uses and releases to the environment. The assessment includes the entire life cycle of the product or the activity, encompassing extracting and processing of raw materials; manufacturing; distribution; use; maintenance; recycling and final disposal; and all transportation involved. LCA addresses the environmental impacts of the system under study in the areas of ecological systems, human health and resource depletion. It does not address economic or social effects.

In the South African Bureau of Standards (SABS) and the International Organisation for Standardisation (ISO) 14040 standard (1997), the definition of LCA is given as follows:

LCA is 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 system,*
- *evaluating the potential 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.*

LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The

general categories of environmental impacts needing consideration include resource use, human health and ecological consequences.

Figure 2.2 presents a graphical representation of an overview of the LCA process.

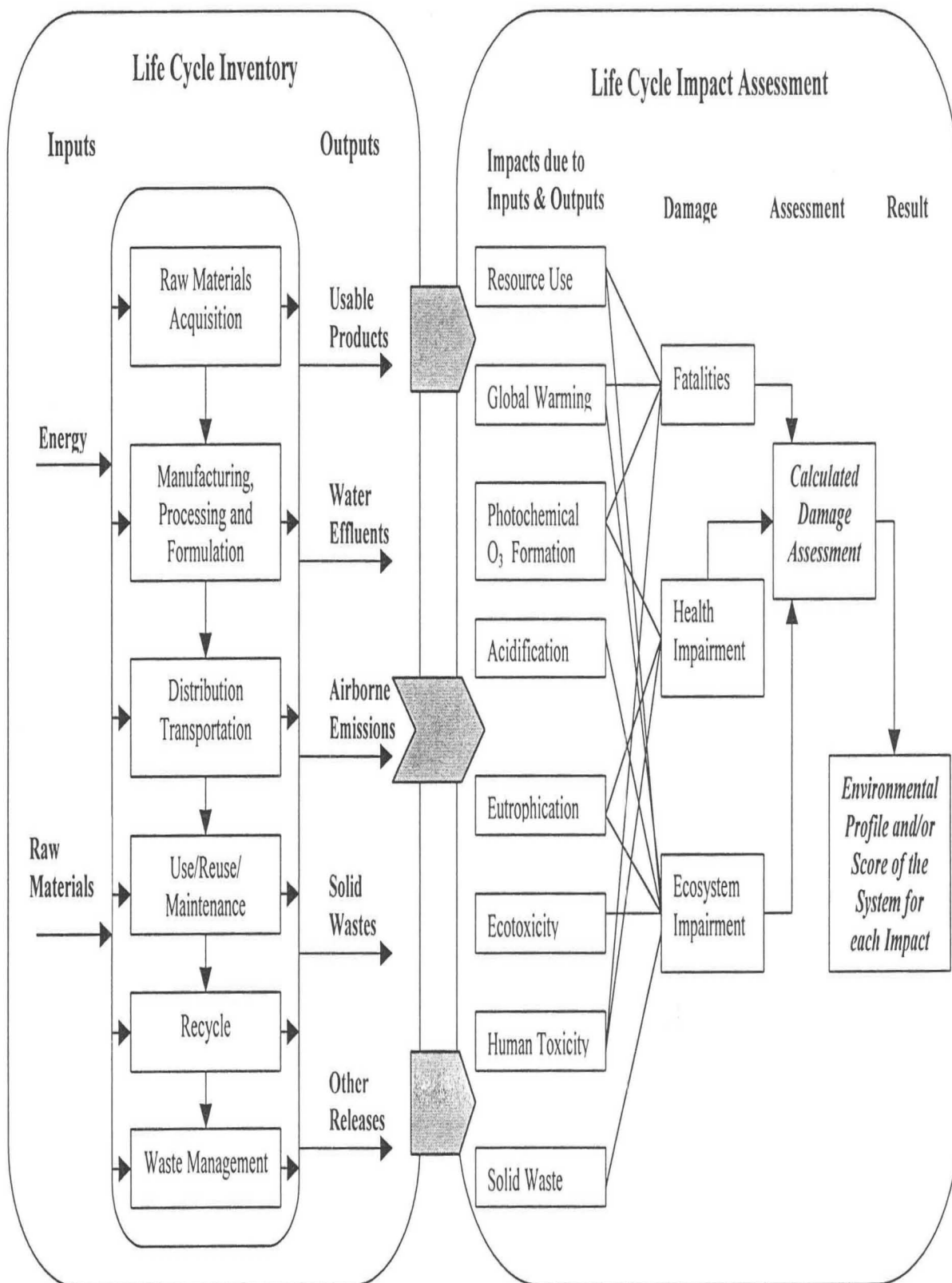
2.3.2 History of LCA

It is believed (Frischknecht, 1993 and Weidema, 1997) that the concept of life cycle inventory was first brought up in 1884 by the Scottish economist Patrick Geddes. He looked at the increasing use of coal as a non-renewable resource and focused on possible efficiency improvements in the life cycle of the process chain (Weidema, 1997).

The early beginnings of modern LCA can be traced back to the 1960s and the studies of this period dealt with issues such as energy efficiency, consumption of raw materials and to a lesser degree with waste production or disposal of waste materials (Curran, 1996 and Weidema, 1997). The focus of these early studies was mainly on material inventory and therefore quantitation was of great importance (material and energy balances).

In 1969 the Coca-Cola Company initiated and funded a study by the Midwest Research Institute to compare and determine which container had the lowest release to the environment and the lowest consumption of material resources (Weidema, 1997). The process of quantifying the resource use and the environmental release became known as Resource and Environmental Profile Analysis (REPA) and in the early 1970s a series of such studies were conducted in the USA and Europe. Especially energy studies gained momentum during this period because of the oil crisis. However, in the late 1970s and early 1980s interest in LCA type of studies declined and only a few specialists, mainly in the academic world, continued LCA activities (Kloepffer, 1997).

It was in the late 1980s with the growing environmental crisis that interest in LCA type of studies was revived, and since then the area of application of LCA has grown continuously, including industries, planners, design establishments, government agencies, retailers, consumers, etc. It was at the beginning of this revival stage when different LCA methodologies were developed, and focus was shifted beyond compiling inventories to including more detailed analyses of impacts and potential impacts due to resource consumption and the emissions produced (Weidema, 1997). Quantitation was and still is important and it continues to grow, especially with the development and release of the first extensive databases, which were made publicly available (the first one (BUWAL) in Switzerland in 1984).



Source: modified from SETAC, 1997 and Wenzel et al., 1997

Figure 2.2: Environmental Life Cycle Assessment - An Overview

Parallel to the quantitative inventory approach, a broader qualitative tradition developed in Germany under the name *Produkt-Linien-Analyse* (Product Line Analysis or PLA). PLA is considered to be an ambitious approach because it includes a comprehensive choice of parameters including social and economical aspects (Weidema, 1997).

In the 1990s, a series of national projects were initiated in order to develop consistent and simple methods, especially for product development. These initiatives are: the product ecology project (Sweden) leading to the EPS (Environmental Priority System) method, the United States Environmental Protection Agency (US EPA) life cycle design project, the NEP (Nordic Environmental Sound Product Development) project in Norway and Sweden, the National Reuse of Waste Research Programme (NOH) methodology in the Netherlands and the Environmental Design of Industrial Products (EDIP) project in Denmark (Weidema, 1997). This evolution, together with the growing number of practitioners, lead to a rapid diversification of the LCA methodology to the point where different studies for the same product gave different results because of different methodologies. In this context it became obvious that the LCA had to be standardised and by the mid 1990's a series of guidelines were produced, like SETACs *Code of Practice* (Consoli et al., 1993), *US EPA Guidelines* (Vigon et al., 1993) and the *Nordic Guidelines on Life-Cycle Assessment* (Lindfors et al., 1995).

The Society of Environmental Toxicology and Chemistry (SETAC) and especially its European branch shaped the development of LCA through a series of workshops and publications which in the early 1990's set the conceptual and methodological basis for the LCA structure. This structure was further refined and improved by work done for the Nordic Council of Ministers, individual contributions from different research centers and universities, work for the International Organisation for Standardisation (ISO), especially the ISO 14040s series and the Society for the Promotion of Life Cycle Assessment Development (SPOLD). Of special importance are the ISO 14040s series of LCA standards since they are based on widespread consensus from within the LCA community.

2.3.3 Overview of the LCA Methodology

Over time different ways of conducting LCAs and different levels of sophistication of the LCA methodology have emerged. As a result a series of guidelines aimed at developing a consistent approach have been produced. The ISO 14040 series of standards (ISO 14040, 14041, 14042 and 14043) are such an initiative and this study tries to follow the methodological procedures laid out in the ISO documents. This section is an overview of the main steps to be undertaken in

an LCA study, in addition **Appendix 1** presents a much more detailed methodological framework.

ISO 14040 (1997) sets the four phases, which have to be part of a LCA as follows: goal and scope definition, inventory analysis, impact assessment, and interpretation. Each of these four phases will be briefly presented.

2.3.3.1 Goal and Scope of the Study

The first step in an LCA study is the goal and scope definition. Defining the **goal** of the study should address issues like intended applications, reasons for doing the study and the intended audience. In addition, the initiator should be mentioned (Heijungs et al., 1992). Under **scope** of the study the ISO documents recommend the following issues be considered and defined: the function of the product system, or, in the case of comparative studies, the systems; the functional unit; the product systems boundaries; allocation procedures; data requirements; assumptions; limitations; type of critical review, if any; and type and format of the report required for the study. From this array of issues special attention has to be given to the functional unit because it provides a reference to which the input and the output data in the inventory phase will be related. In comparative studies like this one it sets the scale for comparison (Jensen et al., 1997). The functional unit of this study is defined as 1 000 kg of potable water at the quality stipulated in the Umgeni Water guidelines (see **Appendix 2**) produced over the life period of a process unit.

The system boundaries are another important issue and decisions on what should be included and what should be excluded will influence data collection. In the literature (Lindfors et al., 1995; Wenzel et al., 1998, and others) there are a series of cut-off rules and they all include a certain degree of subjectivity. It is also recommended to draw a process tree (or flow diagram) when establishing boundaries since it gives a better overview of the system (Heijungs et al., 1992 and Guinee et al., 1998).

2.3.3.2 Inventory Analysis

The **inventory analysis** involves data collection and calculation procedures to quantify relevant inputs and outputs of a process. Process inputs can be divided into two categories: environmental inputs (raw materials and energy resources) and economic inputs (products, semi-finished products or energy - they are outputs from other processes). Similarly there are two kinds of outputs: environmental outputs (emissions to air, water, soil) and economic outputs

(products, semi-finished products or energy). Conducting an LCA is an iterative process and **Figure 2.3** presents the main steps involved in producing an LCA inventory.

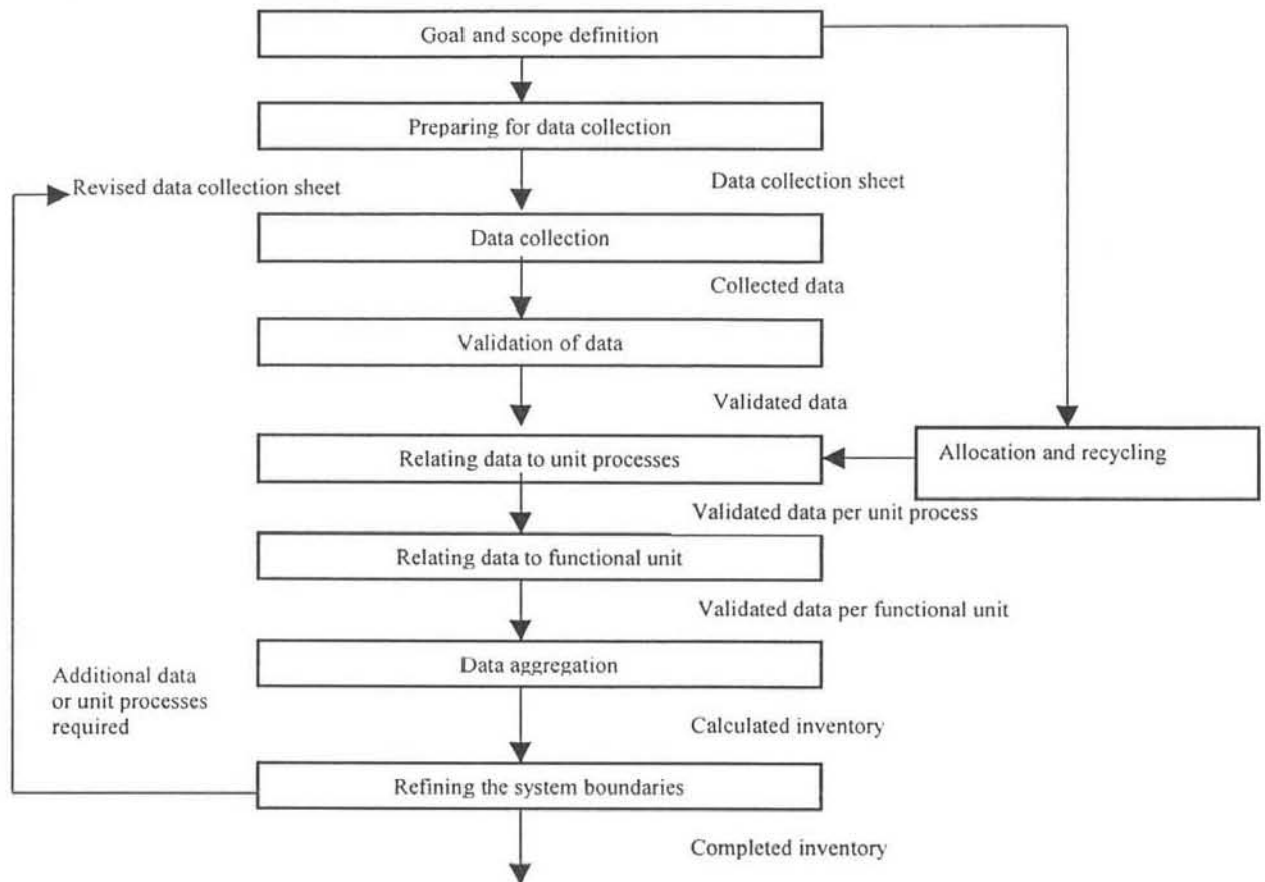


Figure 2.3: Simplified Procedures for Inventory Analysis (Source: ISO 14041)

For each of the processes included in the system (and presented in the flow diagram) all the process inputs and process outputs have to be established and quantified. This step requires good knowledge about each of the processes included and is in most cases the most work intensive part of an LCA study. If quantitative data are not obtainable for some of the processes in the system then qualitative data have to be used. For very detailed studies site specific data are sought, however, in most cases regional or country specific data are considered good enough. More general data can be obtained from trade organisations, public surveys, manufacturers associations, etc., and in reality most of the studies published so far use a combination of site specific and general data.

Usually at this stage, in this type of study, an LCA software package with an inventory database and calculation facilities is used. **Appendix 3** presents a list of LCA software currently available, for more details on individual packages consult Rice et al., 1997. For this project the GABI 3 software was used. It contains data from two European databases: APME (Association

of Plastic Manufactures in Europe) and BUWAL (Bundesamt fuer Umwelt, Wald und Landschaft – the Swiss Environmental Protection Agency) plus some data on processes from the IKP (Institut fuer Kunststoffkunde und Kunststoffprueffung) University of Stuttgart, the initial developers.

All the inputs and outputs from all the processes included in the system are related to the functional unit and together they form the inventory list for that particular system. This inventory list is the input to the next phase of the LCA, which is the impact assessment.

2.3.3.3 Impact Assessment

The **impact assessment** is the third phase of an LCA and its aim is to evaluate the significance of the potential impacts resulting from the inputs and outputs summarised in the inventory list. It is also aimed at reducing the complexity and volume of the inventory data by translating these data into contributions to relevant environmental problems. According to the ISO 14042 document (2000) there are mandatory and optional elements to this phase. The following elements are considered mandatory: selection of impact categories, category indicators and characterisation models (also referred to as category definition); assignments of inventory results to the impact category (classification) and calculation of category indicator results (characterisation). Optional elements are normalisation (calculation of the magnitude of category indicators results relative to reference information), grouping, weighting and data quality analysis. Another term used in the literature for weighting is valuation and in some studies normalisation is merged with valuation.

i) Category definition involves establishing the environmental impact categories for the study. Therefore, it states the environmental problems towards which the contributions from a system should be investigated. These categories have to be chosen in accordance with the goal and scope of the study in order to describe all the impacts caused by the processes under consideration. Lindfors et al. (1995) suggests a few issues to be taken into consideration when choosing environmental impact categories. These issues are:

- completeness (all relevant environmental problems should be covered),
- practicality (it is not practical to have too many categories),
- independence (mutually independent categories should be selected to avoid double counting of impacts – e.g. nitrogen oxides contributing to both acidification and nutrification) and
- relation to the characterisation step (for the categories selected there should be characterisation models available for the next step of the impact assessment).

The most important impact categories used in the literature are enumerated as follows:

- abiotic resource consumption,
- biotic resource consumption (sometimes referred to as renewable and non-renewable resources),
- land use,
- global warming potential,
- stratospheric ozone depletion potential,
- photochemical oxidant formation potential,
- ecotoxicological impacts (aquatic and terrestrial),
- human toxicological impacts,
- acidification potential,
- eutrophication potential,
- waste (sometimes a special category, hazardous waste, is defined) and
- work environment.

Not all categories have to be used in an LCA. In the present study, for example, land use is of less relevance. The software used also influences the choice of categories. Some LCA software tools have predefined categories; however, others allow the researcher to define their own category system. The GABI 3 software tool has predefined categories.

ii) Classification is the process by which inventory input and output data are assigned to the categories chosen. Some of the outputs (e.g. NO_x) contribute to more than one category and therefore such outputs have to be counted for each category once. Double or triple counting is acceptable if the effects are independent of each other, whereas double counting of different effects in the same effect chain (e.g. stratospheric ozone depletion and toxicological effects like skin cancer) is not permitted. Formal rules exist for the different methods.

From a geographical perspective, the impact categories are divided into global, regional and local impact groups. Some outputs, however, contribute to all three levels.

iii) The aim of the characterisation process is to aggregate all the effects in a particular impact category in order to obtain a single score for each impact category defined previously. For this purpose characterisation factors are used. These factors have been derived scientifically and may change with scientific progress. For example, suppose that in the impact category global warming there are two substances (carbon dioxide and nitrous oxide) contributing to this effect. Scientifically it was established that for a timeframe of 100 years, 1 kg of nitrous oxide will produce an effect 310 times higher than 1 kg of carbon dioxide (Hauschild and Wenzel, 1998).

Therefore, 1 kg of nitrous oxide will produce an effect equal to 310 carbon dioxide equivalents and the characterisation factor is 310. Once all substances in the category of global warming are expressed as carbon dioxide equivalents (the reference substance), these can be summed up resulting in a single score for global warming. All the impact categories use characterisation (or equivalency) factors. The total score for each impact category is obtained by multiplying the amount of each substance (classified in that category) by its characterisation factor (expressed in relation to a reference substance) and by adding up all individual scores within an impact category. For most of the impact categories there is consensus regarding characterisation factors and reference substances, however, for human and ecological toxicity, biotic resource consumption and land use such consensus does not exist and different methods have been used by different LCA practitioners. Consensus was and probably will not be possible for these issues because of the complex mechanisms between cause and effect (e.g. different toxicity levels of the same chemical depending on different pathways and exposure of the same organism, bioaccumulation, biodegradation, etc.).

All the scores from all the categories considered make up the environmental profile of the system or product studied. Different environmental profiles obtained through the same methodology can be compared on the basis of environmental criteria.

iv) Normalisation is the step which tries to establish how great the resource consumption and the potential for impacts are relative to the impacts from society's activities as a whole (Wenzel et al., 1997). For example, if total emissions contributing to global warming of a country are known the relative importance of the global warming emissions due to a process or activity are easy to calculate.

v) Weighting/Valuation is a qualitative or quantitative stage, generally based not on science but on political or ethical values. The aim is to produce one single score by weighting and aggregating all the scores for all the impact categories defined. A list of different methods used in weighting is presented in **Appendix 4**.

vi) Grouping is the process by which impact categories are assigned together in one set. For example, impact categories can be ranked in a given hierarchy like high, medium or low priority. It is clear that this process is subjective and not based on scientific criteria but more on social ones.

2.3.3.4 Interpretation

Interpretation is the fourth phase in life cycle assessment. The aim of this phase is to reduce the amount of quantitative and qualitative data gathered during an LCA study to a number of key issues, which will be usable in a decision-making process. However, this reduction should give an acceptable coverage and representation of the previous phases in an LCA.

Interpretation is performed in interaction with the three other phases of the LCA. If the results of these previous phases are not good enough to match the goal and scope as set at the beginning of the study, then improvements are needed. This includes improving the inventory analysis by e.g. further data collection, changing the boundaries or improving the quality of data. As a result, the impact assessment would have to be repeated. These iterative processes must be repeated until the requirements in the goal and scoping phase are fulfilled as described by the interpretation steps (Jenssen et al., 1997). The three principal steps of the interpretation according to the ISO 14043 standard are: identification of the significant issues based on the inventory and the impact assessment phases of the LCA, evaluation (completeness, sensitivity and consistency checks) and conclusions, recommendations and reporting.

2.3.4 Applications of LCA

LCA has become a versatile tool, and although originally it was used mainly as a decision support tool capable of distinctions between different products and activities on environmental criteria, a series of other applications have emerged. Jensen et al. (1997) present some of these emerging application as follows:

- internal industrial use for product development and improvement,
- internal strategic planning and policy decision tool in industry,
- external industrial use for marketing purposes, and
- governmental policy making in areas of ecolabelling, green procurement and waste management opportunities.

In addition Wenzel et al. (1997) mention other areas for applications like: design for the environment (choice of concept, component, material and process), community action plans or consumer information and choice.

The number of LCA applications and the number of users has increased with the development and popularisation of LCA methodologies. Four types of primary users have been distinguished: industry and other types of commercial enterprises; national governments and local, national

and inter-governmental regulative bodies; NGOs such as consumer organisations and environmental groups; and consumers, including governments as consumers (UNEP, 1996).

Jensen et al. (1997) distinguishes three different levels of sophistication of LCA for the different applications. These levels are: the conceptual LCA or life cycle thinking, the simplified (or streamlined LCA) and the academic, detailed LCA. The history described in the previous section applies mainly to the detailed LCA and much of the efforts to develop and standardise LCA methodologies have been applied to these detailed studies. Recently, however, a definite trend towards simplification has been observed.

The **conceptual LCA or life cycle thinking** is the first and most simple type of LCA. It is usually based on qualitative information or on simple scoring systems. This type of LCA is suited to a basic environmental understanding of the life cycle of the product or system under consideration. However, since data are in the form of statements or very general quantitative data it may not be used for public dissemination or marketing purposes (Jensen et al., 1997). Although it is not published, conceptual LCAs are useful in-house environmental tools, since they bring environmental aspects into the day to day functioning of companies and sensitise employees to the potential environmental consequences of their decisions and actions.

The **simplified LCA** is defined as the application of the LCA methodology for a comprehensive screening assessment (i.e. covering the entire life cycle superficially or covering it fully but using qualitative and/or quantitative generic data). For this type of exercise standard modules for transportation and/or energy production, followed by a simplified impact assessment are used. A simplified impact assessment may focus on the most important environmental aspects, on potential environmental impacts, on stages of the lifecycle, on phases of the LCA, or on any combination of these four possibilities. These type of studies usually need a thorough assessment of the reliability of the results (Christiansen, 1997). The rationale beyond simplifying is to obtain the same results as a detailed LCA but in a shorter time and with less data and/or expense. This would make implementation of LCA concepts more efficient and straightforward in practice (Graedel, 1998), and widen the areas where LCAs can be applied. Graedel (1998) presents extensive examples on how different companies and some academia went about simplifying LCAs. In all these examples researchers are trying to preserve the LCA concept and rigour sufficiently to inspire confidence in the results, while at the same time meeting the scientific and logistical constraints that are inevitably present with simplification (Graedel, 1998). The results of most of these simplification techniques are in the form of a matrix, with one axis being the life cycle stages and the other one a list of environmental and health and safety impacts. According to the same author the major shortcomings of the existing approaches

are that the impact analysis is often not covered or poorly incorporated, interpretation is almost always inferred, and improvements may not occur unless the overall approach involves a structured technique for making and implementing recommendations (Graedel, 1998). Since the benefits of simplified LCA are obvious in terms of time and costs, there is a strong international movement (SETAC and ISO) towards standardising the simplification process in order to make it more reliable.

A **detailed LCA** is an application of the LCA methodology for a detailed, quantitative and mostly system-specific life cycle inventory analysis and life cycle impact assessment of all important environmental aspects of a product (activity or service) system. Simple cut-off or allocation rules are not acceptable (Christiansen, 1997). Therefore, the detailed LCA is the most data intensive and time consuming approach and traditionally it is the only one accepted as a real, academic LCA. The theoretical methodological framework for detailed LCAs is presented in **Appendix 1**. However, some of the applications of LCAs do not require such a high level of detail and a successful LCA project will have to match the goal of the study with the degree of detail required and obtainable.

2.3.5 Applications of LCA in South Africa

The range of applications of the LCA methodology in South Africa varies from the applications seen overseas. **Table 2.2** presents some of the applications presented in the literature and highlights which of them are currently used in South Africa.

The difference in applications in South Africa as compared to overseas is due to the internal use of LCA by the different companies and due to the fact that there is no pressure in South Africa to publish LCA data. Therefore, for companies conducting LCA studies, it is a voluntary exercise motivated mainly by the internal benefits they see arising from such studies. The above mentioned motives explain why the first application for LCA in South African companies is the generation of an environmental profile, in other words the generation of information on the environmental burdens of the products produced. The second application mentioned, which is used as frequently as the first one, is using LCA to support other environmental initiatives - most often ISO 14001 environmental management systems. This application is based on the focusing capacities of the LCA methodology. For example, for a particular product an LCA can identify the highest contributor to the total environmental burden and determine the cause (process or stream) of this contribution. By focusing environmental efforts, like the ISO 14001 environmental management systems, towards addressing the cause, the best possible environmental improvement is obtainable. The same mechanism is employed in the third

application mentioned by South African companies, namely for supporting internal waste minimisation projects. Other applications mentioned are strategic environmental assessment, environmental impact assessment support, environmental reporting and design for the environment. Only the SASOL team has employed these last four applications. A number of applications which are listed in the overseas literature are not used in South Africa.

Table 2.2: Some of the Applications for LCA and the Level of Detail Required

Application overseas	Application in RSA	Most used level of detail in LCA		
		Conceptual	Simplified	Detailed
Generation of environmental profiles	SASOL, ISCOR, ESKOM, Impala Platinum Ltd., Mondi Paper		x	X
Design for Environment	SASOL	x	X	x
Decision-making for sustainability	University of Cape Town	X		
Product development	Not applied	x	X	x
Product improvement	Not applied		X	x
Environmental claims (ISO type II-labelling)	Not applied	x		
Ecolabelling (ISO type II-labelling)	Not applied		X	
Environmental declaration (ISO type III-labelling)	Not applied		X	x
Organisation marketing	Not applied		X	x
Strategic planning	SASOL	x	X	
Green procurement	Not applied	x	X	
Deposit/refund schemes	Not applied		X	
Environmental (green) taxes	Not applied		X	
Choice between packing systems	CSIR	x		X

“X” in bold and upper case indicates the most frequently used level

Source: modified after Jensen et al., 1997

It is obvious that the drivers for LCA studies are less in number and by variation in South Africa than in countries in Europe, Japan or the USA, resulting in a limited number of applications. However, there has been an increased demand for South African LCA data from overseas, as many of the products exported from South Africa go to countries where the demand for

environmental data is high and where environmental burdens of products are criteria for choosing (or not choosing) a product. This external driver will probably result in many more LCA studies being conducted by companies and it is expected that the use of LCAs will increase.

The information presented on the South African applications was collected through the interaction with most of the LCA practitioners in South Africa. This exchange of information was facilitated by the creation of the South African LCA network in December 1999. The creation of this network was the initiative of the Pollution Research Group, University of Natal, and it was the first time that South African organisations and people with interests in LCA came together.

2.3.6 Limitations and Common Problems of LCAs

Life cycle assessment is a unique environmental management tool and the potential contribution of this tool towards better decision-making and management is considered to be important. However, besides the unique advantages this tool has, there are also shortcomings and limitations which have to be understood and considered when applying it. This helps prevent situations like those exposed by Krozer and Vis (1998), who believe that many decision makers are lost in an obscure area between too high aspirations and too many imperfections in current practice. There are two types of limitations and problems facing South African LCA researchers. The first set are the limitations and problems related to the LCA tool and methodological framework in general, and the second set of problems is specific for the South African setting.

2.3.6.1 General Limitations and Problems

LCA, as any other environmental tool, tries to convey a complex real life situation or system into a number of parameters, using different simplifications in the process. Part of the limitations of LCA originate from this simplification process and it has become clear that *experience has introduced caution in some previous thinking that LCA could be a complete or comprehensive assessment* (Owens, 1999). As an example, it only addresses those environmental issues specified in the goal and scope of the study. This means that other issues may be left out. The argument of simplification was further elaborated in a SETAC workshop and the most vehement critics argue that comprehensive comparison or the determination of environmental superiority or equivalency using life cycle impact assessment is not a realistic expectation due to the following reasons. Firstly, it is believed that LCAs cannot cover all issues

or every part of complex industrial systems and, therefore, LCAs will always be incomplete in some way. Secondly, critics argue that it does not address absolute considerations since it uses potential environmental impacts which are calculated as opposed to actual environmental impacts which are measured. Thirdly, it is believed that gaps and omissions in inventory data and lack of resolution and environmental representativeness in life cycle impact assessment methods are inevitable to some degree now and in the future (SETAC, 1997 in Owens, 1999).

Finnveden (2000), reviewed some of the current LCA studies and of some of the databases available. This review produced the following observations:

- energy inputs are included in most cases without major gaps,
- other raw materials are included but with severe data gaps,
- water is not included in most cases,
- land use, habitat alterations and impacts on biodiversity are in most cases not included. These categories will continue to pose a methodological problem, since there is no agreement on how to consider them in an inventory analysis,
- toxicological impacts on humans and on ecosystems are often included, but with severe data gaps. It is estimated that these impacts will never be fully described without data gaps, because of the sheer number of chemicals used in society and the lack of knowledge on the behaviour of these chemicals,
- non-toxicological human impacts and impacts in the working environment are lacking,
- impacts like global warming, ozone depletion, acidification, eutrophication and photo-oxidant formation are fairly well covered, however, there are shortcomings. Most notably data on eutrophication of aquatic systems is usually incomplete (due to insufficient data for water emissions) and data for organic compounds contributing towards photo-oxidant formation is expressed as a general parameter (e.g. particulate emission) making differentiation impossible.

As a result, Finnveden (2000) underlines that LCA studies do not cover all environmental impacts and because of this the types of conclusions that can be drawn from these studies are limited. However, other environmental tools like, for example, environmental impact assessments face the same problems (e.g. lack of data for chemicals).

Not only data gaps are seen as a major limitation, but also the quality of the existing data varies and this variation is another shortcoming according to Finnveden (2000). He cites a comparison of different databases for PVC and concludes that uncertainties can be quite large, often an order of magnitude or larger (Finnveden, 2000). This variability is explained by different methods of allocation and different technology levels sometimes existing in the same country at

the same time. An example is the manufacture of PVC using chlorine produced by mercury cell technology as compared with other technologies. Therefore, a careful selection of data for the appropriate technology may improve the quality of a study. In time, problems associated with data gaps and data quality will be reduced with the development of better databases and the collection of more data.

Forbes (1999) and Owens (1997) present a series of other limitations in current LCA methodology. These are related to the fact that the LCA methodology does not consider thresholds and spatial and temporal circumstances. For most environmental impacts, the relationship between the dose of pollutant and the effects caused is not necessarily linear and critical loads or thresholds exist. Critical loads or thresholds imply that below a certain dose of pollutant an ecosystem has the capacity to remove it efficiently, therefore the risks of damage are reduced. Critical loads are specific for each ecosystem and because of that it is impossible to incorporate the concept in a general LCA model or method; however, it is possible to use it in site specific LCA studies. The emissions, as calculated by the LCA methodology and presented in an LCA inventory, do not occur all at the same place and at the same time. This is not considered in the LCA methodology and details regarding emissions (like atmospheric transport, frequency, duration, average exposure, peak exposure, point or diffuse sources of emissions and sensitivity of the recipient ecosystem) are lost. Current LCA methodologies assume that all emissions occur at sensitive sites and that all emissions cause effects, presenting by this the worst case scenario regarding emissions (Forbes, 1999).

The uncertainties associated with the methodology for the inventory and the impact assessment phase are related to processes in which different value choices are introduced. Most notably, allocation (see **Appendix 1**, for the theoretical background on allocation) is one of these processes and Finnveden (2000) argues that multi-input allocation may be difficult to solve even if there is agreement on the guiding principles. A classical example illustrating this point is an incinerator of municipal waste, which receives a multitude of wastes and produces a number of pollutants. If one has to allocate the dioxins to the different inputs, two methods are available. In the first method dioxins are allocated according to the chlorine content of the input and in the second method they are allocated according to carbon content (or calorific value). Both methods are based on the guiding principle of natural science based causality, both are equally valid, however, they produce totally different results. Since the formation mechanism of dioxins is not well understood (Wikstrom et al., 1996 in Finnveden 2000), the only criteria for choosing between these methods is the suitability with regard to the scope and goal of the study. This suitability has to be decided by the researcher on no real scientific grounds. Another example of a methodological choice is the time frame considered for long term processes like the emissions

from landfill sites. The choice between a shorter time period (decades or centuries) and a hypothetical infinite time period has different results. This is a clear value choice for the researcher and Finnveden argues that it is related to ethical views about impacts on future generations (Finnveden, 2000). As a result, it must be acknowledged that methodological choices introduce uncertainty in the results and that these choices are influenced by culture, frames and paradigms (Finnveden, 2000). One way to overcome this problem is standardisation (Consoli et al., 1993 and ISO 14040, 1997), however, standardisation can only go up to a certain point and variation will still remain for many of the methodologies involved.

The valuation (weighting) stage of life cycle assessments is one of the stages most open to subjectivity and value-choices since it is not based on scientific criteria. It is argued that *not only the weighting factors, but also the choice of weighting methodology, and the choice of using a weighting method at all, are influenced by fundamental ethical and ideological valuations and since there is no societal consensus on these fundamental values, there is no reason to expect consensus either on weighting factors, or on the weighting method or even on the choice of using a weighting method at all* (Finnveden, 2000). In the ISO series of standards the weighting stage is an optional element and in this study it has not been performed.

LCA relies on other scientific disciplines for data and methodologies like, for example, toxicology, climatology, chemistry etc. If science does not provide the answers to certain questions (e.g. the mechanism for the formation of dioxins is not known) it is clear that this will impose limitations on LCAs depending on this data. However, this is a problem shared by all other environmental tools.

In conclusion, LCA has a series of shortcomings and limitations, most notably related to data gaps, data quality and value-choices. In spite of these limitations, this tool is valuable because of its unique *cradle-to-grave* approach, which makes it irreplaceable by any other tool.

2.3.6.2 South African Limitations and Problems

Data availability and quality is a common problem for the studies done by academia and research institutes so far in South Africa. With regard to availability of data, there is a general reluctance by South African companies to provide LCA data. This reluctance may be explained by the fact that managers in different companies are not sensitised to LCA and the data requirements of this method. Therefore, few companies have data in the format that can be used in an LCA and usually it is time and effort consuming to compile this data. Another factor, which may explain the reluctance of companies to release environmental data, is historical and

originates from the high protectionism South African companies enjoyed in the past. Some companies realise that South Africa may have environmental problems due to various causes related to the structure of the South African economy as a whole, like energy intensive industries or the economy's mining and primary beneficiation focus.

Data quality and availability is also a problem faced by the companies interested in conducting LCAs. However, because most studies are internal, this problem is not so acute and usually relates to data outside the control of the company.

South African organisations involved with LCA use different commercially available databases like: TEAM, Gabi3 and PEMS (see Rice et al., 1997 for a software review). All these databases have been developed overseas and present the LCA researcher with the problem of applying the data collected elsewhere to the South African situation. This can introduce a margin of error, because data between countries and continents differ due to different factors, in particular different technologies and regulations. However, because of the lack of data for South Africa, LCA practitioners in this country do not have any option other than to use overseas data. Similar problems are faced not only by South Africa, but also by some of the developed countries. The more accurate a study needs to be, the more site-specific data are required. However, collecting data is costly in terms of time and money, so in many cases generic data are used.

Another major problem, which is specific to South Africa, is the *relevance to this country of the assessment* step in the LCA methodology. The impact categories in which environmental effects are categorised (e.g. global warming, stratospheric ozone depletion, ecotoxicological impacts, human toxicology impacts, acidification, eutrophication, land use, abiotic resource consumption, biotic resource consumption and work environment) have been developed for the European and the USA situation. Impacts considered not important in the Northern Hemisphere are of major importance for this country. For example, South Africa is a water scarce country, consequently water, as a resource, is very important. However, this is not a global issue and this importance is not reflected in the established LCA methodology. The same is valid for water salination and soil erosion. Therefore, there is a need to adapt the methodology to include local environmental priorities and small steps are being taken in this direction.

A further South African problem is *the lack of critical review capacity* in South Africa. It is important to have a critical review for any study, which is designed to be published. Because the LCA community in South Africa is small and most of the studies done were for internal consumption, the critical review step was not performed very often. However, with the increasing use of LCA, the need for critical reviewers is increasing.

In spite of these limitations it is expected that the demand for LCA type of studies will grow in South Africa. This development is predicted because environmental LCA information is required in order to access export markets in most of the developed countries. Not only the quantity but also the quality of these studies is expected to rise since they will have to comply with international standards. It is believed that if South African products are to be marketed internationally and specifically exported to first world countries, *LCAs need to be performed as prescribed, for example, by EU legislation, the international customer, etc.* (Stinnes et al., 1996). Therefore it is important to draw attention to the environmental problems specific to this country and to incorporate them in the LCA methodology.

2.4 Conclusion

This is one of the first studies in which LCA has been performed on water treatment processes in South Africa. This study has to be viewed in the context of increased environmental concern, which has emerged due to the widespread environmental degradation experienced in the last few decades. One of the contributing factors to environmental degradation is the expansion of industrial activities. This expansion process has brought development, economic growth, employment and wealth. But it has also brought environmental degradation through depletion of resources, pollution and ecological disruption due to the increased interference of production systems with the ecological support systems of the planet. Sustainable development is the concept which tries to reconcile economic growth and ecological degradation by setting development on a more sustainable path. Cleaner production is the way towards sustainability for industry and in this context environmental management tools like LCA have emerged and are used by companies to identify and reduce their environmental burdens.

An LCA is an environmental management tool in which environmental burdens associated with a product (system or activity) are evaluated, by identifying and measuring energy and materials used and the wastes released to the environment (air, water and soil). This assessment includes the entire life cycle of the product (system or activity) from the extraction of raw materials to final disposal. LCA addresses environmental consequences expected from the system under study like ecological impacts, human health and resource depletion. It does not address economic or social impacts due to the system.

The use of LCA is increasing internationally and locally and there are different degrees of sophistication when applying it. This, together with the fact that it is the only product orientated tool which has a *cradle-to-grave* approach, gives LCA advantages, however, it also has some

limitations, most notably the availability of data. All in all it must be seen as one environmental tool capable of bringing about environmental improvement, the current study being an example of these capabilities.

CHAPTER 3

BACKGROUND INFORMATION ON WATER TREATMENT METHODS AND PROCESSES

*When you drink the water remember the spring.
(Chinese Proverb)*

This chapter introduces two different methods of producing potable water. In the following sections of this study, these two methods will then be compared by means of LCA. The first one is the *conventional method* and it is currently employed at Wiggins Waterworks, a waterworks of Umgeni Water situated in Durban. The main processes involved are pre-ozonation, addition of chemicals, coagulation, flocculation, sedimentation, filtration, ozonation, chlorination and storage. The second method is based on the use of *membrane filtration* and the following processes are involved: prefiltration, membrane filtration, chlorination (different to the previous method) and storage. Currently a pilot study using this method is taking place at Wiggins Waterworks in collaboration with the Water Technology Group (Dr. Lingam Pillay), ML Sultan Technikon and the Institute of Polymer Science (Dr. Ed Jacobs), University of Stellenbosch.

A framework for the comparison of these two methods taking into account the three main life cycle stages of a waterworks is presented in **Figure 3.1**.

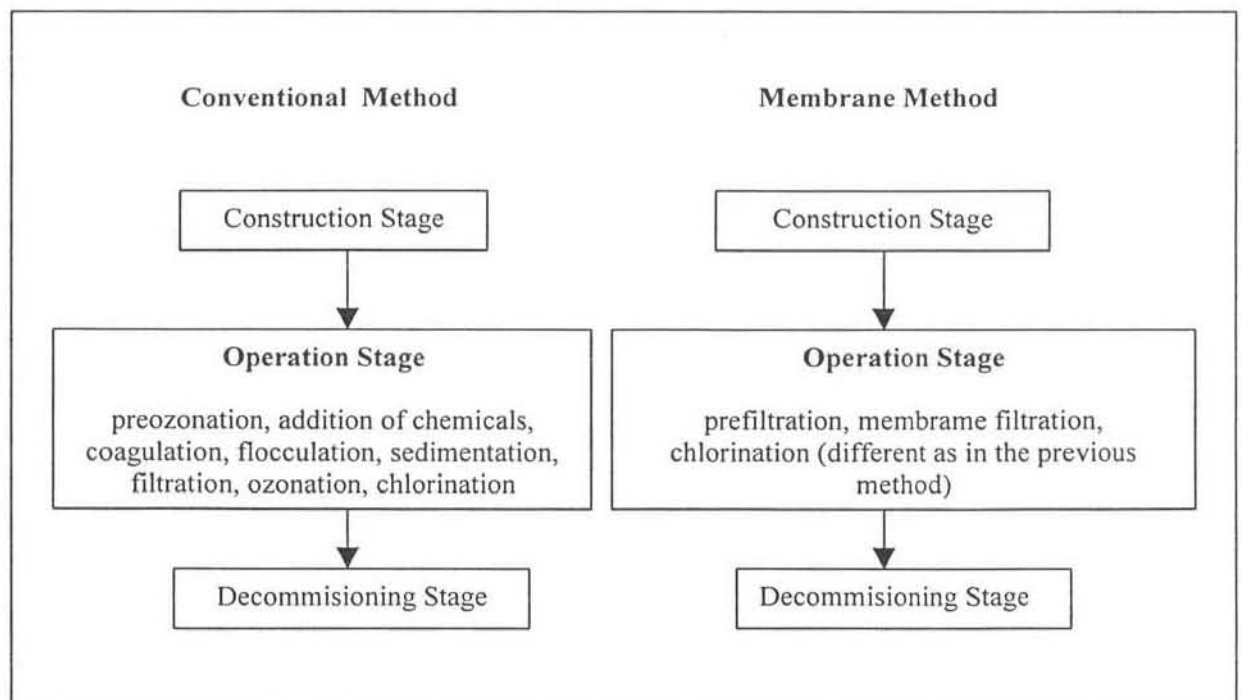


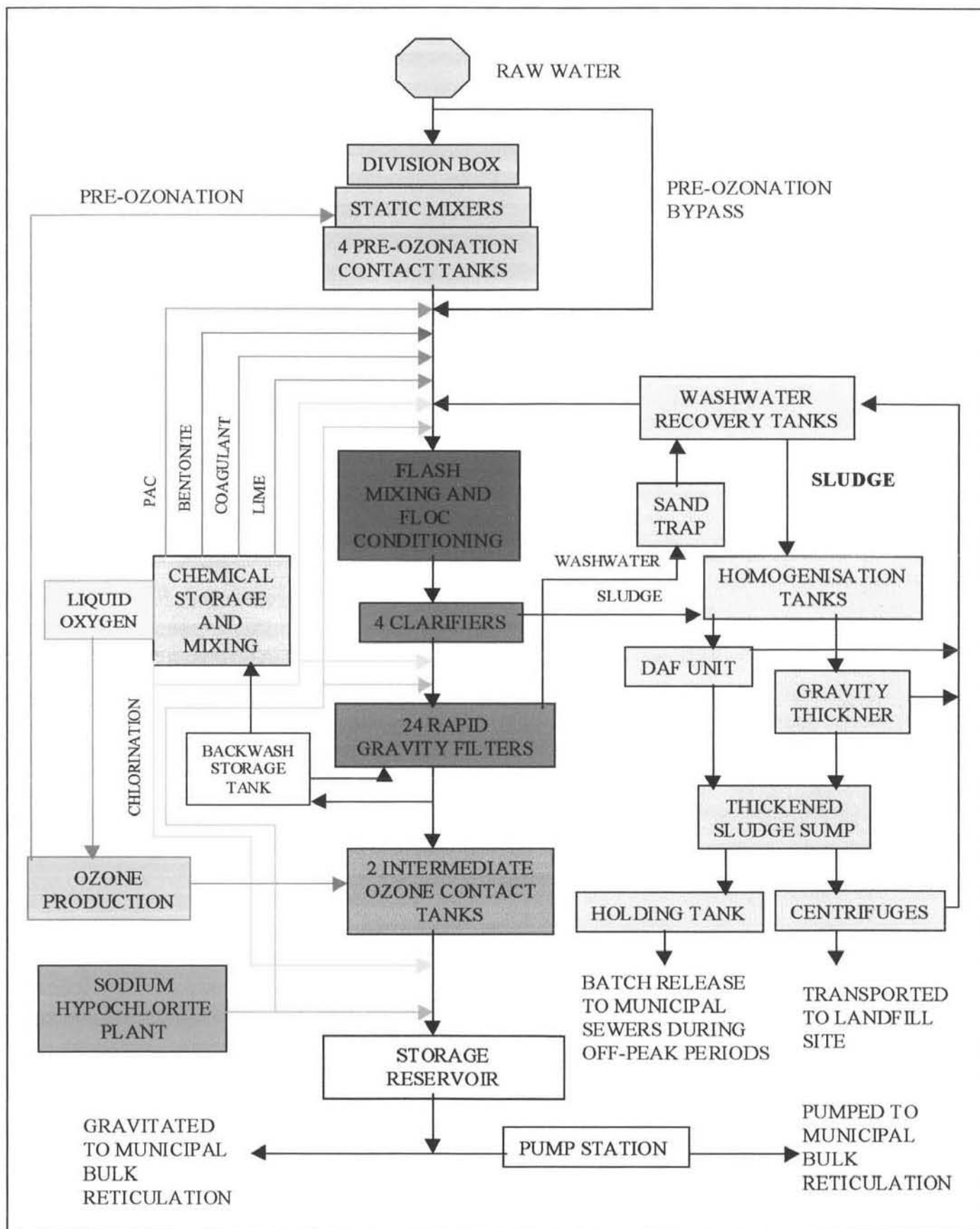
Figure 3.1: Comparison of Two Methods for Producing Potable Water

3.1 The Conventional Method of Producing Potable Water at Wiggins Waterworks

Wiggins Waterworks is one of the eleven waterworks of Umgeni Water, the largest catchment-based water authority in South Africa (Umgeni Water's Public Affairs Department, 1998). It is situated in the Durban Metropolitan Region in the area of Cato Manor. This waterworks was commissioned in August 1984 and it supplies water to the Durban region. The initial capacity was 175 megaliters (ML) per day. In 1995, following an expansion, this capacity was raised to 350 megaliters (ML) per day. A system of tunnels and pipelines supplies the raw water from the Inanda Dam and gravity is used for the transportation of the incoming water.

The raw water enters the waterworks through the intake tower and flows through an aeration tank. The tower eliminates surges in the waterflow and the aeration tank is only operated when necessary. After the aeration tank, the water passes through a covered concrete channel into a pre-ozonation tank. The addition of chemicals follows the pre-ozonation operation and dosing facilities exist for lime, polymeric coagulant, bentonite, sodium hypochlorite, chlorine and powdered activated carbon (PAC). Passing the water over weirs enhances the mixing of water and chemicals. The water then flows into 4 banks of pulsator clarifiers. The clarified water is directed into 24 rapid gravity filters after which it is passed through the intermediate ozonation tank. It is chlorinated before flowing into two storage reservoirs from where it is distributed. The sludge from the clarifiers is directed to the homogenisation tank after which it enters the sludge plant. The washwater from the filters is directed through a sand trap to the washwater recovery tanks from where the clear water is recycled to the head of the waterworks and the settled solids are pumped to the homogenisation tank (Mr. Peter Thompson, personal communication, 1999). An illustration of the overall process is presented in **Figure 3.2**.

Each step in the treatment of water is monitored via a computer system. The quality of water is checked at the beginning of the works when it is still raw water, after the chemical additions, after filtration and the final water is also checked. In-line pH, turbidity, dissolved oxygen and temperature meters monitor raw water. Since the quality of incoming water varies widely, additional facilities exist at the head of the works (before pre-ozonation) to dose powdered activated carbon, bentonite and chlorine (as gas or as sodium hypochlorite) in order to deal with low quality incoming water.



Source: Umgeni Water's Public Affairs Department

Figure 3.2: Process Flow Chart for the Conventional Method

3.1.1 Pre-ozonation

Ozone is produced on the premises by three 30 kg/h Trailgaz ozonators. These ozonators are fed evaporated liquid oxygen. The liquid oxygen is supplied by Fedgas Ltd. and stored on the premises in two pressurised columns (approx. 70 t liquid oxygen) situated adjacent to the chemical house. The ozone is produced in the ozone generation plant and it is dosed at two points in the waterworks. The four pre-ozonation tanks are situated at the head of the works before chemical addition. The two intermediate ozonation tanks are situated after the filtration unit and before the storage reservoirs. The pre-ozonation tanks are fitted with static mixers at their inlets. These mixers diffuse the ozone in the water enhancing the mixing process. A thermal ozone destruction unit accompanies each ozonation unit. The manufacture and destruction of ozone and the functioning of the contact tanks is monitored and controlled by an array of in-line meters. These meters measure oxygen and ozone gas pressure, oxygen, ozone and cooling water flow rates, ozone concentration, oxygen dew point and ozone residual. Pre-ozonation is used at Wiggins Waterworks mainly for the oxidation of iron, manganese, THM (trihalogenated methane) precursors and taste and odour compounds like geosmin and 2-methylisoborneol. It also helps in removing algae, improving the colour of the final water and reducing coagulant demand (Thompson, 2000).

3.1.2 Addition of Chemicals

The addition of chemicals follows the pre-ozonation process. The dosage of powdered activated carbon, lime, chlorine (gas and sodium hypochlorite), bentonite and polymeric coagulant is made possible through a series of pipes from the chemical house to the addition points situated just after the pre-ozonation tanks. In the chemical house, there are storage facilities and facilities for producing and pumping the solutions of these various chemicals.

Powdered activated carbon is used intermittently at Wiggins Waterworks, depending on the quality of the incoming water. On average it is added to raw water for about 4 to 6 months per year. It is used for taste and odour control. The dosage during the period of use is not constant and it usually starts with 20 mg/L and decreases to 5 mg/L (Mr. Thompson, personal communication, 1999). ***Pre-chlorination*** is the next step in the treatment of water and there are facilities for the addition of chlorine and sodium hypochlorite. These chemicals are used for disinfection of the water. Another substance used for disinfection is ***HTH*** (calcium hypochlorite - $\text{Ca}(\text{OCl})_2$), however, it is used only occasionally, mainly for the disinfection of tanks after maintenance works. ***Lime***, more specifically slaked lime $\text{Ca}(\text{OH})_2$, is used for pH control, and as with chlorine, it is a chemical dosed throughout the year in the treatment of water. The pH of the

raw water is measured by an in-line system and the dosage of lime is changed according to the pH readings. It is important to dose lime before the addition of the polymeric coagulant, since the effectiveness of the coagulation process is dependent on the pH. *Polymeric coagulants* were introduced by Umgeni Water in its various works in the mid 1980's (Nozaic et al., 2000) because they proved to be more cost-effective than the inorganic ones used previously. The polymeric coagulant currently used consists of a blend of cationic polyamines, polydiallyldimethylammonium chloride (polyDADMAC) and some inorganic components (Nozaic et al., 2000). *Bentonite* is used as a coagulant aid because of its property to expand, increasing the size, density and strength of the flocs formed. Channelling the water over a weir after the dosage points enhances mixing of the chemicals added. The increased shear in the water contributes not only towards better mixing of the coagulant and coagulant aid into the raw water and therefore towards better coagulation, but also towards better flocculation.

Coagulation and flocculation are usually combined in a two-stage process applied in drinking water treatment to assist with the removal of small, suspended particles (Nazaroff and Alvarez-Cohen, 2001). Most of the impurities in water are colloidal particles, electronegatively charged and in stable suspension. When positively charged ions are added to the suspension, these ions cause a destabilisation of the suspended particles and aggregation. The coagulation process is the aggregation of these suspended particles into larger entities. The flocculation process is the aggregation of these entities into even larger aggregates called flocs. The formation of these aggregates enables phase separation through sedimentation, clarification, floatation or filtration (van Duuren, 1997). Although similar in concept, coagulation and flocculation occur by separate mechanisms. Coagulation is based on electrochemical effects achieved through the addition of positively charged chemicals to the solution (i.e. the raw water). Flocculation further aggregates these destabilised particles primarily by collision, bridging and attachment. To facilitate collision there must be motion and a sufficient number of particles. The rate at which collision can occur during flocculation is thus a function of the number of particles involved, their size and the rate of motion (van Duuren, 1997).

The process of coagulation and subsequent flocculation starts just after the coagulant is added and continues in the clarifier vacuum chambers and tanks. Flocculation continues up to filtration (van Duuren, 1997).

3.1.3 Clarifiers

At Wiggins Waterworks there are four Degremont sludge blanket pulsator type clarifiers. The surface area of each clarifier is 995 m² and they allow for a rise rate of 4 m/h at a flow rate of 350 ML/d with a retention time of 1.09 h. The raw water enters the clarifier tanks through a series of perforated pipes situated near the bottom of each tank. Some of the incoming raw water is induced into two vacuum chambers. The vacuum causes the level of the raw water to rise in the vacuum chamber to about 0.6 to 1 m above the level of water in the clarifier tanks. At which level an air inlet valve is opened automatically and atmospheric pressure is applied to the water in the vacuum chamber. This causes the raw water to flow back into the pulsator. This design facilitates flocculation by promoting collision of the flocs in the raw water and between the much larger flocs already existing in the tank with the smaller incoming ones. The required duration of flocculation can be shortened substantially because of the presence of the macroflocs in the tanks. Stilling plates are situated above the perforated pipes so that the entering water rises uniformly, allowing settlement of the coagulation particles (or flocs) and the formation of a sludge blanket at the bottom of each tank. At the top of each tank a set of perforated channels collect the clarified water evenly and without any velocity disturbances to the other layers of the tank. The clarified water is directed to the filtration unit (Thompson, 2000).

Due to the sedimentation (or settling) process a sludge layer is formed at the bottom of the clarifier tanks and the sludge then overflows into hoppers. The sludge blanket depth is about 2 m and as the sludge reaches a concentration of ca. 0.3 % solids, it is automatically discharged into the homogenisation tank.

Facilities for the dosage of chlorine and sodium hypochlorite to the clarified water are situated just after the clarifiers and before the filtration unit. These facilities are used only if needed.

3.1.4 Filtration

There are 24 Degremont Aquazur “V” type gravity filters that make up the filtration unit at Wiggins Waterworks. Two cells make up each filter and each cell has a surface area of 56 m² allowing for a maximum filtration rate of 6 m/h. This type of filter has a suspended floor/nozzle system. The depth of filter sand (i.e. the filtering media) in the filter is 900 mm and the effective grain size of the sand is 0.95 to 1.35 mm. The water depth above the filter media reaches 1 to 1.2 m depending on the flow rate. Rapid gravity filtration, as employed by this type of filter, usually means deep bed filtration. This is the process by which suspended particles penetrate in

the media (in this case sand) and are captured some distance below the media surface (van Duuren, 1997). To maintain efficiency of filtration in this type of system, backwash is needed at regular intervals. A characteristic of this type of filter is the simultaneous air scour and backwash accompanied by surface sweep, followed by a water rinse of the filter during backwashing (Thompson, 2000). The backwash sequence is as follows:

- air for scouring is blown in a reverse direction (after the level of the raw water was lowered accordingly) for 5 min.,
- simultaneous use of air and water for 3 min. and a
- water only backwash for 3 min. (Thompson, 2000).

The backwash water is collected in a wash water recovery tank after it has passed a sand trap, which collects the sand which was washed out with the wash water. After settling, the resulting sludge is pumped to the homogenisation tank and the recovered water is returned to the raw water stream just after the addition point of polymeric coagulant.

3.1.5 Intermediate Ozonation

Intermediate ozonation is carried out after filtration and the aim of this operation is disinfection. The process occurs in two intermediate ozonation tanks where the ozone/oxygen mixture is introduced at the bottom of the tanks through porous carborundum diffusers (Mr. Thompson, personal communication, 2000). To make sure that the ozone which has not dissolved in the water does not leak into the environment, a thermal destruction unit accompanies the intermediate ozonation unit. This destruction unit is similar in design to the one employed in the pre-ozonation process.

3.1.6 Final Chlorination

Final chlorination is used after intermediate ozonation and just before the treated water enters the storage tanks. At this point there are facilities for dosing chlorine and sodium hypochlorite. The aim of this operation is to disinfect the water and to introduce a residual chlorine dose in the treated water in order to prevent re-inoculation with pathogens during storage and reticulation. The average chlorine residual in the reservoir tanks is about 0.5 mg/L as chlorine gas (Thompson, 2000).

3.1.8 Sludge Treatment

The homogenisation tank collects sludge from the clarifiers and the wash water recovery tanks. From the homogenisation tank, the sludge may follow two routes prior to disposal. In the first route the sludge is pumped to the dissolved air floatation (DAF) unit. This unit uses “air pressurised” water (i.e. water in which air has been dissolved under high pressure) to create microbubbles which rise through the incoming sludge. Small particles of sludge adhere to the microbubbles and are transported to the surface from where they are continuously removed. These floating scrapings are directed to the thickened sludge sump. Larger and heavier particles in the sludge, settle to the bottom of the DAF unit. This settled sludge is scraped continuously and also pumped to the thickened sludge sump. The water recovered from the DAF is pumped to the wash water recovery tanks where it is mixed with the filtration wash water and follows the same recycle path.

In the second route, sludge from the homogenisation tank is passed through a gravity thickener. From the thickened sludge tank the sludge can be either diluted and disposed of into the municipal sewer during off-peak periods (this method is employed most of the time), or it is passed through centrifuges and further concentrated (this method is seldomly used). The sludge has to be diluted in the case of disposal in the municipal sewer in order to obtain a solid concentration around 1 %. The cake resulting from centrifugation has a solid concentration of about 25 to 30 % and it is disposed to a landfill site. The water recovered through centrifugation is pumped to the wash water recovery tanks and recycled.

3.2 The Membrane Method for the Production of Potable Water

In order to compare the environmental burdens resulting from the conventional process employed at Wiggins Waterworks with a membrane process producing the same quantity of potable water of the same quality, a virtual membrane plant had to be designed. This design is based on a pilot membrane filtration unit used for research purposes. This pilot unit is run by staff and students from the Water Technology Group, Department of Chemical Engineering, ML Sultan Technikon under the leadership of Dr. Lingam Pillay and is situated adjacent to the research facility at Wiggins Waterworks. The technology employed is entirely South African, the membranes used have been developed and produced by the research group of Dr. Ed Jacobs from the Institute for Polymer Science, University of Stellenbosch. All these role-players have been involved in the upscaling of the pilot plant to a virtual plant comparable with Wiggins Waterworks, and several design possibilities were considered before agreeing on a final version, considered to be the best for the purpose of this study.

3.2.1 Membrane Technology

There is increasing interest in the application of capillary membrane filtration for large scale water treatment plants because of recent developments in membrane technology. Such developments include:

- the reduction of energy consumption by using dead- or semi dead-end filtration instead of cross-flow filtration,
- the development of capillary membranes with high membrane surface in restricted volume,
- decreasing membrane resistance,
- prevention of fouling by backwashing and forward flushing with water as well as air and
- the tendency towards interchangeable membranes (Oosterom et al, 1998).

The local capillary membrane technology involved in this project has been documented in a series of publications such as Jacobs and Leukes (1996), Jacobs et al. (1997) and Pryor et al. (1998). So far this technology has been employed only on a small scale and in pilot plants. In essence it is based on a low pressure (ultrafiltration) membrane operation. The main advantages of an ultrafiltration plant is that it is able to produce an acceptable quality of potable water, that it provides a means of disinfection of the water and at the same time removes some of the organic contamination of surface waters. It therefore provides a process which is capable of limiting the formation of disinfection by-products during subsequent chlorination (Pryor et al., 1998).

The capillary membranes used for the ultrafiltration pilot plant were manufactured by researchers at the Institute for Polymer Science using a protocol documented by Jacobs and Leukes (1996). They are polysulfone membranes and as such they present a series of favorable characteristics like wide temperature limits (up to 75 and even 125 °C), wide pH tolerances, good resistance to a series of chemicals including chlorine, alcohols, acids and aliphatic hydrocarbons and they are relatively easy to manufacture (Cheryan, 1998). The main shortcomings of these membranes are seen as the low pressure limits (1.7 bar for hollow fibre membranes) and their hydrophobicity which makes them more prone to fouling (Cheryan, 1998). The membranes produced for potable water filtration at the Institute for Polymer Science in Stellenbosch have a well defined internal skin, but they lack an external one. The microvoids in the membrane are narrow-bore and extend the full width of the membrane. The capillaries have an internal diameter of about 1.2 mm and an external diameter of about 1.9 mm. They have good mechanical strength, being able to withstand instantaneous burst-pressures of 1.8 MPa (Jacobs and Leukes, 1996). These membranes are cut to a given length, usually about 1.2 m and packed in bundles with the help of netting. The bundles are then inserted into a 90 mm PVC pipe forming a module. The ends of the modules are sealed off and at the same time the ends of

the membranes are fixed, with the help of a urethane-based epoxy which is poured into a mould and then centrifuged (Dr. Jacobs, personal communication, 1999). The modules have seals for connection to the raw water supply. They also have a product outlet through which the filtered water exits the module.

There have been three pilot plants around the country (Mon Villa - near Stellenbosch; Suurbraak in the Western Cape Province and Wiggins Waterworks - Durban) in which these modules were tested. In these pilot plants up to 12 modules in parallel have been employed. The way the pilot plant at Wiggins Waterworks was run is documented by Pryor et al. (1998) in the following few sentences.

Feed water is pumped through a strainer and pressure sand filter, which in the absence of coagulation and flocculation, serve as grit traps only. Recycle pumps circulate the water through the capillaries, thereby maintaining a maximum cross-flow velocity of 1 m/s and inducing sufficient shear to limit the deposition of material on the inside of the membranes. During normal operation, a positive displacement (product) pump is used to draw a constant flow of permeate through the membranes. The trans-membrane pressure was monitored and regular flow reversal was used as a backflush strategy to assist in limiting the fouling of the membrane surface (Pryor et al., 1998).

The same authors mention the need for regular cleaning-in-place operation and this is usually done when the trans-membrane pressure reaches levels of 80 to 100 kPa. For the membrane pilot plant at Wiggins, with water characterised by colloidal particles and low levels of organic carbon, a chlor-alkali (50 ppm sodium hypochlorite) solution is used for cleaning in place (CIP).

3.2.2 The Layout of the Membrane Plant

In the production of potable water by the membrane method three processes are considered as being necessary. They are the same three processes that are employed at the Wiggins membrane pilot plant, namely pre-filtration with the help of rapid sand filters, membrane filtration to eliminate undesired substances and chlorination to prevent the re-inoculation of pathogens. These processes can be represented as follows:

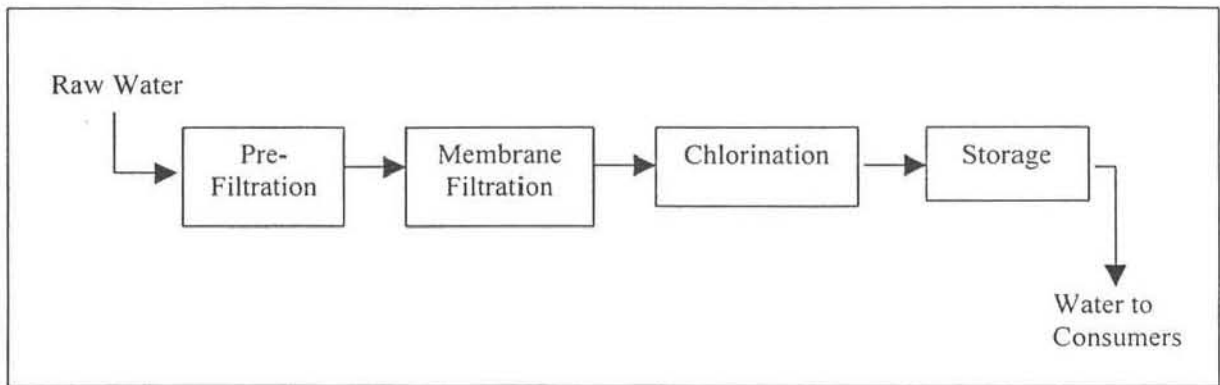


Figure 3.3: Diagram of the Membrane Method

For the filtration process it has been assumed that a filtration unit exactly the same as the filtration unit in the conventional method will be employed (see **Section 3.2.4**). For the chlorination process a dosage similar to the final dosage in the conventional method has been assumed. The storage of the potable water resulting from this method was assumed to be identical to the storage in the conventional method.

3.2.3 Upscaling the Membrane Pilot Plant

The basic unit of design of a membrane plant is a module. There are several types of modules used for large scale water treatment and they vary in: module dimensions, membrane material, pore size, capillary diameter, position (horizontal or vertical), inside-out or outside-in filtration and other specific characteristics like air-flushing, interchangeable membranes or submersible type membranes (Oosterom et al., 1998). The South African modules are vertical ones, with inside-out filtration and the membranes are not interchangeable. As presented above, the module used for this study consists of a PVC shroud, the membranes enclosed in a polyethylene netting, epoxy sealers (at both ends of the module), nitrile lip sealers and a product connector. Each of these components has been weighted for a 90 mm OD (outside diameter) shroud and upscaled to a 250 mm OD shroud, which is what would be used for a large scale plant. Data on how the membranes are produced and on how the modules are assembled have been collected from the Institute for Polymer Science, University of Stellenbosch. Data on how the modules are run in the pilot plant, as well as the different technical parameters for operation, have been collected from Mr. Nareshan Moodley, ML Sultan Technikon. The technical specifications of a single original module used at the Wiggins Waterworks pilot plant are presented in **Table 3.1**.

Table 3.1 Technical Specifications of Original Membrane Filtration Modules**Dimensions**

Number of capillaries per module	6500
Diameter of capillary	0.0012 m
Filtration length of capillary (excludes epoxy moulded part)	1.08 m
Filtration area per capillary	0.0040 m ²
Filtration area per module	26.45 m ²
Cross-sectional flow area per capillary	1.13E-06 m ²
Cross-sectional flow area per module	0.0073 m ²

Conditions for ideal filtration

Crossflow velocity through capillary	1 m/s
Feed pressure	1.5 Bar max
Assumed flux	50 L/m ² h
Assumed water recovery	95 %

Flowrates and Cleaning in Place (CIP)

Permeate / product flowrate per module	1 322.56 L/h
Raw feed flowrate per module	1 392.18 L/h
Reject flowrate per module	69.61 L/h
Backflush flowrate per module*	69.61 L/h
Downtime duration per CIP	6 h
Assumed no. of CIP's over a 30 day period	2
Other downtime per 30 day period	10 h
Vol. of water required per module for CIP	262 L/CIP

* *Observation: reject flow equals backflush flow for dead end filtration*

For the planned large scale plant a dead-end filtration process will be employed, therefore there will be no separate backflush line. To perform this operation at the same scale as Wiggins Waterworks (i.e. to purify about 200 000 kL/day) 1 620 to 4 740 modules are needed, depending on the size of the modules and the flux assumed during the operation stage. The modules can be arranged in different ways. For the purpose of this study batches of 30 and 60 modules were considered. In total eight different scenarios were used for calculation:

- short modules (1 250 mm), low flux (50 L/m²h), banks of 30 and 60 modules,
- short modules (1 250 mm), high flux (100 L/m²h), banks of 30 and 60 modules,
- long modules (1 500 mm), low flux (50 L/m²h), banks of 30 and 60 modules, and
- long modules (1 500 mm), high flux (100 L/m²h), banks of 30 and 60 modules.

New technical specification sheets have been calculated for all four types of modules (see **Appendix 5**).

Membrane filtration modules are arranged in banks of modules (30 and 60 modules) and each bank is serviced by a supply and a product (or permeate) line. The supply line consists of small pipes, intermediary pipes and two large pipes. The small pipes are directly connected to the modules and the average length of small pipes was considered to be 0.2 m. The small pipes connect to intermediary pipes, which for the raw water supply line branch off from two big incoming pipes. The length of the intermediary pipes was assumed to be 7.5 m. After membrane filtration, the permeate is collected in another line namely the product line. This line also consists of small pipes, individual for each filtration module, and of modular intermediary pipes which then collect in two major pipes conducting the clean water to the storage facility. The same lengths were assumed for the small and intermediate pipes of the permeate line as for the pipes of the raw water supply line. For the large pipes (two for the supply line and two for the product line) an average length of 100 m was assumed. The sizes of the pipes were calculated using economical piping calculations based on the flowrates in these lines. The flows were different for the different scenarios considered. The material consumption for constructing these pipes was calculated by using data from pipe manufacturers expressed as kilogram material per metre of pipe for the required pipe thickness. Thickness is dependant on the pressure of the water in the pipes and standardised schedules were obtained from pipe manufacturers.

Similar engineering design calculations were done for pumps. For pumps, in addition to the pressure and the flow needed, efficiency calculations were included in order to approximate electricity consumption. Calculations on the pipes and pumps needed are presented in **Appendix 6**. This appendix also presents a sample calculation for pipes and pumps.

3.3 Conclusion

This chapter has introduced two methods of producing potable water. The conventional method, employed at Wiggins Waterworks since 1984, has been continuously improved. The membrane method is more recent and it has been used in three pilot plants around the country. The operational data from the Wiggins Waterworks membrane pilot plant was used for this study, because the quality of the incoming water will be the same for this method as well as for the conventional method to which it is being compared.

For the membrane plant a series of assumptions had to be made, not only with regard to individual processes on the plant, but also with regard to the entire design of the plant, including the way it should be build, materials used, etc. A part of these assumptions have been presented in this chapter, others will be clearly stated in the methodology section (see **Chapter 4**) and the author is aware that they may introduce a margin of error for the membrane method of producing potable water. However, since there is no membrane facility of the size required for this study, one had to upscale to a virtual plant and make use of assumptions.

CHAPTER 4

THE DIFFERENT STAGES OF THE STUDY AND THE METHODOLOGY EMPLOYED

This chapter defines the goal and scope of this study and presents the means and the stages used to achieve them. In general, the methodology of a study comprises the construction of a logical and rigorous investigation process in order to achieve the goal(s) of a study. In this case a combination of quantitative and qualitative research methods had to be employed in order to answer the research questions posed. Since LCAs are quantitative studies, the quantitative methods dominate and actual measured values were preferred. However, in the absence of various measurements for the different processes involved, calculations based on literature data and qualitative methods had to be used. The general methodology used in this study follows the ISO standards procedural framework. The methodology used for the impact assessment phase (or stage) uses the CML (Center for Environmental Science, University of Leiden) methodology for impact category definition, classification and characterisation.

4.1 Literature Review

A literature review was undertaken in order to establish the theoretical framework and the paradigm in which the concept and the methodologies of LCA were developed. Different readings about sustainability and sustainable development provided the background to cleaner production and the need for developing tools like LCAs. In trying to relate these broad concepts to the functioning of industry the literature search was widened, and a body of literature relating to the responses by industry to environmental problems was accessed.

An even more extensive literature review was undertaken (as presented in Chapter 2) in order to collect information about LCA: definitions, history, development, methodologies, etc. Since this is a relatively new field to South Africa, there was not much information available locally. Most of the textbooks were ordered from overseas and a few were obtained through the interlibrary loan service. Internet searches and materials downloaded from various websites played a large role at this stage, because it allowed access to some of the more recent information pertaining to the LCA methodology.

Another area where a literature search and consequent review was used was the search for technical information on the different water treatment processes. This search was more specific than the previous ones, targeting only the processes involved in the two case studies, i.e. the

conventional method and the membrane method. This literature search was undertaken in order to understand the two methods of producing potable water and subsequently to create the model used to establish the initial boundaries and determine where to start data collection.

4.2 Goal and Scope Definition

The goal and scope definition is one of the most important steps in performing an LCA. This step defines the system to be studied, the reasons for performing the study and the breadth and depth of the study in relation to the reasons stated (see **Appendix 1, Section 1.2.1**) (Guinee et al., 1998). This step also fixes the objectives of an LCA, determining the potential applications of an LCA study and assessing for what it can and cannot be used for (Wenzel et al., 1997).

4.2.1. Defining the Goal of the Study

The *goal* of the study (as presented in **Chapter 1**) is to generate environmental information on the life cycle of water treatment processes, to identify the improvement potentials for these processes and to compare the environmental burden of a conventional water treatment process with that of a process involving membranes. Therefore, this study aims to:

- present designers and owners of water and wastewater treatment facilities with the life cycle environmental consequences of selected treatment methods or processes,
- highlight areas for improvement of the environmental performance of selected water and wastewater treatment processes, and
- alert the water industry to the benefits of using full life cycle assessment in the selection of processes and methods.

Therefore the objectives of the study, as presented in **Chapter 1**, are:

- to conduct life cycle assessments for one conventional and one membrane water treatment method,
- to compare the environmental burdens associated with each process, and
- to make the results and the methodology available to designers and owners of water and wastewater treatment facilities and to the water industry in general.

The *intended audience* or the target group for this study is made up of water authorities (in particular environmental and operational managers), engineers involved in designing new waterworks, scientists involved in the development of membrane technology, environmental authorities and environmental planners. In addition, LCA practitioners are expected to use this study since water is an input in most manufacturing processes.

The *reasons* for carrying out this study are primarily to generate LCA type of environmental information on the production of potable water. There is an increased demand for this type of information from other LCA practitioners, because water is an input in most industrial processes and, therefore, it is important to know the environmental consequences of producing this water. Another reason for performing this study is to compare a conventional method for producing potable water with a membrane method. Since the membrane technology is in development, the results of this study may influence and guide new developments in this area. These reasons explain why the Water Research Commission of South Africa funded this study.

4.2.2 Defining the Scope of the Study

The scope of the study should be *sufficiently well defined to ensure that the breadth, the depth and the detail of the study are compatible and sufficient to address the stated goal* (ISO 14040, 1997). Issues to be considered when defining the scope of the study are: the system under study with its functions and boundaries, the functional unit, allocation procedures of the environmental burdens for products and by-products resulting from the same process, data requirements, assumptions, limitations, type of critical review (if any) and type and format of the report for the study.

The *systems* under scrutiny in this study are the two methods (conventional and membrane) for producing potable water. These two methods have been described in **Chapter 3**. Both systems have one function, namely to produce potable water of a certain quality (see **Appendix 2** for quality guidelines) starting with raw water of identical quality. These quality specifications enable comparison on the base of the functional performance of the two systems.

The *functional unit* for this study is defined as follows: 1 000 kg (or 1 kL) of water at the quality stipulated in the Umgeni Water guidelines produced over the life period of a process unit. The functional unit is the unit to which all data collected in the inventory phase will be related and it will be the basis for comparison for the two methods of producing potable water. All impact scores produced in the impact assessment phase of this LCA study will be expressed referring to the functional unit.

The *boundaries* of the two systems are presented in **Figure 4.1** and **Figure 4.2**. These figures show the processes included and also show the processes which have been excluded and considered to be unimportant to the comparison. Initially the transportation for all the processes was included, however, after collecting data for the first few processes (cement production and the production of sand and stone) it became obvious that transport was responsible for only a

very small (in these cases insignificant) proportion of the environmental impacts. As a result it was decided to exclude transport and to perform a sensitivity analysis at the end of the study to justify this decision. Should the sensitivity analysis prove that for the overall system, transport is important, then it would be re-included. However, the sensitivity analyses proved that the exclusion was justified (see **Section 5.5.1**) for both systems. No other process was left out in the first iteration of this study and all direct inputs for both the methods have been included. However, due to the lack of data some second and third degree processes (i.e. processes used in production of the raw materials used for producing the direct inputs) were left out. The exclusion of these processes was considered acceptable due to their small contribution to the function of the system, as expressed in terms of the functional unit. In general, the contribution of these inputs was in the order of a few nanograms per kilolitre of potable water produced.

Allocation of environmental burdens (resource consumption and emissions) to products and by-products resulting from the same industrial process is a debated issue in LCA (see **Section 2.3.6.1** and **Appendix 1**). A series of methods have been used (LCA-NORDIC, Technical Reports No 1-9, 1995), but all of these methods have shortcomings. For this study, the production of potable water process does not need allocation, since there are no by-products; however, the production processes for many of the inputs (e.g. chlorine) require allocation, since a series of by-products result from the production process. In accordance to the precautionary principle, worst case scenarios have been used for these processes and the environmental burdens have been attributed in totality to the main product. The Author is aware that this may add an additional burden to the studied system. However, most of the allocation was needed at the secondary and tertiary level of data collection, where material amounts per kilolitre of potable water get smaller and smaller, and therefore, this additional burden is considered to be small.

Data requirements and priority were established.

- Direct measurements and first hand data on the processes involved were preferable.
- Mass and energy balances were employed where no direct measurements exist, but enough data must be obtained for the processes under scrutiny.
- Calculations based on the technical literature were used only if direct data could not be obtained. If such calculations were used, the results were checked against international data on the same process or the same technology.
- Data collected for the operation stage of the two methods of producing potable water covered a period of 28 months from 01 March 1998 to 30 July 2000. These data included monthly consumption of chemicals and electricity. The general timeframe for the data

collected on other processes was proposed to be up to 10 years, however, data based on older technology had to be accepted for a few of the processes involved.

- The geographical area for data collection was South Africa. In cases where information was lacking and could not be obtained, European or global data had to be used.
- With regard to the nature of the technology involved, if no information was available an average of the actual technology (as opposed to best available technology or worst operating unit) was used.
- Data quality indicators are needed in order to conform to the ISO 14041 standard. The methodology for data quality is still under debate; therefore, one of the most accepted models - the data pedigree developed by Weidema (see **Appendix 7**) – is used. The following indicators are considered: data precision, data completeness, data representativeness, data consistency and reproducibility.

A series of *assumptions* had to be made for both methods of producing potable water. The main assumptions for the conventional method are related to what is planned for the decommissioning stage (see **Section 4.3.1.3**) and to the calculations of the inputs for the polymeric coagulant. In the case of these calculations, it was assumed that for the production of allyl chloride and dimethylamine (the chemicals used for producing the monomer) the processes and the yields documented in the literature were the ones used in the actual manufacture. For the inputs on which international data had to be used, it is assumed that similar technology and processes as overseas are used in South Africa. Another important assumption for the conventional technology was made with regard to the different life spans of the components of process units in a waterworks. It was assumed that civil engineering structures (concrete tanks and buildings) have a life span of 30 years and that mechanical engineering structures (pumps and motors) have a life span of 10 years. The average life span for pipes was assumed to be 10 years, with the exception of steel, stainless steel and copper pipes which were assumed to last 30 years.

For the membrane plant a series of assumptions had to be made, not only with regard to individual processes on the plant, but also with regard to the entire design of the plant including the way it should be build, materials used, etc. These assumptions are enumerated in the following paragraphs.

- The membrane plant is housed in a warehouse type building with concrete foundations, steel structural frames and pillars and corrugated iron walls and roof. Calculations on the building materials needed for this type of structure were done with the help of Prof. King, School of Civil Engineering, University of Natal.

- The filtration unit preceding membrane filtration is the same in size and design as the one used for the conventional method.
- In the membrane plant, the pressure needed in the different lines for the transport of water and for actual filtration is as follows: filtration pressure 1.5 Bar, pressure loss 0.4 Bar, backflush pressure 2.2 Bar and permeate pressure 1 Bar. These pressures are important, since they are the basis for pumping requirements and electricity consumption due to this method.
- The arrangement of the pipes in the membrane plant was considered modular in accordance with current practice. Calculations have been done for different scenarios including different numbers of modules per bank (see **Section 3.2.3** and **5.2**). At this stage a series of assumption had to be made with regard to pipe lengths and thickness. These assumptions are based on chemical engineering design principles and are presented in **Section 3.2.3**. Similar engineering design calculations were used for pumps. For pumps, in addition to the pressure and the flow needed, efficiency calculations were included in order to approximate electricity consumption (see **Appendix 6**).
- In the manufacture of the filtration membranes three chemicals (polysulphone, polyvinylpyrrolidone and poly(ethylene glycol)) are used on which no data could be obtained, therefore calculations had to be employed. It was assumed that processes and yields as presented in the literature are used in the actual production of these chemicals.
- In the case of overseas data, it is assumed that a similar technology is employed to produce the same substance in South Africa.

Limitations to this study were expected in certain areas (see **Section 2.3.6**). A series of limitations specific to South Africa have emerged during the study (see **Section 2.3.6.2**). The limitations and problems experienced in this study are summarised below, more detail with regard to limitations of data obtained for individual processes is presented in the following section.

- The quality of the data obtained from some South African companies (e.g. Eskom and Polifin) was low and, therefore, South African data could not be used in a few instances.
- Some companies refused to release production data. As a result international data had to be used.
- Some data was not available locally and the producers overseas did not co-operate. Calculations base on literature had to be employed in these cases.
- In these calculations energy requirements are usually underestimated, due to the non-existence of energy consumption data.
- Data quality assessment is incomplete for two processes, since a combination of actual data and calculations had to be used. The two process are the production of the polymeric

coagulant for the conventional method and the production of membranes (i.e. three of the four chemicals used in the process) for the membrane method.

- Validation of some data was impossible, since access to company records was not granted.
- The lack of valuation methods for South Africa and the methodological uncertainties associated with this step prevented the Author from performing this optional step.

With regard to a *critical review* process, this study will undergo two of them. The first one is through the Water Research Commission steering committee procedure and the second one through the examining process (internal and external) of the current thesis. The steering committee has a critical review function; however, in terms of the ISO 14040 standards it may be considered as an internal review process, since it has been involved with the project from the beginning and had the opportunity to influence the research. Publication according to ISO 14040 standards is not possible without an external review process. The external and the internal examiners may perform the external review process, since they are independent and have not influenced the study in any way.

Reporting is done in the form of this thesis and a final report for the Water Research Commission.

4.3 Collection of Data and the Inventory Analysis

The inventory analysis is the second phase of an LCA study and it involves data collection and calculation procedures to quantify relevant inputs and outputs of the system studied. The collection of data was the most difficult and time-consuming stage in the entire research project. Once the processes involved in the production of potable water were investigated for both methods, all the inputs to and outputs from each process became known. Data was collected for all the processes used to produce these inputs (including energy) and for all processes used to deal with the outputs.

4.3.1 Collection of Data for the Conventional Method

For the conventional method, data collection started with the processes employed at Wiggins Waterworks (see **Section 3.1**) and **Figure 4.1** presents them in the context of the life cycle of the Wiggins Waterworks. In this figure the boundaries used for this study are illustrated and initially some of the processes now omitted were included.

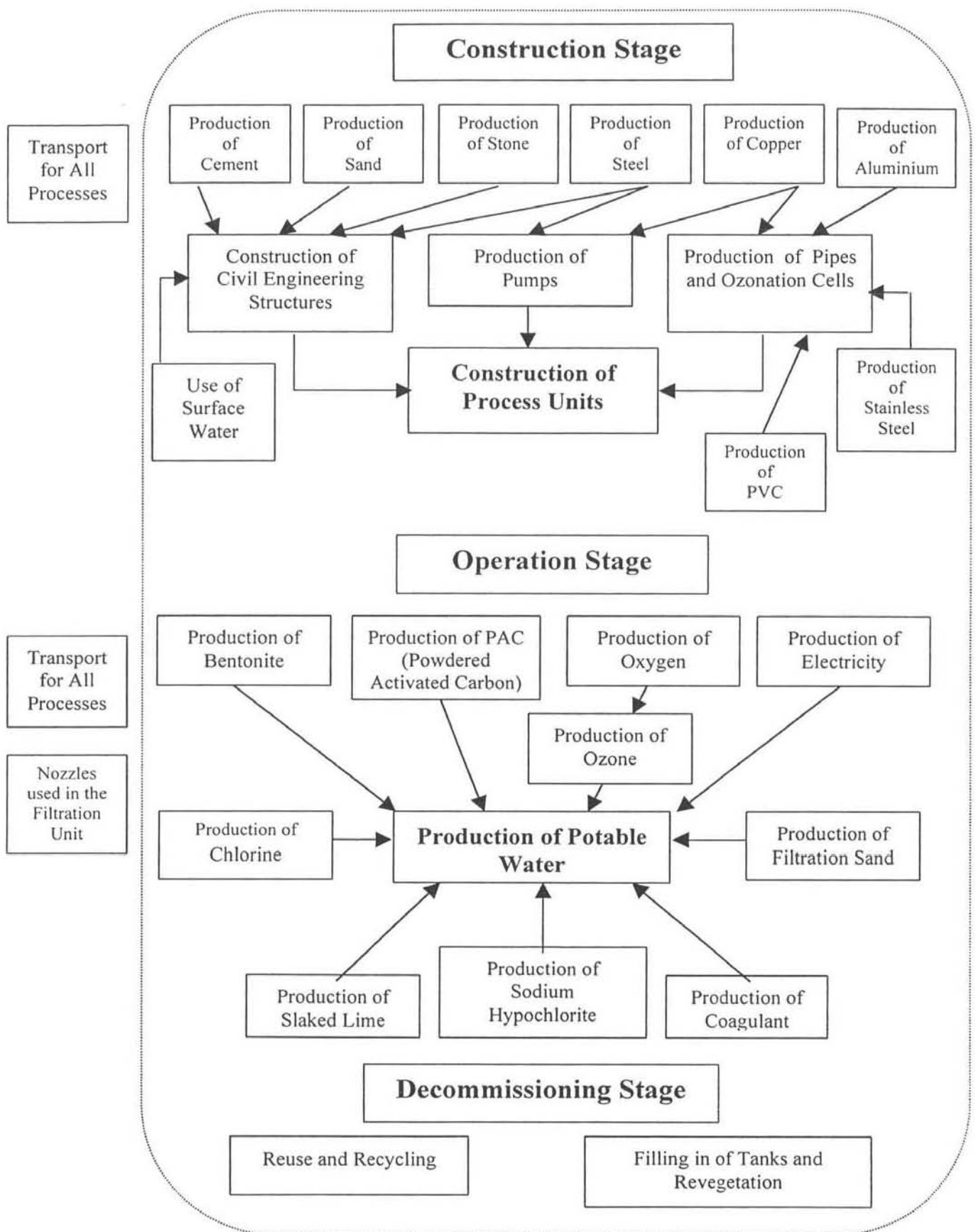


Figure 4.1: Life Stages and Processes Involved in the Production of Potable Water (Conventional Method).
The box represents the boundaries of the study, processes left out have not been included in the calculations.

The collection of data for the conventional potable water case proved to be one of the most time consuming steps. Most of the chemicals involved in the treatment of water were not included in the database purchased, nor were they in three other commercial databases consulted, since they are considered to be specialty chemicals. Therefore, basic data on the processes involved were obtained initially from the literature and then from different companies. Actual production data were requested from the suppliers and producers. This proved to be a challenging task because many of the companies involved, especially the small and medium enterprises and companies with perceived environmental problems, were not prepared to release this data.

An important educational effort was needed to change the attitudes of the people involved. Several meetings and many phone calls were necessary until they were convinced that LCA is not a threat to their products or markets but can be quite the opposite. With one exception, the supplier of bentonite, it was possible to gather local data for the production processes of the chemicals involved in the conventional method (calcium hypochlorite, molecular chlorine, sodium hypochlorite, polymeric coagulant, slaked lime and molecular oxygen). The situation was more complex with the polymeric coagulant, because many of the substances used in the blend are imported from overseas and Solvay (Belgium) and DuPont (Canada) had to be contacted for manufacturing data. However, there is very little control over the quality of the production data obtained, since the figures given by companies can not be directly checked. Where available, international figures were used to check if the range of the data given was correct. Data sheets containing information on the production process of each of the substances involved (excluding bentonite are included in **Appendix 9**.

In addition to data problems with external suppliers there were problems experienced with obtaining data from Wiggins Waterworks. Delays were experienced in collecting data on electricity consumption and on motors and pumps. Partially these delays can be explained by the preoccupation of technical staff with Y2K problems in October, November and December 1999 and partially by the nonexistence of data required. For example, there was no complete inventory of motors and pumps, and electricity consumption of individual processes is not measured. Special arrangements had to be made in order to obtain this data.

The educational aspect of this work has to be highlighted, because through interaction in the data gathering phase, the concept of life cycle assessment and the basic methodology was introduced to a broad spectrum of people. This included technical staff at Wiggins Waterworks and in the following companies: Natal Portland Cement, ARCH Chemicals, Zetachem, Natal Plastics, Fedgas, Polifin, Eskom, Transnet, SMX Explosives and Shell S.A.

4.3.1.1 Obtaining Data for the Construction Phase

The main inputs in the construction phase were: cement, sand, stones and steel for reinforcement (see **Figure 4.1**). Data on the production of cement were obtained from Natal Portland Cement. This company had a proactive attitude and allowed data collection and verification; therefore the quality of the data is good. The results, as presented in the final report presented to the company, are shown in **Appendix 9**. Some data on the production of construction stone and sand had to be estimated. For example, measurement data on emission gases resulting from the blasting explosions are not available. Locally, some studies have been done on underground explosions and estimates for blasting emissions have been obtained for underground conditions.

From the processes used in the construction phase, data collection problems have been experienced with regard to the production of steel and stainless steel, the production of copper and the production of PVC. The metals enumerated are produced in South Africa by ISCOR Ltd. and the company refused to release any data. It was motivated that the company is in the process of collecting this data to be aggregated in an international study initiated by the International Steel Manufacturer Association and at this stage their data set is incomplete and anyway the results will be published by the association. PVC manufacturers approached motivated that they do not measure data such as air and water emissions. Therefore, international data had to be used for these processes. It became obvious in the assessment stage, that the construction stage is of secondary importance in the life cycle, since it accounts for less than 10 % of the environmental burden for most of the impact categories considered in the production of potable water. Therefore, further detailed time consuming investigations have not been carried out.

4.3.1.2 Obtaining Data for the Production Phase

In the production of potable water, the main inputs are electricity and the chemicals used (see **Figure 4.1**). These chemicals are calcium hypochlorite, molecular chlorine, sodium hypochlorite, polymeric coagulant, slaked lime, activated carbon and molecular oxygen. Complete information on individual production processes has been obtained (see **Appendix 9**) with four exceptions: bentonite, electricity, chlorine and the polymeric coagulant. Data on bentonite had to be obtained from international sources (Denmark, Germany) since the South African company involved did not forward the relevant information, even after several attempts and months of waiting. Data for the production of electricity has been obtained from Eskom; however, since electricity proved to be very important in the assessment phase, similar data on

electricity production were used from a German coal plant. This was necessary because the data released by Eskom lacked detailed information, such as the trace elements emitted when burning coal and the complete list of inputs in the production of electricity. Eskom release only data on the amount of coal and water used and other inputs are not made public. It was particularly disappointing with regard to the Eskom data, since the company sponsored a study at UCT (University of Cape Town) to obtain a life cycle inventory for the production of electricity and the Author agreed to a confidentiality agreement in order to access that data. For the production of chlorine the same situation occurred. South African data on chlorine production was obtained from Polifin Ltd., however, detailed measurements on the inputs and outputs were not available and average international data had to be used. As mentioned in the previous chapter, the polymeric coagulant used is a blend of a variety of chemicals, most of them being imported and as a result South African data were not available. Solvay (Europe) and DuPont (Canada) were contacted, however, there were no LCA data available from these companies. Therefore, calculated data has been used. These calculations have been confirmed by Prof. Michael Overcash, Department of Chemical Engineering, North Carolina State University, USA. Prof. Overcash and his research group are doing extensive calculations for gate-to-gate life cycles on different chemicals based on chemical engineering process design (Overcash et al., 2000).

4.3.1.3 Obtaining Data for the Decommissioning Phase

Data for the decommissioning phase was obtained from the existing information on decommissioning of waterworks by Umgeni Water. Particular attention was paid to what is recycled and what is disposed of and how. Since no waterworks of this size has been decommissioned by Umgeni Water, some assumptions had to be made. The two major assumptions were that all materials which can be recycled will be recycled and that if tanks can not be used for other purposes (for example fish farming) they will be filled in with soil and the area revegetated.

4.3.2 Collection of Data for the Membrane Case

The collection of data for the membrane case proceeded in the same fashion and presented similar problems as the conventional case. However, as it can be seen from **Figure 4.2** in the production of water by the membrane method, there are some identical processes (production of cement, sand, stone, steel, copper and PVC) to the conventional method, so separate collection of data for these processes was not repeated. The collection of data started with the production of the membranes and the production of filtration modules. It continued with the collection of

data on how potable water is produced at the membrane pilot plant. An upscaling exercise followed whereby a large-scale membrane filtration plant was designed to produce the same quantity of potable water at the same quality as the conventional plant at Wiggins Waterworks. This was necessary to enable comparison between the two methods using the LCA methodology, where a functional unit of 1 kL of water of a stipulated quality was used.

As can be seen from **Figure 4.2** there are only three new processes in the membrane case as compared with the conventional case. These are the production of epoxy resin, the production of polyethylene and the production of membranes. South African data for the production of epoxy resins and polyethylene was incomplete and therefore European data (contained in the GaBi 3 database) had to be used. The chemicals involved in the manufacture of membranes are: polysulphone, polyvinylpyrrolidone, poly(ethylene glycol) and N,N-dimethylformamide. Manufacturing data on the latter chemical was obtained from Prof. Overcash, University of North Carolina. Data on the production of membranes had to be calculated for three chemicals (polysulphone, polyvinylpyrrolidone, poly(ethylene glycol)) since the manufacturing company BASF Europe, was not prepared to co-operate. From the production data in the literature it was impossible to calculate complete energy figures, thus energy figures for these three chemicals are underestimated.

4.3.3 Validation of Data

Validation of data has been done for each of the processes presented in **Figure 4.1** and for those presented in **Figure 4.2**. For processes on which data was collected directly from the manufacturing company validation was done by comparing this data with similar South African and/or international data. For example, data on cement production was compared with partial data (only greenhouse gases) from the South African Cement and Concrete Institute and with complete Danish data on the manufacture of a similar type of cement. For processes on which data could not be obtained or was incomplete, international data were used. The international data were obtained from the GaBi 3 LCA tool and for a few specialty chemicals (not included in the GaBi database) from Prof. Overcash, University of North Carolina. These data were validated overseas and therefore they were used as such. Checking the calculations and the parameters was the technique used to validate calculated data.

4.3.4 Relating Data to Unit Processes and Functional Unit

The data for each process was scaled for the production of 1 kg of product when mass was used, for energy the unit required by GaBi 3 is the MJ (mega Joule). This involved simple conversion

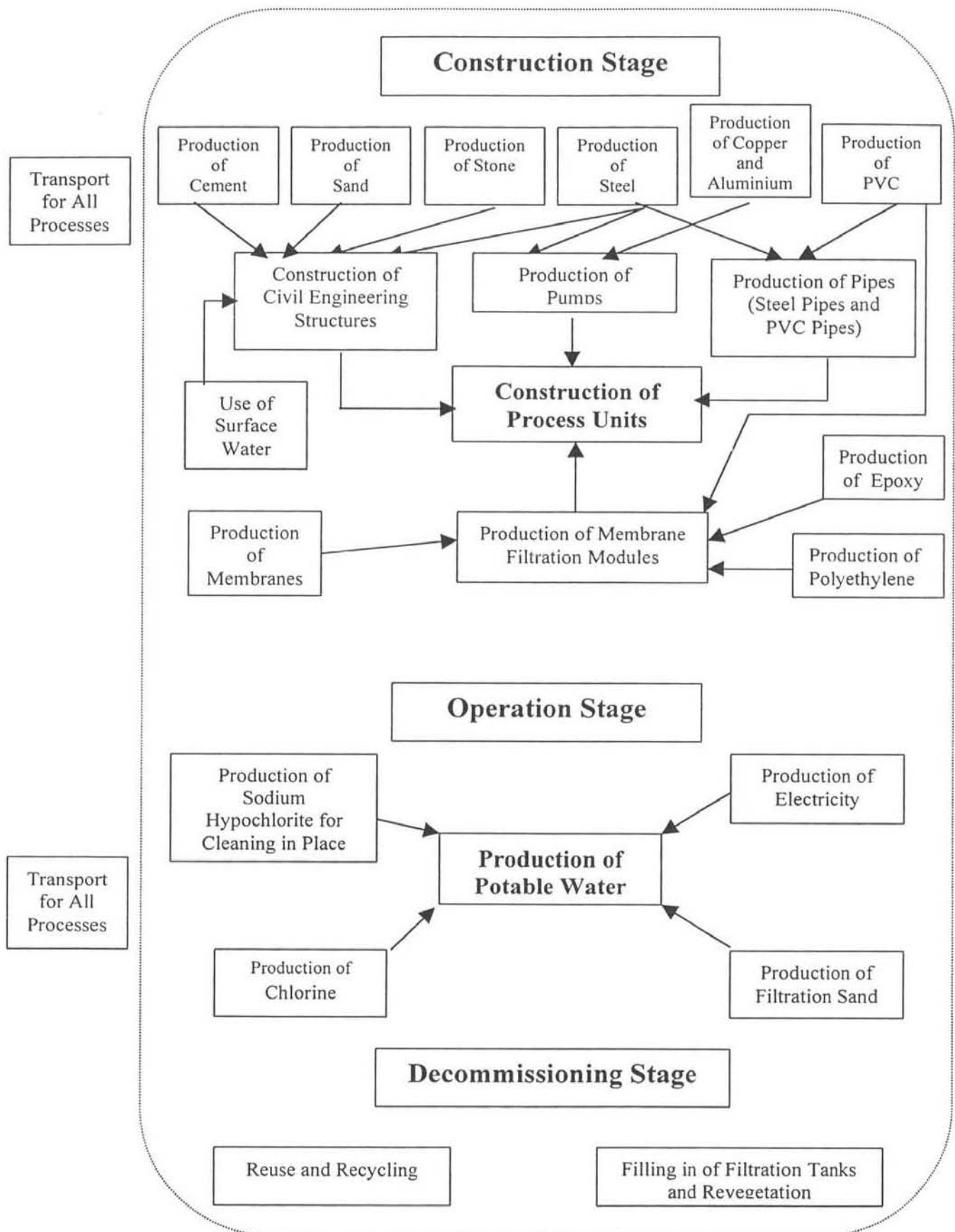


Figure 4.2: Life Stages and Processes Involved in the Production of Potable Water (Membrane Method).

The box represents the boundaries of the study, processes left out have not been included in the calculations.

calculations. In this form it was entered into the GaBi 3 LCA tool as new individual processes. A new flowsheet for each method of producing potable water (conventional and membrane) had to be drawn in this programme. Since they are the bases for the following calculations, these flowsheets had to be configured according to the requirements of the LCA tool, and mass was used as reference flow from one process to the other. All the processes on each flowsheet were then scaled for the production of the functional unit (1 kL of potable water). This is another simple calculation performed by the program.

4.3.5 Data Aggregation and the Inventory

Data aggregation leads to the production of the inventory table, which is a collection of all normalised (or scaled) values for all inputs and outputs for all processes involved in a system. Two inventory tables have been produced, one for the conventional method of producing potable water and one for the membrane method. These inventory tables are presented in **Appendix 8**. To produce an inventory, the individual processes have to be entered with their inputs and outputs in the GaBi 3 tool, and the flowsheet (also called process plan in the GaBi tool) has to be designed. The program then allows a system balance to be calculated and the inventory is automatically produced. Once the inventory is produced, the relative importance of the inputs and outputs from the different processes in relation to each other and the functional unit become evident. At this stage some of the processes may be excluded because of their small contribution and some additional processes may be required. By this the boundaries of the system under study are refined (see **Figure 2.3**). However, for this study, for both systems (conventional and membrane) no process was excluded or included at this stage. The inventory table enables further calculations for the next phase of the LCA, namely the impact assessment.

4.4 The Impact Assessment and the Use of the GaBi 3 Electronic LCA Tool

The impact assessment (see **Section 2.3.3.3** and **Appendix 1** for theoretical background) is the third phase of an LCA study. It has been defined as the phase of the LCA aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis (ISO 14040, 1997). In other words, it is the phase in which all the inputs and outputs from a system are related to potential environmental impacts and effects. These impacts and effects are quantified, allowing for comparison between two systems. For this phase the ISO 14042 standard (2000) stipulates three mandatory elements (category definition, classification and characterisation) and four optional elements (normalisation, valuation, grouping and data quality analysis) to be carried out. In this study the mandatory elements were believed to be sufficient and only these elements were performed on both systems (conventional and

membrane). Sensitivity analyses, which are part of the optional data quality step, were also performed. The other optional steps were left out because they involve value choices and introduce a high degree of subjectivity without enhancing the value of the study.

The GaBi 3 LCA tool influences the way the three optional elements were performed. For the category definition step, this tool has a list of predefined categories and for the classification step the calculation tool of GaBi 3 is based on the CML (Center of Environmental Science, University of Leiden, The Netherlands) methodology.

4.4.1 Category Definition

A number of environmental impact categories have been defined and used in LCA studies. These impact categories are selected in order to describe the environmental impacts caused by the system under study (see **Section 2.3.3.3**) and most of the current studies will select from the categories already developed. It is important that the impact categories selected are consistent with the goal and scope of the study (Jensen et al., 1997).

Categories developed so far in the literature have been grouped in to two major classes:

- impacts due to depletion of resources (renewable and nonrenewable or sometimes biotic, abiotic and land use) and
- impacts due to pollution (greenhouse effect, depletion of the ozone layer, photochemical oxidant formation, acidification, eutrophication, terrestrial and aquatic ecotoxicity, human toxicity, working environment or occupational health, radiation, waste heat, noise and odour).

These impacts cause direct or indirect environmental degradation and sometimes human casualties.

In this study the impact categories predefined by the GaBi 3 tool were used. These categories are resource consumption (biotic and abiotic expressed together), energy consumption, global warming, ozone depletion, acidification, eutrophication (or nutrification), photochemical oxidant formation, radioactivity, aquatic ecotoxicity, terrestrial ecotoxicity and human toxicity. In addition to these categories, two separate ones considered important to the South African environment are discussed. These are water consumption and salination. These categories and some background information on their characterisation models, as described by the CML methodology, will be presented in the following paragraphs.

4.4.1.1 Global Warming

Global warming is the impact caused by the emission of certain substances (e.g. carbon dioxide) which absorb infrared radiation emitted by the earth, upsetting the earth's natural radiation balance. They cause an increase of the temperature of the atmosphere due to an additional greenhouse effect. Global warming is predicted to have far reaching consequences like rises of the sea level (due to the melting of icecaps and glaciers, as well as due to heat expansion of the oceans), regional climatic changes and other indirect negative impacts on ecosystems and the society (spreading deserts, floods, loss of arable land and loss of habitats and species). The most important man-made greenhouse gases are carbon dioxide, methane, nitrous oxide and halocarbons (Hauschild and Wenzel, 1998).

In the order of causality in the global warming effect chain, the man-made greenhouse effect is the primary effect, the change in temperature (i.e. global warming) is the secondary effect and the rises in sea level would be a tertiary effect. The ease of predicting these effects and the accuracy of the prediction decreases as the order of the effect increases and therefore it is best to link the inputs and outputs of a system with the lowest order of effect (Forbes, 1999).

The characterisation model for global warming is based on the above causality and global warming characterisation factors have been developed through the work of the Intergovernmental Panel on Climatic Change (IPCC). This is an international panel of researchers established by the United Nations Environmental Programme (UNEP) and the World Meteorological Organisation (WMO). The reference substance is carbon dioxide and through modelling, characterisation (or equivalency) factors were developed for a number of greenhouse gases (Hauschild and Wenzel, 1998). The characterisation factors are sometimes called global warming potentials (GWP) and are expressed as kg carbon dioxide equivalents per kg of gas. A list of the characterisation factors for global warming is presented in **Appendix 10** and it includes different time horizons (20, 100 and 500 years) for degradation. These are the values used by GaBi 3 in this study and a global warming potential can be calculated for all three time frames. For comparison of the different methods of producing potable water, in this study, the 100 years timeframe was used since it is the one most frequently selected by studies in the literature.

4.4.1.2 Stratospheric Ozone Depletion

The thinning of the ozone layer in the stratosphere is allowing increased levels of ultraviolet radiation to reach the earth, leading to impacts on humans (skin cancer and cataracts) and on

ecosystems (plants and animals – e.g. effects on the phytoplankton around the South Pole) (Jensen et al. 1997). The concentration of ozone in this part of the atmosphere is a result of natural processes which break down and regenerate ozone. These processes are based on complicated reaction systems, including both solid phase and gaseous phase reactions, and a limited number of substances are involved (Hauschild and Wenzel, 1998). Most notably methane, nitrous oxide, water vapour, chlorine and bromine compounds (like methyl chloride and methyl bromide) are responsible for the breakdown of ozone molecules.

Human activities have increased the amount of substances involved in the breakdown of ozone and especially stable, long-lived chlorine and bromine containing hydrocarbons (i.e. chlorofluorocarbons or CFCs, tetrachloromethane, trichloroethane, etc.) are believed to contribute considerably. As a result a seasonal reduction of up to 50% of the ozone quantity above the South Pole has been observed since 1985. Less dramatic seasonal reductions (shorter and with less ozone depletion) were observed also over the northern hemisphere. As a result an international initiative called the Global Ozone Research and Monitoring Project was launched by UNEP (United Nations Environmental Programme) in co-operation with WMO (World Meteorological Organisation), NASA (National Aeronautics and Space Administration, USA), NOAA (National Oceanic and Atmospheric Administration, USA) and the UKDoE (United Kingdom Department of Environment). This initiative developed models on ozone depletion mechanisms and calculated consecutive characterisation (or equivalency) factors for the major substances involved in ozone depletion (Hauschild and Wenzel, 1998). The reference substance for calculating characterisation factors is trichlorofluoromethane - CFC-11 (with the chemical formula CFCl_3). **Appendix 11** presents a list of characterisation (equivalency) factors for ozone depletion and these are the ones used in the GaBi 3 tool in this study.

4.4.1.3 Acidification

Acidification is the environmental impact caused by the build-up of protons in soils and lakes or, according to Hauschild and Wenzel (1998), it is a fall in the system's acid neutralisation capacity. Higher acidity in certain types of soils cause the mobilisation of different fixed ions, which are then absorbed by plants and damage them. Run-offs from acidic soils can harm aquatic ecosystems in the different lakes and rivers and in worst cases render them lifeless (Mannion and Bowlby, 1995). Acidification can be caused directly by acids and indirectly by acidic anhydrides (sulphur dioxide and trioxide and oxides of nitrogen) and ammonia. For the indirect mechanism, acidic anhydrides form the relevant acid after the contact with water (e.g. moisture in the atmosphere and in the soil). In the case of ammonia, hydrogen ions are released upon bacterial mineralisation.

The reference substance in the calculation of characterisation factors (or equivalency factors – EF) is sulphur dioxide and these factors are calculated based on the maximum quantity of hydrogen ions which can be released to the environment by an acidifying substance (Hauschild and Wenzel, 1998). **Appendix 12** presents a list with the equivalency factors used in this study.

4.4.1.4 Eutrophication or Nutrification

Eutrophication or nutrification is an “overfertilisation” of soils and waterbodies. In waters it causes excessive algal growth and negative modification of the aquatic ecosystems involved (oxygen depletion and death of certain species). In soils it promotes monocultures and loss of biodiversity (Miller, 1995). Since nitrogen and phosphorus are the limiting nutrients for most of the aquatic systems, leaching of these nutrients into waterbodies results in eutrophication.

The calculation of characterisation (or equivalency) factors takes into account the amounts of phosphorus and nitrogen a substance can release into the environment when degraded and the reference substance used by GaBi 3 is phosphate. The equivalency factors for this category are listed in **Appendix 13**.

4.4.1.5 Photochemical Oxidant Formation

This environmental impact is caused by the presence of nitrogen oxides and volatile hydrocarbons in air in combination with sunlight. This combination results in the photochemical oxidation of hydrocarbons and the formation of smog. Smog is harmful to people, flora and fauna. Different photo-oxidants (some more stable than others) are the constituents of smog, the most important ones being ozone and peroxyacetyl nitrate (PAN) (Hauschild and Wenzel, 1998). The so-called winter smog occurs during cold conditions and is made up mainly by small particulate matter and sulphur dioxide. It causes respiratory problems (Miller, 1995).

The capacity to contribute to photochemical oxidant formation varies greatly between the different volatile organic compounds (VOC) and in the literature it is described by the Photochemical Ozone Creation Potential (POCP) (see Hauschild and Wenzel, 1998, for a detailed discussion of POCPs) for individual substances. The reference substance for photochemical oxidant formation is ethene (C_2H_4). The equivalency (or characterisation) factors are calculated by using POCPs and the list of characterisation factors used for this impact category in this study is presented in **Appendix 14**.

For the four impact categories presented above there is a high degree of agreement within the LCA community about the mechanisms of causality and the characterisation (or equivalency) factors derived. However, for the following impact categories associated with toxicity there is no consensus, and different methods of quantifying toxicity are used in the literature. Debate on methodology to quantifying toxicity (especially ecotoxicity) is expected to continue, because of the complexity of the mechanisms involved where emissions, fate, exposure, bioaccumulation and biodegradation have to be considered.

4.4.1.6 Aquatic and Terrestrial Ecotoxicity and Human Toxicity

Toxicity to humans, flora and fauna is caused by a variety of substances, ranging from carcinogens to persistent toxins such as heavy metals. Some act directly by poisoning organisms, others are more insidious, causing indirect harm to ecosystems.

In the GaBi 3 tool, the reference substance is 1, 4 dichlorobenzene (DCB). The characterisation (or equivalency) factors have been calculated based on the *Uniform System for the Evaluation of Substances* (USES), of the Leiden University (The Netherlands) and the Netherlands National Institute of Public Health and Environmental Protection. The model is described in detail in the publication *LCA Impact Assessment of Toxic Releases* (Publication No.1996/12 of the Dutch Ministry of Housing, Spatial Planning and Environment Industry; Building, Manufacture and Consumers Directorate).

In calculating equivalency factors for toxicity, the following issues have been incorporated: lethal concentration for 50 % of a population (LC_{50}), no observed effect concentration (NOEC), equilibrium partitioning factors (soil – water, water – air and air – soil) and a bioaccumulation factor. However, it must be underlined again that biological processes involving toxicity are very complex and simplifications, as expressed by the equivalency factors, have to be regarded with caution. Some shortcomings of the methodology involved in the calculation of equivalency factors are:

- for some chemicals there are no experimental LC_{50} and NOEC values, approximations are used,
- the LC_{50} and NOEC values derived experimentally are determined by testing chemicals on one or sometimes up to three species, however, for other species these values are totally different,
- for heavy metals and pesticides background levels are important, however, in this method they are not considered.

There are international initiatives to reduce these shortcomings (most notably work done at the Universities of Leiden and Amsterdam – The Netherlands) and probably in the future equivalency factors for ecotoxicity and human toxicity will be perfected. The ones used in this study are presented in **Appendix 15**.

4.4.1.7 Resource and Energy Consumption

In this study resource and energy consumption are taken into account with regard to total material consumption for a process and total energy consumption for a process. Since in this study the amounts of non-renewable substances per functional unit are small for both methods of producing potable water, these resources have not been treated separately and were included in the overall material consumption of the two methods.

4.4.1.8 Water Consumption and Water Intensity of Processes

Water consumption should be included as an impact category because South Africa is a water scarce country. It is a semi-arid country with an average rainfall of ca. 500 mm p.a. This is well below the world average of 860 mm. There is also a problem with the geographical distribution of the water supplies in relation to the demand, in the sense that the demand is greatest in the interior of the country, whilst untapped water resources are situated along the coast (Middleton, 1998).

With planned industrial growth and increasing demand for water, every possible step should be taken towards the optimum use and recovery of water. The South African industry accounts for about 7% of the consumption of fresh water in South Africa, however, the volume and nature of wastewater generated in industry has a substantial effect on the quality of water in the country (Middleton, 1998).

The consumption of water expressed as litres of water per kilogram of product for each process was initially calculated. In a next step the water consumption for each method of producing potable water (conventional and membrane) was calculated as liter of water per functional unit (1 kL of potable water). It was thought that these consumption figures should give a measure of the water intensity of the processes considered. However, for many of the processes on which data from overseas was used, water consumption figures were lacking. As a result the calculated water consumption for each method was incomplete and a comparison between methods was not possible. This shortcoming highlights the need for developing a South African methodology for assessing the importance of water consumption and the water intensity of processes.

4.4.1.9 Salination

Salination is another impact category of particular importance for the South African environmental context. Salination is listed as one of the key pollution areas in this country (Department of Environmental Affairs and Tourism, 2000) and has important economical and financial implications (Urban Econ, 2000). Salination is the increased concentration of dissolved inorganic compounds in waterbodies and it causes a decrease of the quality of water. The effects on the users are known and in most cases pre-treatment of water is necessary due to the decreased quality of water. However, little is known on the effects of salination on aquatic ecosystems.

There is no developed impact assessment methodology for salination and this problem has to be addressed urgently by initiating research on the topic. Of special interest are the chemical species which play an important role in this process, the development of equivalency factors and the choice of a reference substance. In this study salination was not used as a quantitative impact category.

4.4.2 Classification

Classification is the second step in an LCA impact assessment. This is the step in which all the inputs and the outputs from an inventory list are assigned to the impact categories chosen (see **Section 2.3.3.3**). In this study this step was done automatically by the GaBi 3 LCA tool. The database created for each inventory has a search field which enables this function. Therefore, it is important when entering data about processes to check that all inputs and outputs have this field correctly entered.

4.4.3 Characterisation

Characterisation is the third step in an impact assessment in an LCA study and it entails mathematical calculation procedures in order to obtain one score for each impact category (see **Section 2.3.3.3**). The characterisation (or equivalency) factors used for this study for each category are presented in **Appendices 10 to 15**. The mathematical calculations whereby the amount of a substance is multiplied by its equivalency factor and the adding of scores for each impact category, are done automatically by the GaBi 3 tool. Contributions of each substance group (like heavy metals to air) to the overall score of an impact category can be delimited by using the GaBi 3 tool, and the results can be displayed in the form of tables or in the form of

graphs. The tables produced by the GaBi 3 tool are of limited use since they are highly aggregated, however, graphs are more explicit, as can be seen in the following chapter.

The last stage in conducting an LCA according to ISO 14040 is the interpretation stage. In this thesis the interpretation stage is presented as two different chapters, since, from an academic point of view, it represents the results and discussion chapter and the conclusion and recommendation chapter.

CHAPTER 5

RESULTS, DISCUSSIONS AND THE INTERPRETATION OF THE LCA STUDY

*But by measure and number and weight thou didst order all things
(The Bible – Wisdom of Solomon)*

The interpretation is the fourth phase in an LCA study and according to the ISO standards the objectives of this stage are to analyse results, explain limitations, reach conclusions and provide recommendations. In this thesis the interpretation phase is presented in two chapters. The current chapter will be concerned with the first two objectives, namely the analysis of results and the explanation of limitations, and the next chapter will present the conclusions and recommendations.

This chapter presents the environmental profiles of the two systems studied for the production of potable water. Individual contributions to each impact category will be discussed and the major contributors underlined. The environmental profiles (with scores for each impact category) are used to compare the environmental performance of the two methods for producing potable water, based on the processes and the conceptual framework presented in **Figure 3.1**. This chapter also compares the results of this study with those of similar international studies and presents the sensitivity analyses undertaken.

5.1 Results for the Conventional Method for Producing Potable Water

As presented in **Figure 3.1** and in **Figure 4.1**, the life cycle stages considered for the conventional method of producing potable water are the construction stage, the operation stage and the decommissioning stage. Individual processes associated with each of these stages are presented in **Figure 4.1** and data were collected on these processes (see **Appendix 9**), tracing each input and each output to the system - environment interface. With regard to the inputs, the first two impact categories considered are resource consumption and energy consumption and the values for these two categories are presented in **Table 5.1**.

Table 5.1 Material and Energy Consumption for the Conventional Method

Stage	Material Consumption (kg/kL)	Energy Consumption (MJ/kL)
Construction	0.0515	0.0873
Operation	2.7000	2.0670
Decommissioning	0.0002	0.0015

The operation stage carries the highest burden with regard to material and energy consumption and the decommissioning stage the lowest.

With regard to the outputs, by using the data gathered and the LCA methodology as presented in the previous chapter, the environmental profile for the conventional method was calculated. This environmental profile is presented in **Table 5.2**.

Table 5.2: The Overall Environmental Profile for the Production of Potable Water by the Conventional Method (Worst Case Scenario)

Impact Category	Score	Unit
1. Global Warming Potential	1.85E-01	kg CO ₂ equivalents
2. Ozone Depletion Potential	3.61E-09	kg CFC-11 equivalents
3. Acidification Potential	1.10E-03	kg SO ₂ equivalents
4. Eutrophication Potential	7.40E-05	kg Phosphate equivalents
5. Photo-oxidant Formation Potential	1.57E-05	kg Ethene equivalents
6. Aquatic Ecotoxicity Potential	2.73E-03	kg DCB* equivalents
7. Terrestrial Ecotoxicity Potential	2.59E-01	kg DCB equivalents
8. Human Toxicity Potential	4.09E-03	kg DCB equivalents

*DCB is 1, 4 dichlorobenzene

For the construction phase there were two sets of data for the volume of concrete poured when constructing the process units in 1983 and 1984. The one set of data was collected from civil engineering plans, however, plans for some units were missing and therefore tanks had to be measured and the concrete volume estimated. This was problematic for tanks which are totally or partially underground and/or are filled with water. The other figure for total concrete consumption was taken from an Umgeni Water publication and it represents the total concrete used for Wiggins Waterworks, including the concrete ducts from the dam to the waterworks and the storage reservoirs. This figure includes buildings not used directly in the production of

potable water (e.g. the control center and the research facility) and therefore it is higher. It was used for the worst case scenario – the scenario presented in the table above. To put it in perspective it must be mentioned that the volume of concrete for the worst case scenario is about 4 times larger than the volume estimated through calculations.

The overall score is made up by the summation of the scores for the individual life cycle stages, i.e. construction of operation units, production of potable water and decommissioning of operation units. **Table 5.3** presents the scores for these stages and their proportion to the overall score. Note that the units for the impact categories are the same as in **Table 5.2** and are therefore not repeated.

Table 5.3: Environmental Profiles for the Construction, Operation and Decommissioning for the Conventional Method (worst case scenario)

Impact Category	Construction	Operation	Decommissioning
1. Global Warming Potential	1.14E-02 (6.18)*	1.73E-01 (93.74)	1.48E-04 (0.08)
2. Ozone Depletion Potential	3.90E-10 (10.81)	3.21E-09 (88.94)	9.16E-12 (0.25)
3. Acidification Potential	7.81E-05 (7.09)	1.02E-03 (92.87)	4.92E-07 (0.04)
4. Eutrophication Potential	8.47E-06 (11.44)	6.55E-05 (88.50)	4.30E-08 (0.06)
5. Photo-oxidant Formation Potential	2.48E-06 (15.75)	1.32E-05 (83.89)	5.67E-08 (0.36)
6. Aquatic Ecotoxicity Potential	6.25E-05 (2.29)	2.66E-03 (97.65)	1.52E-06 (0.06)
7. Terrestrial Ecotoxicity Potential	2.73E-02 (10.55)	2.31E-01 (89.22)	5.85E-04 (0.23)
8. Human Toxicity Potential	7.39E-04 (18.08)	3.31E-03 (81.00)	3.75E-05 (0.92)

** the values in brackets represent the percentage value of the total score for that category*

From the percentage values presented in brackets, it is obvious that for the conventional method the operation stage (the stage in which potable water is produced) has the most significant contribution for the overall environmental profile. For all of the categories considered the contribution from this stage is greater than 80 %, with some of the categories such as aquatic toxicity, global warming and acidification being greater than 90 %. Since this stage is predominant, the major contributors to the environmental scores for each impact category were deaggregated. The flow diagram used to model this stage in the GaBi 3 software tool is presented in **Figure 5.1**. All the processes presented in this figure have been

A: Production of potable water

GaBi 3 - Prozeßplan

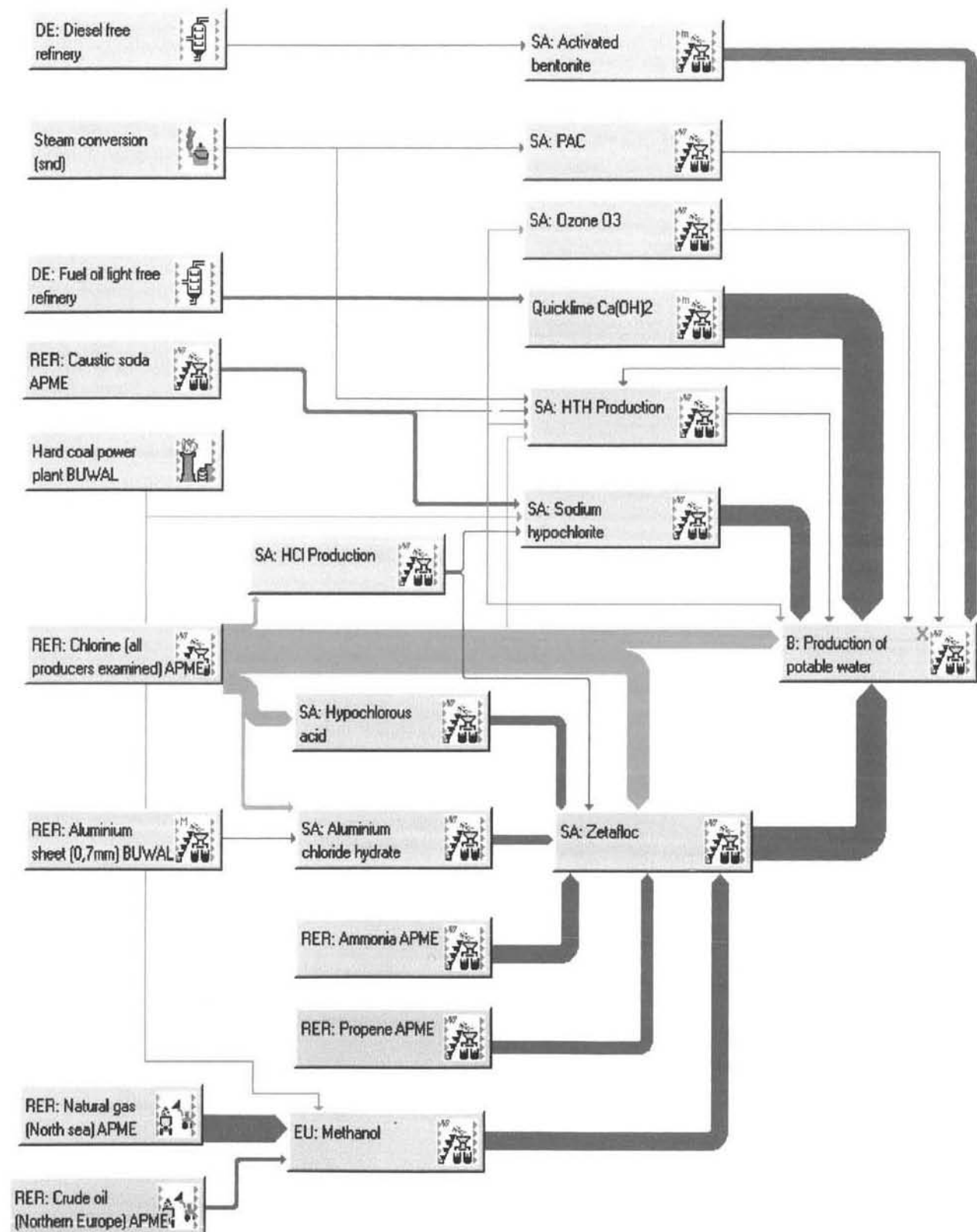


Figure 5.1: GaBi 3 Process Plan for the Conventional Method for the Production of Potable Water – Operation Stage

traced to the interface between the system and the environment (see **Appendix 9**), i.e. the inputs have been followed to raw materials extracted and the outputs have been classified as usable products and emissions to water, air and soil. The thickness of the arrows in the diagram is proportional to the quantity of mass transferred from one process to another (with the exception of electricity and steam where energy units (MJ) are used). As can be seen, some of the inputs (e.g. chlorine) are used directly in the production of water but also indirectly for the production of other chemicals which enter the production process. Note that in the case of aluminium production, data on the production of aluminium sheets was chosen to be closest to those of aluminium chips which are used in the production process for aluminium chloride hydrate. The abbreviation in the process boxes identify the origin of the data used (i.e. EU stands for European Union, APME for Association of Plastic Manufacturers in Europe, etc., please see the list of abbreviations).

For the impact category of *global warming* the major contribution in the operation stage is traced back to the production of electricity from coal. Electricity production accounts for about 93 % of all the contributions to global warming from the operation stage and, as shown in **Figure 5.2**, the inorganic emissions to air resulting from this process are the main contributors. The chemicals with the highest contributions are carbon dioxide and methane. For the operation stage, carbon dioxide accounts for about 85 % of the score and methane for about 8 %.

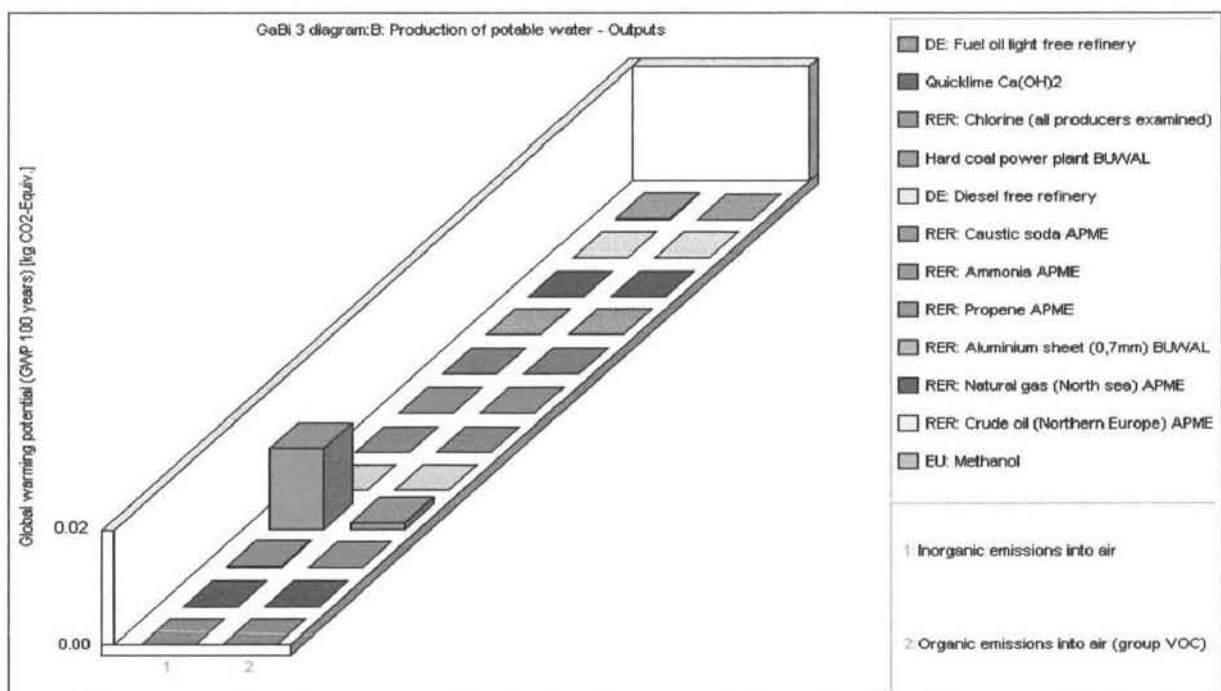


Figure 5.2: Contributors to Global Warming for the Operation Stage (Conventional Method)

For the construction stage (which accounts for 6.18 % of the overall, see **Table 5.2**) the two main contributing processes are the production of steel, accounting for 49.80 % (of the 6.18 % overall), and the production of cement, which accounts for 49.32 % (of the 6.18 % overall). For the decommissioning stage the main contribution to global warming (96.67 % of the 0.08 % overall) comes from the recycling of steel from pipes and pumps.

The recycling of steel has an environmental burden, however for this system the burden is small. It must be noted that besides this burden, steel recycling has positive environmental consequences because it replaces a virgin non-renewable resource. In this study, this positive spin-off is taken into account only with regard to the mass flow (i.e. the amount of virgin steel which does not have to be produced) and not with regard to emissions (i.e. the emissions which are not produced due to the replacement of virgin steel with recycled steel). Therefore, the environmental burdens are not completely compensated for by the benefits. In this case, because of the small amounts involved, this shortcoming is considered to be of minor importance. However, in other studies it may be important, and this aspect should not be neglected.

For the impact category of *ozone depletion* the same pattern is observed, with electricity generation being the main contributor. For the operation stage 95.24 % (of the 88.94 % overall, see **Table 5.2**) come from VOC (volatile organic compounds) emissions due to the generation of electricity from coal. The remaining 4.76 % of the overall are traced to the production of aluminium. For the construction stage (which accounts for 10.81% of the overall) the two contributing processes are steel production (94.95 % of the 10.81 % overall) and aluminium production (the rest). For the decommissioning stage the recycling of steel has the highest contribution (91.85 % of the 0.25 % overall).

For the impact category of *acidification*, of the 92.87 % (see **Table 5.3**) contribution due to the operation stage about 84 % is attributed to the generation of electricity, specifically to the inorganic emissions to air due to this process. **Figure 5.3** illustrates these contributions. When deaggregating further it becomes evident that sulphur dioxide and nitrogen oxides are the dominant inorganic contributors. About 59 % of the acidification potential of the operation stage is attributed to sulphur dioxide and about 26 % to nitrogen oxides due to the generation of electricity.

In the construction stage, the main contributor to acidification comes from the production of cement (76.6 % of the 7.09 % overall). The main contributor in the decommissioning stage (representing 0.04 % of the overall) is steel recycling (accounting for 94.88 % of the 0.04 % overall).

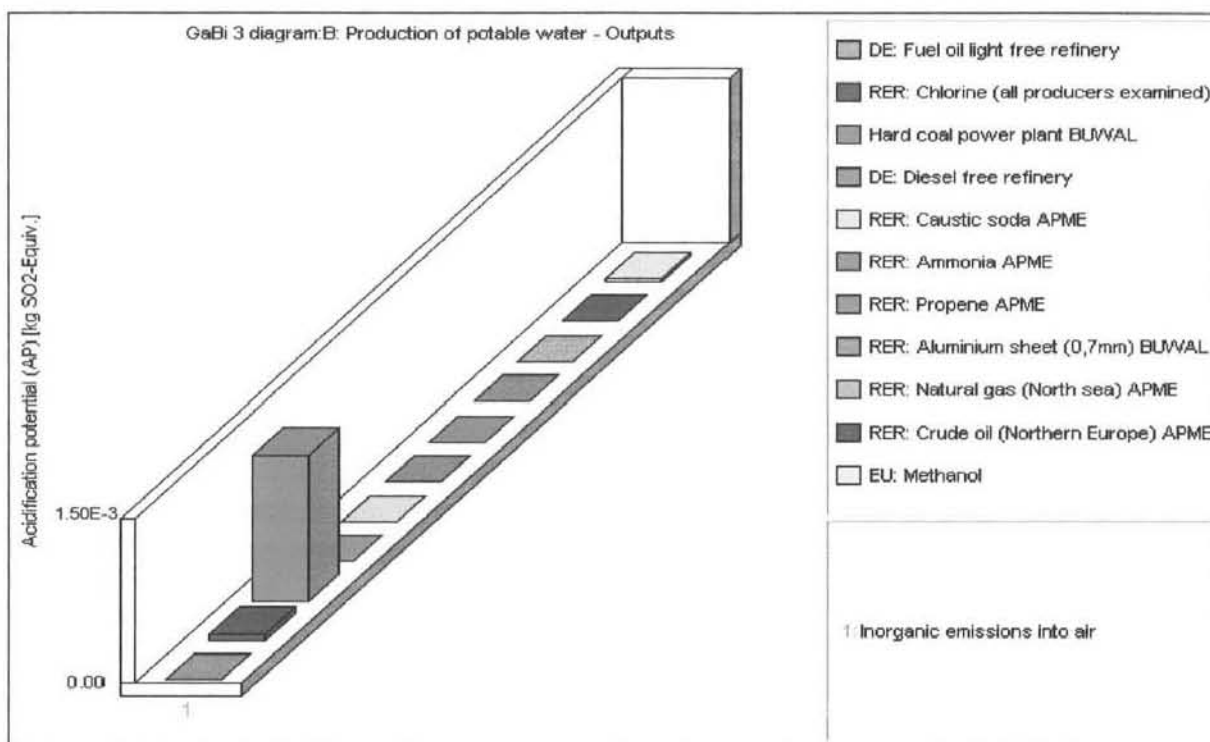


Figure 5.3: Contributors to Acidification for the Operation Stage (Conventional Method)

A similar pattern of contributions is observed with regard to *eutrophication* (or nutrification). In the operation stage 91.87 % of the 88.50 % overall (see **Table 5.2**) is traced to the generation of electricity in hard coal power plants as shown in **Figure 5.4**. In the construction stage the production of cement has the highest contribution (82.68 % of the 15.75 % overall) and in the decommissioning stage the recycling of steel contributes the most (92.16 % of the 0.06 % overall).

For the dominating stage (i.e. the operation stage) the main contributors to this impact category are the inorganic emissions to air (responsible for about 84 % of the overall 88.50 %) and inorganic emissions to water. Nitrogen oxides to air account for about 75 % of the 88.50 % overall and phosphates emissions to water account for about 13 % of the overall. These emissions are traced back to the generation of electricity.

For the environmental impact category of *photo-oxidant formation* (or smog formation) the main contributor in the operation stage (which accounts for 83.89 % of the overall) is the generation of electricity, responsible for 87 % of the 83.89 % overall. For the construction stage 90.3 % of the 15.75 % overall is traced to steel production and for the decommissioning stage 89.95 % of the 0.36 % overall is traced to steel recycling.

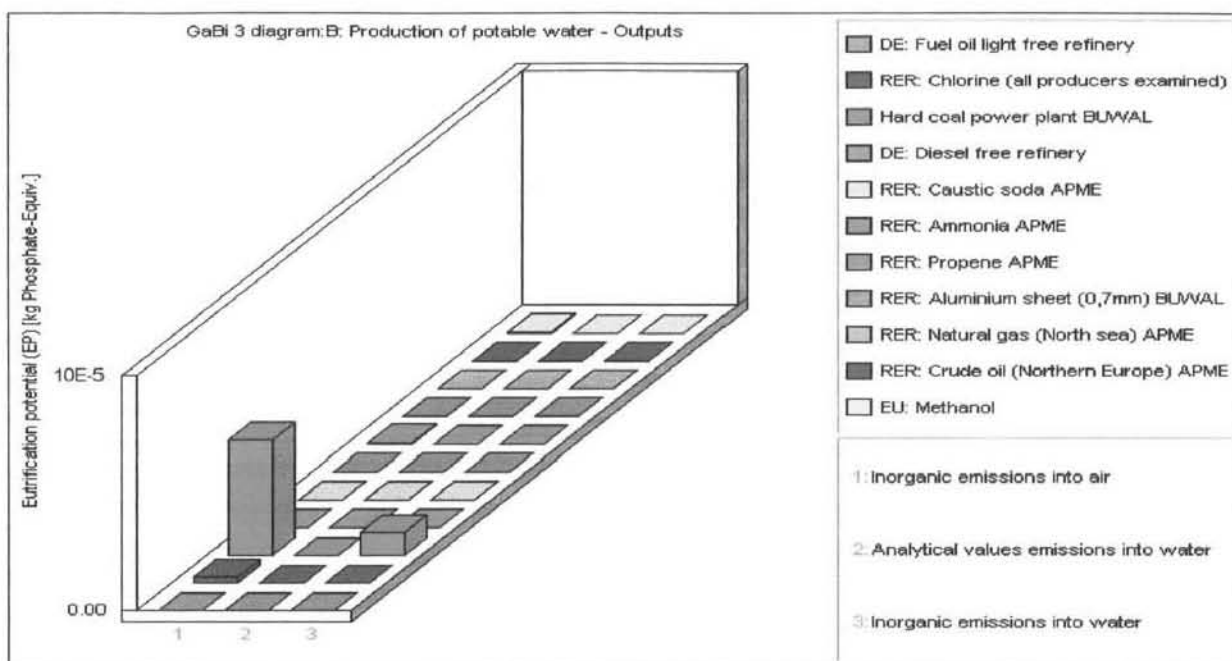


Figure 5.4: Contributors to Eutrophication for the Operation Stage (Conventional Method)

For the three *toxicity* impact categories (terrestrial, aquatic and human) the major contributors and in the different stages are presented in Table 5.4.

Table 5.4: Scores and Contributions for Toxicity (Conventional Method)

Toxicity	Contribution and Dominant Process		
	Construction	Operation	Decommissioning
Aquatic	6.25E-05* (2.29)** of which 99.45 % from steel production	2.66E-03 (97.65) of which 97.03% from electricity generation	1.52E-06 (0.06) of which 96.47 % from recycling of steel
Terrestrial	2.73E-02 (10.55) of which 98.92 % from steel production	2.31E-01 (89.22) of which 94.31% from electricity generation	5.85E-04 (0.23) of which 97.84 % from recycling of steel
Human	7.39E-04 (18.08) of which 97.53 % from steel production	3.31E-03 (81.00) of which 97.04% from electricity generation	3.75E-05 (0.92) of which 99.84 % from recycling of steel

* the units for all toxicity values are kg DCB (1, 4 dichlorobenzene) equivalents.

** the values in brackets represent the percentage value from the total score for that category

From Table 5.4 it can be observed that in each of the life stages of the waterworks these three toxicity categories are dominated by the same processes. In the construction stage the dominant process is steel production, in the operation stage it is electricity generation in hard coal power plants and in the decommissioning stage it is the recycling of steel. For these three toxicity categories, terrestrial toxicity (notably in the operation stage) has the highest absolute value.

For all three toxicity categories the main contributors are heavy metals. In the operation stage (which dominates for all three categories) aquatic ecotoxicity is due to nickel emissions to water (accounts for about 75 % of the 97.65 % overall). For the same stage terrestrial ecotoxicity is due to cadmium (40 % of the overall), mercury (33 %), zinc (15 %) and nickel (8%) to air. For human toxicity the main contributors are lead to air (56 % of the overall for the operation stage) and nickel to air (21 % of the overall for the operation stage). All these heavy metals are traced back to the generation of electricity.

5.2 Interpretation of the Results for the Conventional Method

From the scores presented in the above section it becomes evident that electricity generation is the dominant overall process for all impact categories considered. Therefore, it is important to look at how electricity is consumed in the system and to identify processes which have the highest consumption. However, electricity consumption has to be considered together with electricity generation and both processes are an integral part of the energy balance of the system. **Table 5.5** presents an overview of the energy values of the system investigated in the production of potable water by the conventional method.

With regard to the electricity used in this system, two types of situations have to be distinguished and clearly delimited. In the first situation electricity generation is presented as a separate process, which is subsequently linked to the processes which consume electricity (see **Figure 5.1** – red line). In this section this is referred to as direct electricity. An example of a process which needs direct electricity is the production of sodium hypochlorite (see **Figure 5.1**). In the second situation electricity consumption and generation are followed up to the interface system-environment and the inputs and outputs are included with the inputs and outputs of a particular process. Examples of processes in which electricity consumption and generation have been included are the production of ammonia, propene and chlorine. For these processes a link to the process of electricity generation (see **Figure 5.1**) would be double counting and a mistake in the inventory.

From this table it is obvious that the process with the highest energy consumption in the system is the generation of electricity. To produce the 0.544 MJ/kL direct electricity needed for the processes presented in **Figure 5.1** (see red line) 1.813 MJ/kL energy is needed. This represents an energy efficiency of 30 % (for generation and transmission), close to the value of 34 % achieved by Eskom in South Africa (Eskom Environmental Report, 1999).

Table 5.5: Energy Values for the Operation Stage (Conventional Method)

Process / Substance	Energy Input – Calorific Value (MJ/kL)	Percentage
Electricity generation	1.813	87.72
Potable water production**	0.306	N/A
Sodium hypochlorite prod.**	0.233	direct N/A
Ozone production**	0.004	electricity N/A
Methanol production**	0.019 (0.001 as direct electricity)	0.88
HTH production**	2.27E-05	N/A
Propene production	0.065	3.15
Chlorine production	0.059	2.86
Natural gas	0.053	2.57
Light oil - fuel	0.015	0.73
Crude oil	0.011	0.53
Aluminium production	0.009	0.45
Quicklime production	0.008	0.39
Ammonia production	0.008	0.39
Caustic soda production	0.006	0.29
PAC production	2.55E-04	0.02
Steam conversion	1.23E-04	0.00
Diesel – fuel	1.75 E-04	0.01
Total	2.067	99.99

** The electricity consumed by these processes totals up to 0.544 MJ/kL direct electricity, which needs to be generated. To generate these 0.544 MJ/kL about 1.813 MJ/kL are needed. Out of the 0.019 MJ/kL energy inputs for the production of methanol 0.018 MJ/kL are added towards the total and only 0.001 MJ/kL are direct electricity.

Direct electricity is used in the system as follows: for the on-site production of potable water (excluding ozone production) 0.306 MJ/kL, for sodium hypochlorite production 0.233 MJ/kL, for ozone production 0.004 MJ/kL, for methanol production 0.001 MJ/kL and for HTH production 2.27E-05 MJ/kL (see **Table 5.5**). From these consumption values at the waterworks, the electricity consumed on-site for the production of potable water and for the production of ozone totals 0.310 MJ/kL and it represents about 57 % of the direct electricity demand. However, to produce this direct electricity about 1.033 MJ/kL are needed, which means that out of the 2.067 MJ/kL energy needed in the operation stage (see **Table 5.1**) 50 % are used at the waterworks and are under the control of water authorities. Therefore, it is useful to look at the electricity consumption of individual processes employed at Wiggins Waterworks.

Table 5.6 presents the electricity consumption for individual process used in the production of potable water at Wiggins Waterworks and **Appendix 16** shows in detail how these values have been obtained.

Table 5.6: Electricity Used by Individual Processes at Wiggins Waterworks

Process	Electricity Consumption (kWh/d)	Percentage
Sludge plant	2272.3	18.0
Filtration (Machine Hall)	1428.0	11.3
Clarifiers		
▪ pulsators	1108.0	8.8
▪ compressors	264.0	2.1
Chemical addition	823.6	6.5
PAC Plant	16.3	0.1
Ozonation:		
▪ pre-ozonation thermal destruction unit (TDU)	1610.9	12.8
▪ intermediate ozonation thermal destruction unit (TDU)	1530.5	12.1
▪ ozonators	1200.0	9.5
Miscellaneous:		
- wash water recovery	1242.0	9.9
- mixers and pumps for homogenisation	660.0	5.2
- sample pumps	66.0	0.5
- res outlets	312.0	2.5
- pre-chlor sample pumps (post clarifiers)	26.4	0.2
- sodium hypo pump station	52.9	0.4
Total	12612.9	99.9

From this table it can be seen that the process with the highest electricity consumption is ozonation (totals 4341.4 kWh/d), a process which includes the production of ozone and the thermal destruction of ozone emissions. The second highest electricity consumer is the sludge plant and the third highest the filtration unit. These processes should be a priority for energy efficiency measures in order to improve the total environmental performance of the Wiggins Waterworks.

The electricity values for the production of various chemicals used in the production of potable water could be manipulated indirectly by using chemicals which need less electricity for their

production instead of chemicals which need more electricity. The overall reduction of the electricity used in the system will reduce the environmental burdens of the system and will result in an improved environmental performance as measured by the LCA.

5.3 Results for the Membrane Method for Producing Potable Water

The life cycle stages considered for the membrane method of producing potable water are the same as for the conventional method, namely the construction stage, the operation stage and the decommissioning stage. For this method eight different scenarios were considered (as presented in Section 3.2.2). Calculations were done for each of these scenarios with regard to inputs and outputs and also environmental profiles have been produced for all eight scenarios. For a better understanding of the presentation of the results the scenarios are defined in Table 5.7. Details on the technical specification of the membrane filtration modules are presented in Appendix 5.

Table 5.7: Scenarios for the Membrane Method

Scenario	Filtration length (m)	Flux (L/m ² h)	Modules per bank	Total modules needed
1A	1.025	50	30	4 740
1B	1.025	50	60	4 740
2A	1.025	100	30	2 370
2B	1.025	100	60	2 370
3A	1.500	50	30	3 240
3B	1.500	50	60	3 240
4A	1.500	100	30	1 620
4B	1.500	100	60	1 620

The first part of this section presents the environmental scores for each of the impact categories considered. Since environmental scores are very similar for some of the eight scenarios, an average value may be presented together with the highest and the lowest contribution. The second part of this section will present an analysis of the environmental scores in relation to the different scenarios. Finally, the third part of this section will present an interpretation of the environmental scores in relation to the processes identified as having the highest environmental contribution.

5.3.1 Environmental Scores for the Membrane Case

As with the conventional method, the first two parameters on the input side are material consumption and energy consumption. **Table 5.8** presents the material consumption and in **Table 5.9** the energy consumption for the eight scenarios considered is presented.

Table 5.8 Material Consumption for the Membrane Method (kg/kL)

Scenarios	Total	Stages		
		Construction	Operation	Decommissioning
1A	2.343	0.043	2.300	0.00054
1B	2.343	0.043	2.300	0.00052
2A	2.324	0.024	2.300	0.00030
2B	2.424	0.024	2.400	0.00030
3A	2.432	0.032	2.400	0.00041
3B	2.332	0.032	2.300	0.00038
4A	2.318	0.018	2.300	0.00032
4B	2.317	0.017	2.300	0.00023

Table 5.9 Energy Consumption for the Membrane Method (MJ/kL)

Scenarios	Total	Stages		
		Construction	Operation	Decommissioning
1A	2.033	0.068	1.960	0.00487
1B	1.999	0.067	1.926	0.00460
2A	1.966	0.038	1.925	0.00262
2B	2.464	0.038	2.422	0.00264
3A	2.649	0.055	2.590	0.00365
3B	2.086	0.054	2.028	0.00337
4A	2.061	0.031	2.027	0.00285
4B	1.836	0.027	1.806	0.00205

There are two important observations to be made from **Table 5.8** and **Table 5.9**. Firstly, for all membrane scenarios the operation stage carries the highest burdens with regard to the materials and the energy consumed to produce potable water. The decommissioning stage carries the smallest burdens. Secondly, from the eight scenarios considered, scenario 4B (long, high flux modules arranged in larger banks) needs the smallest amounts of materials and energy. Scenario 3A (long, low flux modules arranged in smaller banks) the highest. Therefore, from an material

and energy point of view the flux and the arrangement in banks is more important than the module length.

From **Table 5.7** and **5.8** it can be seen that the scenarios needing the greatest number of modules are the scenarios with the largest material consumption per volume of water produced. However, the arrangement of modules in the banks also plays a role, albeit a small one, since scenarios with the same number of modules may have slightly different material consumptions per volume of potable water produced.

A summary of all eight environmental profiles is presented in **Table 5.10**. The scores are based on the outputs, in the form of emissions to air, water and soil, contributing to different environmental impacts. An environmental profile was calculated for all eight scenarios presented. The calculations were based on individual inventories produced for each of these scenarios. For a better overview, the environmental scores were normalised by dividing all the scores of an impact category by the smallest score (see **Table 5.10**). This normalisation should not be confused with the LCA step with the same name, since the procedure is different.

From the eight scenarios for which environmental profiles have been produced, scenario 4B has the lowest scores for all the impact categories considered and scenario 3A the highest. For the outputs, as reflected in the different categories, the operation stage carries the highest scores for all the impact categories and for all the scenarios considered.

Table 5.10: Environmental Profiles for the Membrane Method Scenarios

Impact Category	Unit	Scenario							
		1A	1B	2A	2B	3A	3B	4A	4B
Global Warming	kg CO2 Equiv.	0.22117	0.216541	0.214815	0.270032	0.289511	0.227059	0.225819	0.201038
Normalised Value*		1.100	1.077	1.069	1.343	1.440	1.129	1.123	1.000
% from Operation Stage		98.07	98.01	98.75	99.00	98.75	98.44	98.94	98.91
Ozone Depletion	kg CFC-11 Equiv.	7.63E-10	7.43E-10	7.12E-10	8.75E-10	9.55E-10	7.58E-10	7.40E-10	6.64E-10
Normalised Value		1.148	1.119	1.072	1.318	1.438	1.141	1.113	1.000
% from Operation Stage		83.23	83.89	87.58	89.89	88.17	86.72	88.81	87.92
Acidification	kg SO2 Equiv.	1.39E-03	1.36E-03	1.35E-03	1.70E-03	1.82E-03	1.43E-03	1.42E-03	1.26E-03
Normalised Value		1.099	1.079	1.070	1.342	1.439	1.131	1.124	1.000
% from Operation Stage		97.93	97.90	98.69	98.94	98.66	98.36	98.89	98.92
Eutrophication	kg Phosphate Equiv.	4.41E-05	4.34E-05	4.26E-05	5.30E-05	5.69E-05	4.51E-05	4.46E-05	3.97E-05
Normalised Value		1.109	1.091	1.071	1.334	1.433	1.136	1.121	1.000
% from Operation Stage		94.93	94.83	96.56	97.18	96.65	95.81	97.04	97.10
Photo-oxidant Formation	kg Ethene Equiv.	4.06E-06	3.99E-06	3.62E-06	4.40E-06	4.87E-06	3.96E-06	3.72E-06	3.34E-06
Normalised Value		1.216	1.193	1.084	1.317	1.458	1.184	1.112	1.000
% from Operation Stage		75.12	75.22	82.74	85.74	82.80	79.81	84.92	84.12
Aquatic Ecotoxicity	kg DCB Equiv.	1.66E-04	1.64E-04	1.57E-04	1.95E-04	2.11E-04	1.68E-04	1.64E-04	1.47E-04
Normalised Value		1.135	1.116	1.072	1.333	1.441	1.145	1.119	1.000
% from Operation Stage		88.46	88.38	91.97	93.40	92.40	90.80	92.80	92.36
Terrestrial Ecotoxicity	kg DCB Equiv.	0.59064	0.58024	0.57709	0.727096	0.779177	0.60937	0.607395	0.540368
Normalised Value		1.093	1.074	1.068	1.346	1.442	1.128	1.124	1.000
% from Operation Stage		98.54	98.54	99.02	99.22	99.06	98.85	99.14	99.08
Human Ecotoxicity	kg DCB Equiv.	0.001445	0.001409	0.001332	0.001639	0.001783	0.001427	0.001392	0.001235
Normalised Value		1.170	1.141	1.078	1.327	1.444	1.155	1.127	1.000
% from Operation Stage		83.03	83.02	88.04	90.27	88.74	86.62	88.76	88.99

* Normalised value in this table means the ratio between the score value and the lowest value for each impact category

A similar analysis to the conventional case was produced for the membrane method with regard to the outputs. For the environmental impact category *global warming* the scores, the percentage contribution and the dominant processes for each stage are presented in **Table 5.11**.

Table 5.11: Percentage Contribution and Dominant Processes for Global Warming (Membrane Method)

Scenarios	Percentage Contribution and Dominant Process		
	Construction	Operation	Decommissioning
1A	0.00387*(1.75)** of which 22.24 % from steel production	0.21690 (98.07) of which 99.16% from electricity generation	0.0004 00 (0.18) of which 97.95 % from recycling of steel
1B	0.003845 (1.78) of which 22.01 % from steel production	0.21224 (98.01) of which 99.14 % from electricity generation	0.000456 (0.21) of which 97.83 % from recycling of steel
2A	0.002437 (1.13) of which 27.40 % from steel production	0.21212 (98.75) of which 99.14 % from electricity generation	0.000258 (0.12) of which 97.47 % from recycling of steel
2B	0.002452 (0.91) of which 27.23% from steel production	0.26732 (99.00)of which 99.32 % from electricity generation	0.000260 (0.10) of which 97.84 % from recycling of steel
3A	0.003272 (1.13) of which 23.18 % from steel production	0.28588 (98.75) of which 99.37 % from electricity generation	0.000359 (0.12) of which 97.49 % from recycling of steel
3B	0.003217 (1.42) of which 22.86 % from steel production	0.22351 (98.44)of which 99.19 % from electricity generation	0.000333 (0.15) of which 97.68 % from recycling of steel
4A	0.002118 (0.94) of which 28.82 % from steel production	0.22342 (98.94) of which 99.18% from electricity generation	0.000281 (0.12) of which 97.57 % from recycling of steel
4B	0.001986 (0.99) of which 30.98 % from steel production	0.19885 (98.91) of which 99.09% from electricity generation	0.000202 (0.10) of which 96.39 % from recycling of steel

* the units for all global warming scores are kg CO₂ equivalents.

** the values in brackets represent the percentage value from the total, overall score for that scenario

From this table it is clear that for each scenario the scores lie within a narrow range. For global warming all scenarios have the same dominant process for the construction, operation and decommissioning stage. For the construction stage, the production of steel carries the highest environmental burdens, however, methanol production, electricity production, cement production and epoxy production also contribute. For the operation stage, electricity production dominates and for the decommissioning stage the recycling of steel is the dominant process with regard to environmental scores for global warming. Since the operation stage is the stage with the highest contribution (more than 98 %) it is clear that the generation of electricity is the process which carries the highest environmental burden for the overall global warming impact category for the membrane method.

For the impact category of *ozone depletion* electricity generation was found to be the main contributor, although the operation stage had a slightly smaller contribution to the overall score when compared to other impact categories. This contribution ranged from 83.23 % (scenario 1A) to 89.89 % (scenario 2B) as can be seen in **Table 5.10**. On average, the proportion which is due to electricity generation is 99 % of the scores of the operation stage. For the construction stage the dominant process is steel production, as shown in the following figure for scenario 1A.

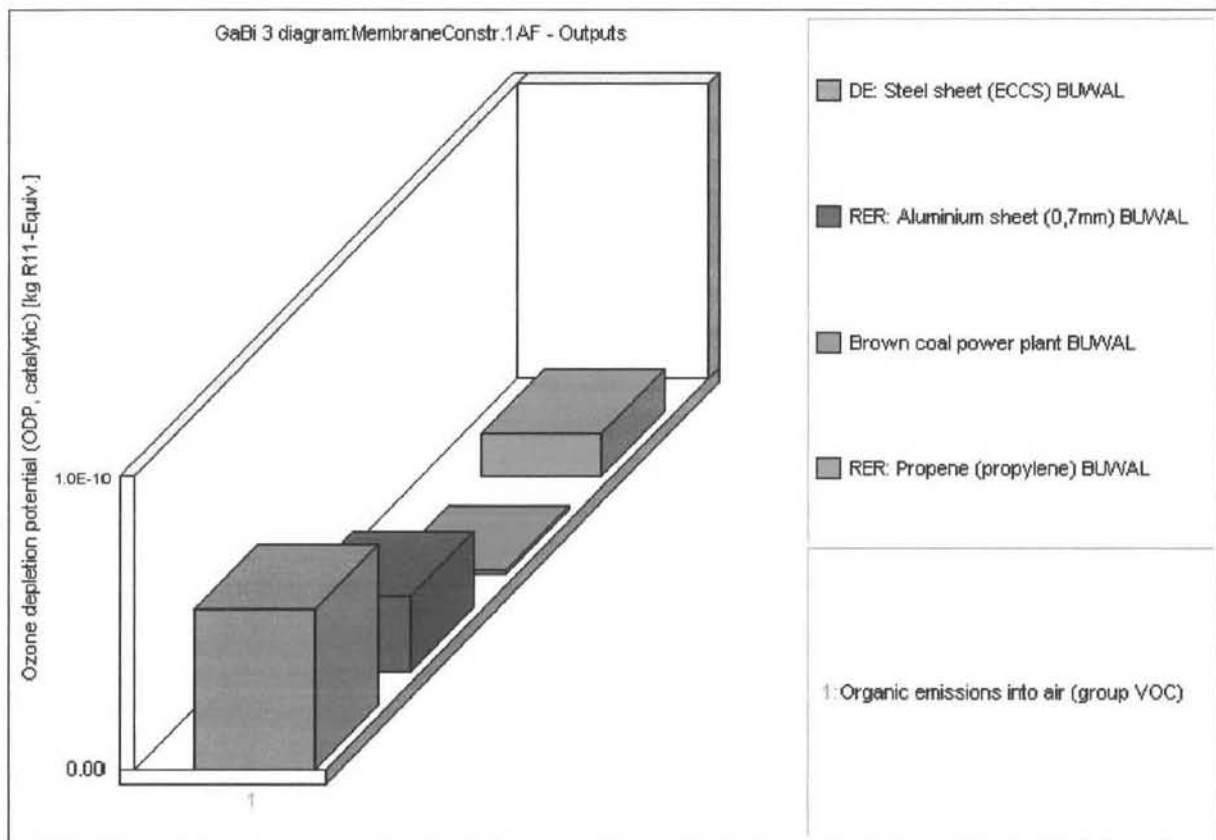


Figure 5.5: Ozone Depletion in the Construction Stage (Membrane Method)

The construction stage accounts, on average, for about 10.41 % of the total overall ozone depletion scores (scenario 1A with the highest of 13.04 % and scenario 2B with the lowest of 8.30 %). The decommissioning stage has the lowest contribution with an average of 2.57 % of the overall score (scenario 1A with the highest of 3.73 % and scenario 2B with the lowest, namely 1.80 %). The dominant process for the decommissioning stage for this impact category is steel recycling, accounting on average for about 97 % of the contribution of the decommissioning stage.

For the environmental impact category of *acidification* a similar pattern emerged. The dominant overall process is electricity generation, accounting on average for about 98 % of the contribution of the operation stage (see **Table 5.10** for percentage contribution of the operation

stage for each scenario). For the construction stage which accounts on average for 1.39 % of the overall number (scenario 1A with the highest of 1.96 % and scenario 2B with the lowest, namely 1,01 %), the process with the highest contribution is methanol production. However, as can be observed in **Figure 5.6**, other processes like cement production and the production of PVC also have significant contributions.

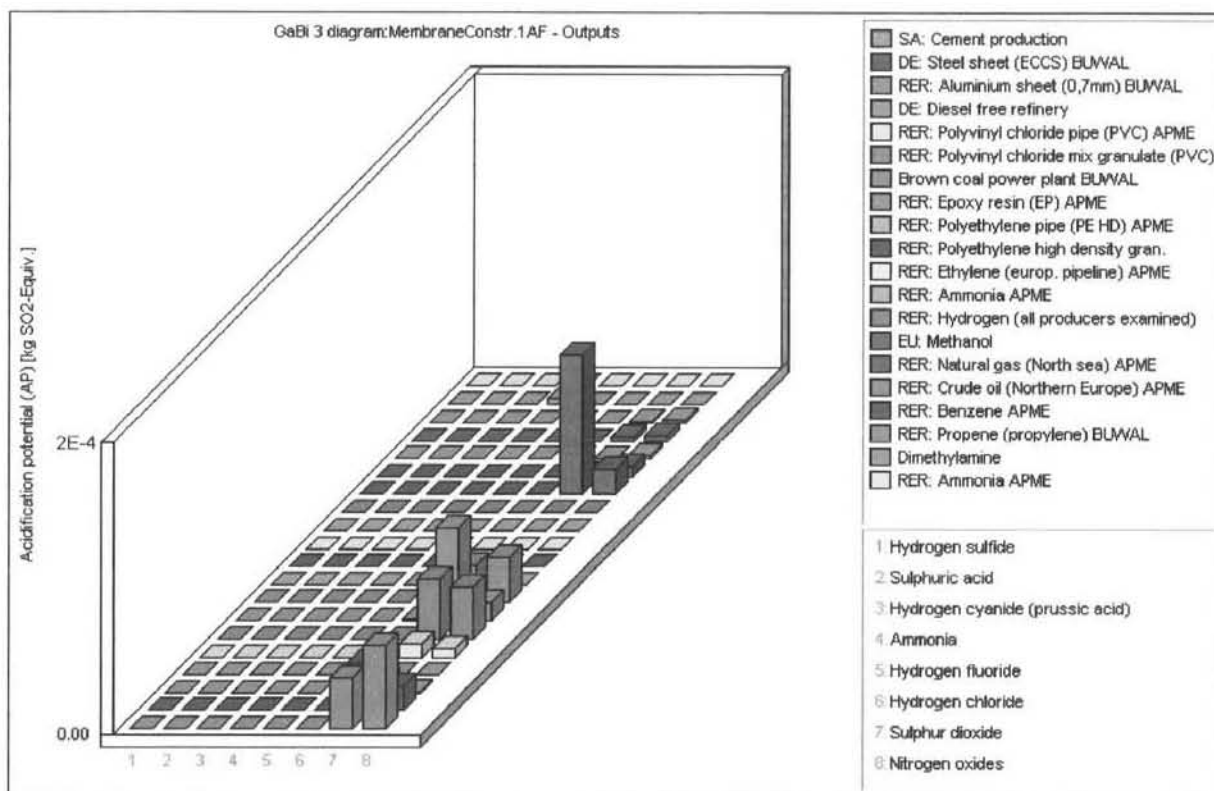


Figure 5.6 Contributions to Acidification in the Construction Stage (Membrane Method)

For the decommissioning stage which accounts on average for 0.07 % (scenario 1A with the highest 0.11 % and scenario 2B with the lowest 0.05 %) of the overall burden for acidification, the dominant processes is steel recycling (aprox. 97 % of the 0.07 % overall).

For the environmental impact category of *eutrophication* the same pattern is repeated with electricity generation dominating the operation stage and, due to the prominence of this stage, the entire life cycle. The generation of electricity accounts for about 96 % of the contribution to this impact by the operation stage. The main contributions from the construction stage are presented in **Figure 5.7**.

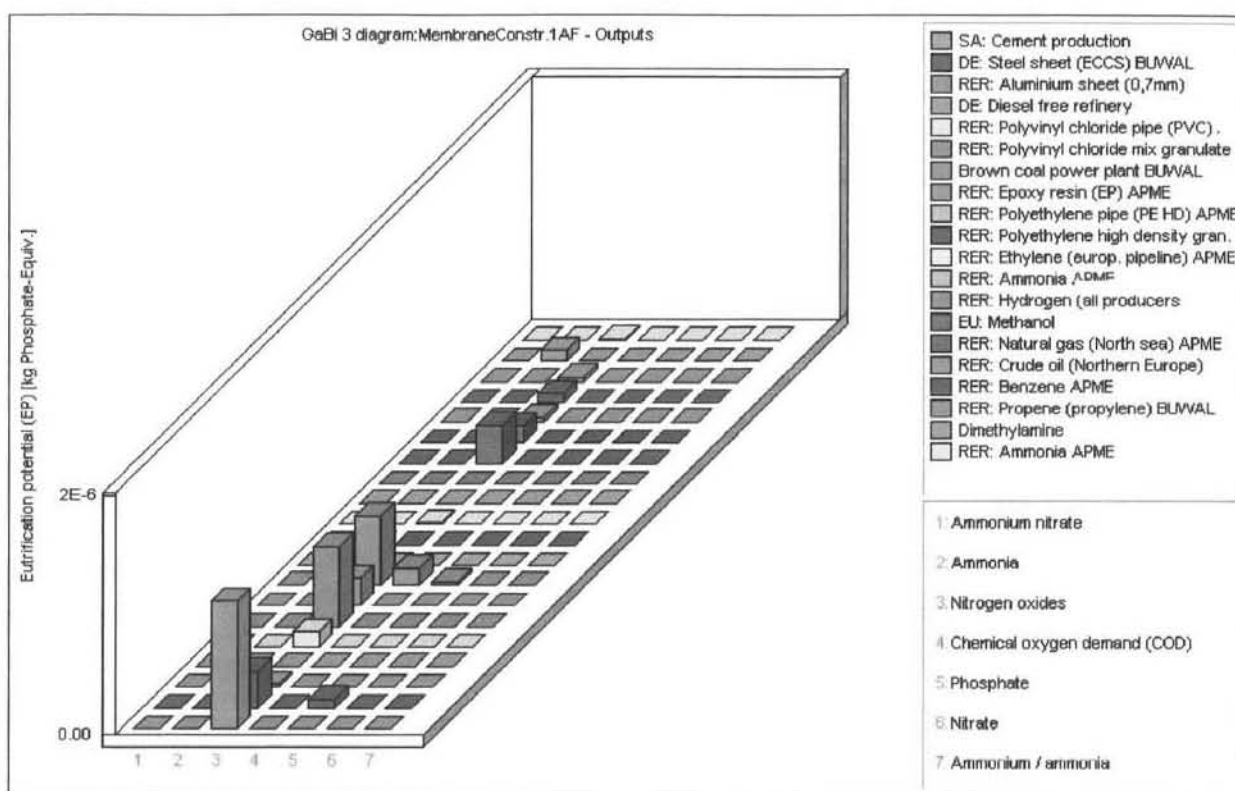


Figure 5.7 Eutrophication in the Construction Stage (Membrane Method)

As can be seen, the production of cement carries the highest burdens for this stage. For the decommissioning stage (which accounts on average for 0.25 % of the overall) the main contribution towards acidification comes from the recycling of steel (about 97 %).

For the environmental category of *photo-oxidant formation* (or smog formation) the generation of electricity is the dominant overall process, since it accounts for more than 98.4 % of the environmental burdens of all scenarios in the operation stage. The operation stage accounts for more than 75 % of the overall burdens for all scenarios studied (see **Table 5.10**). For the construction stage, the dominant process is steel production (accounts for 37.69 % of the environmental burdens of this stage for this category), followed by the production of dimethylformamide (20.10 %) and the production of dimethylamine (14.34 %). The last two chemicals are used in the production of the filtration membranes; dimethylformamide being a co-polymer and dimethylamine being used to produce this co-polymer. The construction stage is responsible, on average, for about 15.56 % (scenario 1A being the highest with 20.47% and scenario 2B the lowest with 11.98 %) of the overall burdens for photo-oxidant formation. The smallest contribution to this impact category comes from the decommissioning stage, which, on average, accounts for 3.13 % of the overall. Scenario 1A has the highest contribution from this stage with 4.42 % and scenario 2B has the lowest with 2.27 %. The dominant process of this stage is steel recycling, accounting for about 89 % of the burdens of this stage for this category.

Toxicity (aquatic, terrestrial and human) scores were produced in a similar fashion as for the other environmental impact categories presented. **Table 5.10** presents the contributions for each scenario and **Table 5.12** presents the dominant processes for each stage for this environmental impact category.

Table 5.12: Average Percentage Contributions and Dominant Processes for Toxicity

Toxicity	Percentage Contribution and Dominant Process		
	Construction	Operation	Decommissioning
Aquatic	6.46 % steel production (see Figure 5.8)	91.32 % electricity generation responsible for 100 %	2.22 % recycling of steel responsible for 87 %
Terrestrial	0.85 % steel production (see Figure 5.8)	98.93 % electricity generation responsible for 100 %	0.22 % recycling of steel responsible for 95 %
Human	7.12 % steel production (see Figure 5.8)	87.18 % electricity generation responsible for 99.6 %	5.70 % recycling of steel responsible for 99 %

It is important to note that the generation of electricity is the overall dominant process, accounting for almost all toxicity environmental burdens in the operation stage, which is the predominant stage. Heavy metals into air and water are the main polluters causing this toxicity. For the construction stage, individual contributions are presented in **Figure 5.8** and heavy metals feature predominantly. For the decommissioning stage, the recycling of steel has the highest contribution in this stage, with heavy metals into air also being the main polluters.

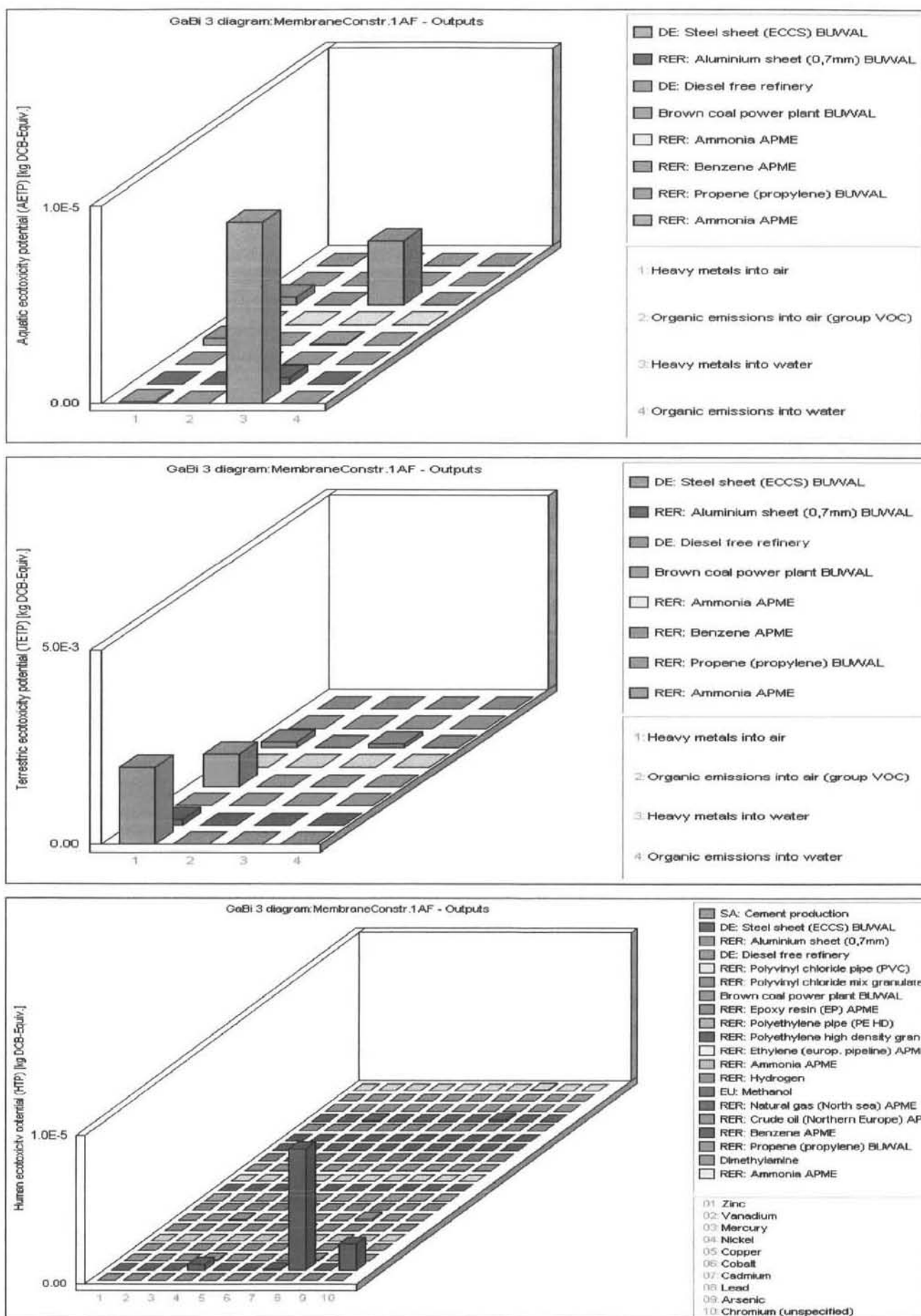


Figure 5.8: Aquatic, Terrestrial and Human Toxicity in the Construction Stage (Membrane Method)

In conclusion, for the environmental scores for the membrane method of producing potable water, the generation of electricity is the process which carries the highest environmental burdens for all the impact categories examined. It is also the process which dominates the operating stage in the life cycle of a membrane plant. In the construction stage, the production of steel is of importance and in the decommissioning stage the recycling of steel. However, the last two life cycle stages account only for little of the overall environmental burdens.

5.3.2 Environmental Scores and the Different Scenarios

For a better view of the different scenario scores for the different impact categories and to enable a comparison against each other, a ranking procedure was performed. By using the normalised values presented in **Table 5.10**, scores were ranked for each impact category. The results are presented in **Table 5.13**. Since the electricity consumed per volume of water produced was found to be important, figures for direct electricity consumption in the operation stage have been added to this table in order to assess the relationship between the overall ranking and the approximate amount of electricity consumed.

Table 5.13: Ranking of Environmental Scores for the Different Scenarios

Impact Category	Scenarios							
	1A	1B	2A	2B	3A	3B	4A	4B
Electricity Consumed (kWh/kL)	0.143	0.140	0.140	0.179	0.192	0.148	0.148	0.131
1. Global Warming	4	3	2	7	8	6	5	1
2. Ozone Depletion	6	4	2	7	8	5	3	1
3. Acidification	4	3	2	7	8	6	5	1
4. Eutrophication	4	3	2	7	8	6	5	1
5. Photo-oxidant Formation	6	5	2	7	8	4	3	1
6. Aquatic Ecotoxicity	5	3	2	7	8	6	4	1
7. Terrestrial Ecotoxicity	4	3	2	7	8	6	5	1
8. Human Toxicity	6	4	2	7	8	5	3	1
Overall Ranking	5	3	2	7	8	6	4	1

The overall ranking order presented in the above table reinforces the figures presented in **Table 5.7** (normalised value) by showing that scenario 4B has the lowest scores for all categories and scenario 3A the highest. These two scenarios (4B and 3A) together with scenarios 2A and 2B show consistency in ranking for all environmental categories considered. For the other four scenarios this consistency is lacking.

Since most of the environmental burdens are traced back to the generation of electricity, it was expected that the scenarios using the highest amount of electricity per volume of water produced would have the highest environmental scores. This hypothesis is confirmed and **Figure 5.9** presents this correlation for the impact category of global warming.

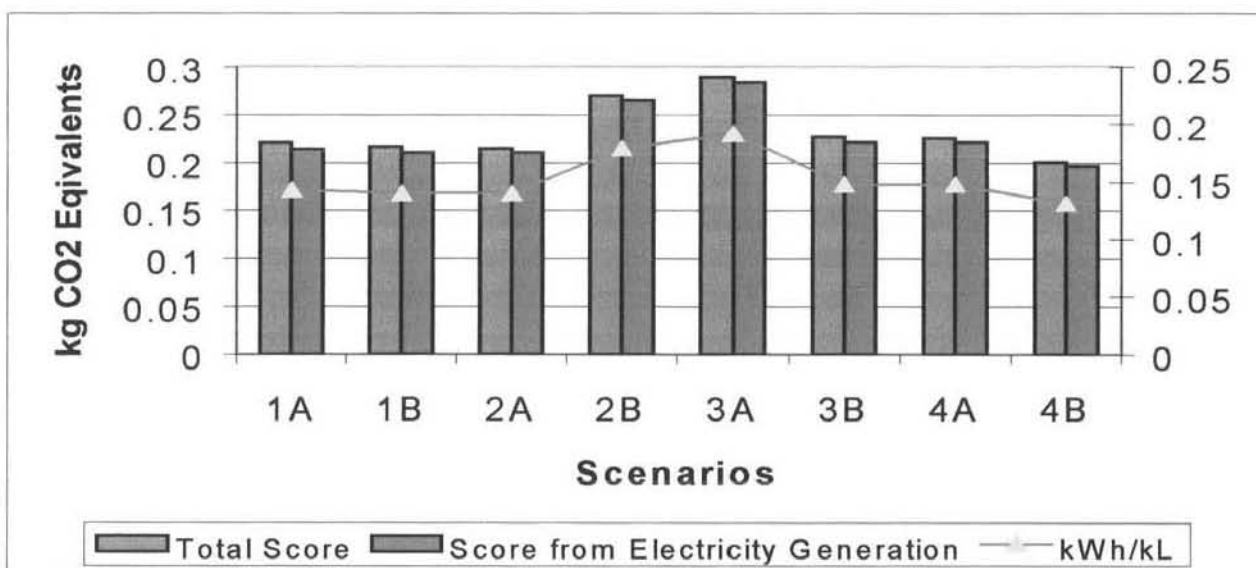


Figure 5.9: Global Warming and Electricity for the Membrane Case

Similar correlation have been found for all the other environmental impact categories, with some exceptions like scenario 1A (see **Table 5.13**). **Table 5.10** and **Table 5.13** also show that if figures for electricity consumption are the same or very similar for the scenarios considered, other factors differentiate environmental scores and subsequent ranking.

The electricity consumption calculated for the eight scenarios for a membrane plant is due to pumping. Scenario 4B has the lowest electricity needs per volume of potable water, because of the way the banks of modules are grouped together. The grouping of 60 high flux modules needs large pumps and large pumps have higher efficiencies than smaller ones. Scenario 4A uses the same type and numbers of modules and the same flux, but a different grouping (banks of 30 as opposed to 60 modules) and needs more electricity for pumping.

5.3.3 Interpretation of the Environmental Scores in Relation to the Contributing Processes

As in the case of the conventional method, for the membrane method the dominant process for all eight scenarios investigated proved to be the generation of electricity. Therefore, it is important to look at how electricity is consumed and generated, and, in general to analyse the energy flows in the system. This was done for one of the eight scenarios investigated, namely for scenario 3A, which is the worst case scenario for the membrane method.

From the energy inputs used in this scenario (see **Table 5.9** scenario 3A) the operation stage accounts for 2.590 MJ/kL or 97.75 % of the total. Out of this 2.560 MJ/kL energy (or 96.62 % of the total) is needed to produce the 0.751 MJ/kL direct electricity needed in the system. For electricity generation an energy efficiency of about 30 % was used in the calculation. It is evident that the bulk of the energy inputs go towards electricity generation and therefore it is important to follow up how the electricity is used in the system.

The electricity requirements for this scenario have been calculated based on the pumping needed in this system (see **Appendix 6** for pumps needed for scenario 3A). As can be seen from the calculations in **Appendix 6** the highest electricity consumption for pumping is required by the raw feed line (23 961.72 kWh/d or 62.9 %), followed by the permeate line (12 751.40 kWh/d or 33.5%), the reject line (1145.71 kWh/d or 3.0 %) and the backflush line (203.38 kWh/d or 0.5 %). Therefore, the highest contribution to the environmental burdens of this method is traced back to the pumping of raw feed to the filtration modules.

In the case of the membrane method, another interesting aspect from a design point of view is to look at the burdens of producing the filtration modules and in particular the burdens of producing the filtration membranes. Since these are small components in the overall burdens of the system, a separate GaBi 3 model had to be made in order to calculate these burdens per kilogram of module produced for scenario 3A. The technical specifications of this module are presented in **Appendix 5**, (section 3). The materials needed to build these module have been calculated by upscaling the module which is currently being produced by the group of Dr. Ed Jacobs, Institute for Polymer Science, University of Stellenbosch. The type of materials and the amounts involved are presented in **Table 5.14**. It must be noted that data on the production of the nitrile lipseal is a major data gap for the production of filtration modules and for the membrane method in general. However, per kg of module, the nitrile lipseal has the lowest material contribution (6 g nitrile / kg module).

The polymer filtration membrane is made up by co-polymerising four chemicals (polysulphone, dimethylformamide, polyvinylpyrrolidone and poly(ethylene glycol)). The GaBi 3 process plan for modelling this production process, as well as the overall production of filtration modules is presented in **Figure 5.10**, and **Table 5.15** presents the environmental scores for the overall process.

Table 5.14: Quantities Needed for One Module (250/1500mm, low flux, 3 240 modules)

Component	Material	Amount	Unit	Material per unit	Material per module (kg)	Total material for all modules	Total material per kg of module	Kg material per kL water
Shroud	PVC	1.6	m	8.93 kg	14.288	46293.1	0.396	1.34E-04
Netting	PE	234.6	g		0.235	760.1	0.007	2.20E-06
Lipseal	Nitrile	213.3	g		0.213	691.1	0.006	2.00E-06
Endings	Epoxy	4742	g		4.742	15364.1	0.131	4.44E-05
Outlet Saddle	PVC	55	g		0.055	178.2	0.002	5.15E-07
Membranes	Polymer	10350	pcs.	1.603 g	16.591	53755.0	0.459	1.55E-04

From **Table 5.15** it can be seen that the production of the membranes has a significant contribution to the overall burdens of the filtration module. For some environmental impact categories (i.e. ozone depletion and aquatic ecotoxicity) it is the only contributor.

Table 5.15 Environmental Scores for the Production of Filtration Modules (per kg)

Environmental Category	Score for the production of modules	Score for the production of membranes	Dominant processes for the production of modules
Global Warming Potential (kg CO ₂ -Equiv.)	5.655	3.831 (67.75 %)*	Methanol production Electricity generation
Ozone Depletion Potential (kg R11-Equiv.)	3.94E-8	3.94E-8 (100.00 %)	Propene production (through the release of halon 1301)
Acidification Potential (kg SO ₂ -Equiv.)	0.045	0.027 (60.00 %)	Methanol production (through emission of SO ₂)
Eutrophication Potential (kg Phosphate-Equiv.)	0.003	0.001 (33.33 %)	PVC production (through emission of NO _x)
Photochemical Oxidant Potential (kg Ethene-Equiv.)	0.001	0.0009 (90.00 %)	Production of dimethylamine and dimethylformamide
Aquatic Ecotoxicity Potential (kg DCB-Equiv.)	0.010	0.010 (100.00 %)	Benzene production (through emission of mercury)
Terrestrial Ecotoxicity Potential (kg DCB-Equiv.)	5.546	5.537 (99.83 %)	Electricity generation (through Cd emission)
Human Ecotoxicity Potential (kg DCB-Equiv.)	0.032	0.028 (87.50 %)	Dimethylamine production Benzene production

**The percentages presented are the contribution of the membrane production process to the total score of that category.*

Module Production

GaBi 3 - Prozeßplan

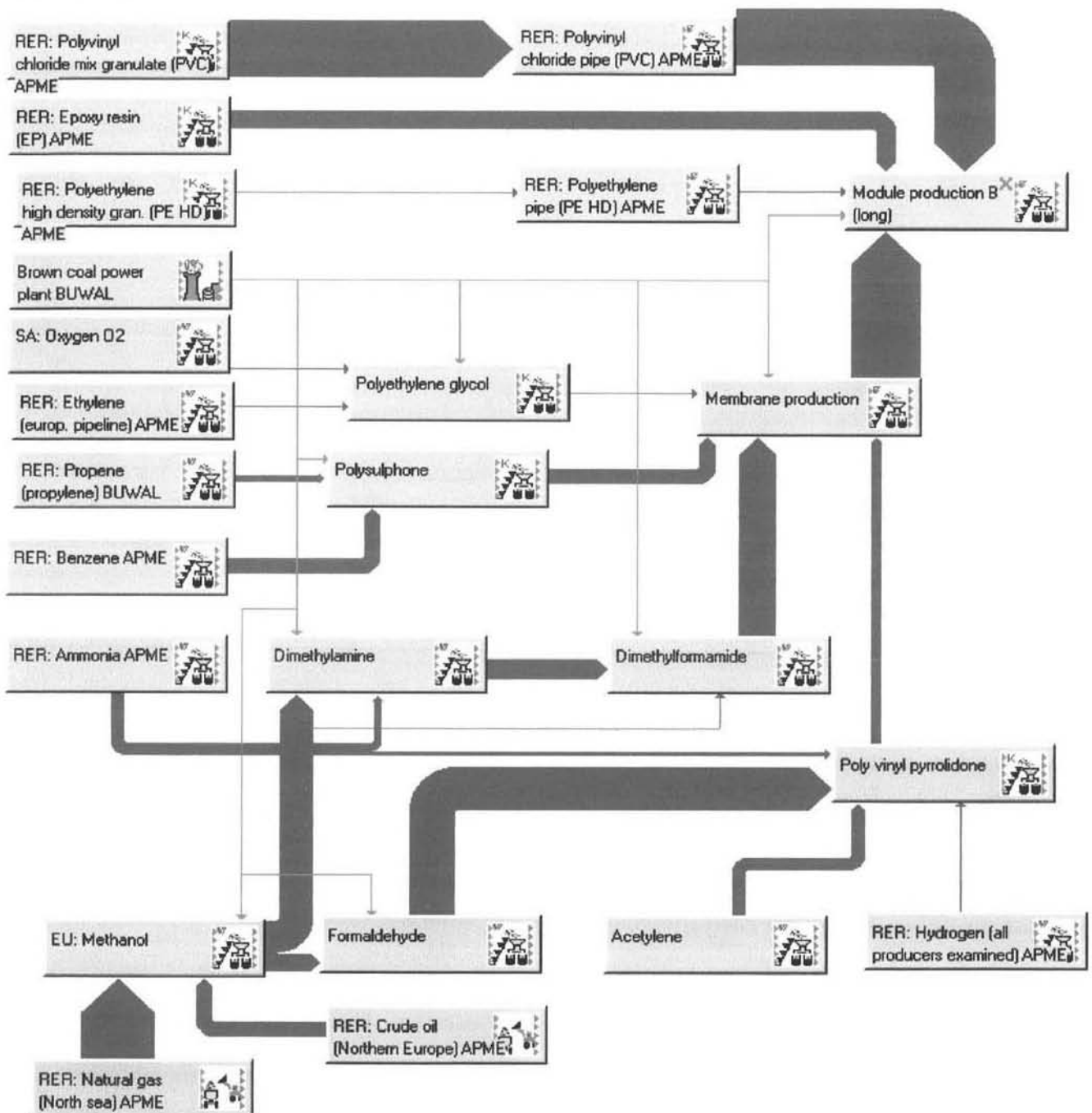


Figure 5.10: Process Plan for the Production of Filtration Modules

From a design point of view, for the filtration modules, this life cycle assessment exercise does not provide straight forward answers, since it does not identify one overall dominant contributor which can be targeted for improvement. Different processes dominate different environmental impact categories, and if environmental improvement for a category is targeted, then those processes contributing to that category should be addressed.

5.4 Comparison of the Two Methods for Producing Potable Water

For the comparison of the two methods of producing potable water the worst case scenarios for both methods have been used. For the conventional method this meant the scenario with the highest concrete requirements in the construction stage, and for the membrane method it is scenario 3A as presented in the previous section.

With regard to inputs, the two methods of producing potable water are compared in **Table 5.16**.

Table 5.16: Material and Energy Consumption for the Two Methods

Stage	Mass (kg/kL)		Energy (MJ/kL)	
	Conventional Method	Membrane Method	Conventional Method	Membrane Method
Construction	0.0514	0.0329	0.0873	0.0557
Operation	2.6000	2.5000	2.0670	2.5900
Decommissioning	0.0001	0.0004	0.0009	0.0036
Total	2.6515	2.5333	2.1552	2.6493

For both methods, the operation stage is the most energy and material intensive stage in the life cycle. The figures for material and energy consumption for both methods are comparable, with the conventional method having a slightly higher mass consumption and the membrane method having a higher energy consumption.

With regard to the outputs, the two methods of producing potable water were compared by using the environmental profiles for the scenarios considered. **Table 5.17** presents this comparison.

As this table above shows, for some impact categories (global warming, acidification and terrestrial ecotoxicity) the conventional method scores better; for the rest of the categories the membrane method has better scores. The environmental impact category with the closest scores for both methods is eutrophication, and the impact category for which the scores vary most is aquatic ecotoxicity.

Table 5.17: Comparison of the Environmental Profiles for the Two Methods

Environmental Impact Category	Unit	Conventional Method	Membrane Method
Global Warming Potential	kg CO ₂ -Equiv.	1.85E-01	2.90E-01
Ozone Depletion Potential	kg R11-Equiv.	3.61E-09	9.55E-10
Acidification Potential	kg SO ₂ -Equiv.	1.10E-03	1.82E-03
Eutrophication Potential	kg Phosphate-Equiv.	7.40E-05	5.69E-05
Photochemical Oxidant Potential	kg Ethene-Equiv.	1.57E-05	4.87E-06
Aquatic Ecotoxicity Potential	kg DCB*-Equiv.	2.73E-03	2.11E-04
Terrestrial Ecotoxicity Potential	kg DCB-Equiv.	2.59E-01	7.79E-01
Human Toxicity Potential	kg DCB-Equiv.	4.09E-03	1.78E-03

**DCB is 1, 4 dichlorobenzene*

5.5 Sensitivity Analyses

A series of sensitivity analyses have been performed in order to assess the sensitivity of the environmental scores to the omission of certain processes, most notable being transport. The sensitivity analyses were performed using the two worst case scenarios as defined in the previous section.

5.5.1 Sensitivity Analysis for Transport

The transportation of inputs and outputs for the two methods of producing potable water has environmental consequences due to the consumption of fuels and the emissions of combustion gases. To see how important these emissions are to the overall scores a series of sensitivity analyses were performed. For local manufacturers an average distance of 50 km by road was assumed and an average load of 13 t. It was assumed that once the load was delivered, the truck would return empty to the supplier. For regional South African manufacturers an average distance of 700 km by road was used for calculations. An average capacity of 30 t was assumed. It was assumed that the truck would not return empty. For overseas suppliers a distance of 10 000 km by ship was assumed. These assumptions were based on local and international statistical data on the transportation of goods. This information was obtained telephonically from the Department of Transport (Mr. van der Merwe, personal communication, 2000).

To enable the GaBi 3 tool to use this data, as well as to incorporate individual distances, the process plans for all three stages (construction, operation and decommissioning) for both methods had to be remodelled. **Table 5.18** and **Table 5.19** present the impact assessment data,

i.e. the environmental profiles for each method (worst case scenarios) including and excluding transport.

Data on fuel consumption and emissions per kg of goods transported (by road, rail, ship and plane) are available in the GaBi 3 tool. For transportation by road it includes eight types of trucks and lorries. This data is of European origin and there will be minor differences in the amount of emission gases due to engine combustion when applied to South Africa. These differences are expected because of a different average for the ambient temperatures, and also due to the fact that in Europe a higher proportion of the car pool uses catalytic converters. However, these differences are not expected to be high and to influence this LCA study. A South African study on emissions due to transportation (the Vehicle Emission Project) is almost complete (May 2001) and local data on transport will be available in the future from the Department of Minerals and Energy Affairs.

Table 5.18: The Sensitivity of the Conventional Method Scores for Transport

Environmental Impact Category	Environmental Score Excluding Transport	Environmental Score Including Transport	Difference %
Global Warming Potential (kg CO ₂ -Equiv.)	1.848E-01	1.852E-01	0.25
Ozone Depletion Potential (kg R11-Equiv.)	3.608E-09	3.697E-09	2.43
Acidification Potential (kg SO ₂ -Equiv.)	1.099E-03	1.104E-03	0.44
Eutrophication Potential (kg Phosphate-Equiv.)	7.400E-05	7.431E-05	1.02
Photochemical Oxidant Potential (kg Ethene-Equiv.)	1.570E-05	1.572E-05	0.20
Aquatic Ecotoxicity Potential (kg DCB*-Equiv.)	2.726E-03	2.727E-03	0.04
Terrestrial Ecotoxicity Potential (kg DCB*-Equiv.)	2.586E-01	2.592E-01	0.33
Human Ecotoxicity Potential (kg DCB*-Equiv.)	4.090E-03	4.127E-03	0.51

**DCB is 1, 4 dichlorobenzene*

For the membrane method there are similarities with the conventional case and **Table 5.19** presents the results.

Table 5.19: The Sensitivity of the Membrane Method Scores for Transport

Environmental Impact Category	Environmental Score Excluding Transport	Environmental Score Including Transport	Difference %
Global Warming Potential (kg CO ₂ -Equiv.)	2.895E-01	2.896E-01	0.02
Ozone Depletion Potential (kg R11-Equiv.)	9.549E-10	9.549E-10	0.00
Acidification Potential (kg SO ₂ -Equiv.)	1.818E-03	1.819E-03	0.04
Eutrophication Potential (kg Phosphate-Equiv.)	5.694E-05	5.717E-05	0.40
Photochemical Oxidant Potential (kg Ethene-Equiv.)	4.873E-06	4.943E-06	1.41
Aquatic Ecotoxicity Potential (kg DCB*-Equiv.)	2.113E-04	2.113E-04	0.00
Terrestrial Ecotoxicity Potential (kg DCB*-Equiv.)	7.792E-01	7.792E-01	0.00
Human Ecotoxicity Potential (kg DCB*-Equiv.)	1.783E-03	1.783E-03	0.00

*DCB is 1, 4 dichlorobenzene

As can be observed from **Table 5.18** for the conventional method, the environmental impact category most sensitive to the inclusion of transport is ozone depletion. The least sensitive impact category is aquatic toxicity. The changes were less than 3 % and therefore not considered to be significant to the overall results. For the membrane method the most sensitive environmental impact category is photochemical oxidant formation (or smog formation) (see **Table 5.19**). Ozone depletion, aquatic, terrestrial and human toxicity show no change. In general, the changes were less than 1.5 %.

For both methods changes due to the inclusion of transport are less than 5 % and therefore are not considered significant. As a result, the exclusion of transport was proven to be a valid assumption.

5.4.2 Sensitivity Analysis for Filtration Nozzels (Conventional Method)

At Wiggins Waterworks plastic (PVC) nozzels are used for the filtration units and the amount of plastic used in producing them was not included in the inventory. It was assumed that the amount of plastic is not significant and to prove this a sensitivity analysis was performed. **Table 5.20** presents the results of this analysis.

Table 5.20: The Sensitivity of the Conventional Method Scores for Filtration Nozzels

Environmental Impact Category	Environmental Score Excluding Nozzels	Environmental Score Including Nozzels	% Difference
Global Warming Potential (kg CO ₂ -Equiv.)	1.848E-01	1.848E-01	0.00
Ozone Depletion Potential (kg R11-Equiv.)	3.608E-09	3.609E-09	0.03
Acidification Potential (kg SO ₂ -Equiv.)	1.099E-03	1.102E-03	0.30
Eutrophication Potential (kg Phosphate-Equiv.)	7.400E-05	7.407E-05	0.10
Photochemical Oxidant Potential (kg Ethene-Equiv.)	1.570E-05	1.586E-05	1.00
Aquatic Ecotoxicity Potential (kg DCB*-Equiv.)	2.726E-03	2.726E-03	0.00
Terrestrial Ecotoxicity Potential (kg DCB*-Equiv.)	2.586E-01	2.586E-01	0.00
Human Ecotoxicity Potential (kg DCB*-Equiv.)	4.090E-03	4.090E-03	0.00

*DCB is 1, 4 dichlorobenzene

As can be observed from this table, the percentage difference between the two situations is minimal and therefore the exclusion of filtration nozzels for the conventional method of producing potable water is considered justified.

5.6 Comparison with International Studies

This is one of the first published LCA studies in South Africa and the first one in the local water industry. Because of this the results of this study could not be compared with similar local or regional results. In the water industry, internationally, LCA has been employed in a few studies, mainly in Europe (UK, Sweden, Switzerland and the Netherlands) and mainly for wastewater treatment. There is only one published LCA study investigating the production of potable water by membrane filtration.

Unfortunately, even these few studies use different methodologies and because of that comparisons of results are limited and even impossible. The latter is true in the case of the Swiss study (Grabski et al., 1996). In this study the environmental burdens of treating wastewater are balanced against the burdens which would have been incurred if that water had not been treated. Therefore, a comparison with the current study is not applicable, since this study does not address the environmental burdens of not producing potable water.

Emmerson et al. (1995) investigated a British small-scale sewage treatment plant by using LCA. They concluded that operational energy is one of the important contributors in the overall life cycle of the plant and that the operation stage has the highest contribution. This is a similar result to those emerging from the current study.

Meijers et al. (1998) reach a similar conclusion by investigating a membrane filtration process in The Netherlands. The operation stage was found to dominate the life cycle, and energy consumption in this stage proved to be the highest contributor. In addition to energy consumption the use of acids for cleaning in place (CIP) proved to be environmentally important for their system. It must be mentioned that a totally different membrane filtration process to the one in this study was investigated (i.e. high pressure, low flux and different CIP).

In summary, the comparison of the results of this study with those of similar studies undertaken internationally is limited due to the different objectives and methodologies and also due to the fact that different processes were investigated. In spite of these differences, a similar result pattern emerged for two international studies. Energy consumption in the operation stage was identified as having a major environmental burden for the treatment of water and the operation stage was seen as the most important stage. This is in accordance with the results of the current study.

5.7 Summary of Results

For both methods of producing potable water the life cycle of the waterworks is dominated by the operation stage. This stage has the highest material and energy consumption and the highest environmental scores for all the impact categories considered. The decommissioning stage is the least important one and the construction stage has an intermediate, but minor position.

The most important process to which most of the environmental burdens for producing potable water are traced is the generation of electricity. This process dominates all environmental categories for the operation stage and, because of the predominance of this stage, it dominates the entire life cycle for the waterworks, for both methods considered.

When comparing the environmental scores for the two methods of producing potable water, the figures involved are of the same magnitude and therefore, from an environmental point of view, the two methods are comparable. When comparing the results of this study with other similar studies some common trends have been observed, i.e. the importance of energy consumption in the operation stage and the importance of the operation stage to the life cycle of the waterworks.

The exclusion of transport was proven to be a valid assumption for both methods investigated. The same is valid for the exclusion of filtration nozzels for the conventional method.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This chapter is the second part of the interpretation phase as set by the ISO 14040 standard. The first part presents the conclusion of this study and the second part the recommendations. In the conclusion section, the researched material is drawn together and the main points of the research undertaken are summarised. The recommendations section relates the analysis and the theory used back to reality and tries to give relevance to this research, not only in academic circles, but in the practical world too.

6.1 Conclusion

This is one of the first studies in which an LCA has been performed on the production of potable water, and it has to be seen in the context of the current environmental status quo. Over the last few decades environmental degradation has become an issue of public concern. One of the contributing factors to environmental degradation is the expansion of industrial activities, which besides creating economic growth, employment and wealth, also causes resource depletion, pollution and ecological disruption. In response to these environmental problems the concept of sustainable development was born. Sustainable development should guide towards another development path with less environmental problems and disruption. Consecutive international treaties, most noteworthy Agenda 21, endorse cleaner production as the way to implement sustainable development in industry and business. A series of environmental tools emerged as means to achieve cleaner production in companies and one of these tools is LCA. LCA is unique in its *cradle-to-grave* approach, taking into account the entire system necessary for the manufacture of a product (service or activity). There are different degrees of sophistication in the application of LCA methodologies, ranging from the conceptual, to the simplified, to the detailed LCA. The applications of LCA are growing internationally and in South Africa there is growing demand for LCA studies. The greatest limitations to LCA are linked to the availability of data and to some of the methodological steps in the impact assessment phase. In this study, due to the non-availability of local data, European data had to be used for many inputs, the most important one being electricity generation. In addition, South African users are faced with a set of problems special to the local application of LCA, like the relevance of the impact categories to the local environment and the lack of external review capacity for LCA studies. However, these problems have to be overcome and they give the opportunity for relevant input in the development of a methodology suited for South Africa; a methodology which should reflect local environmental concerns and values.

This research should be seen as a LCA base-line study for the production of potable water and it has investigated, by using LCA methodology, two methods of producing such water. The conventional method has been employed at Wiggins Waterworks, Durban since 1984. It is a tried and tested method which has been continuously improved. For this study operational data from a period of 28 months was used. The membrane method is based on a more recent technology and so far it has been used in three pilot plants around the country. One of these pilot plants is situated at the Wiggins Waterworks research facility. This location gave the unique opportunity for a LCA comparison of the two methods, since the quality of the incoming water is the same. However, there is no membrane facility of the size required for a comparison and a virtual plant had to be upscaled, and in this process various assumptions had to be made. The author is aware that these assumptions may introduce a higher margin of error for the membrane method of producing potable water. For this method there was no design optimisation undertaken during the upscaling.

The LCA methodology employed in this study follows the ISO 14040 series of standards which prescribe 4 phases: goal and scope definition, inventory analysis, impact assessment and interpretation. For the impact assessment phase the CML (Center for Environmental Science, University of Leiden) methodology was used. In conducting this study the GaBi 3 software tool played an important role and partially pre-empted the methodological choices, since it is programmed to use the above mentioned methodology in the impact assessment phase.

When looking at the results it must be underlined that for both methods of producing potable water the life cycle of the waterworks is dominated by the operational stage. This stage has the highest material and energy consumption and the highest environmental scores for all the impact categories considered. The decommissioning stage is the least important one and the construction stage has an intermediate, but minor position. Therefore, for future waterworks, if any environmental trade-off between life stages is possible, it should be encouraged towards decreasing the environmental burdens of the operation stage. For example, the building of an additional tank in the construction phase should be encouraged, provided it decreases the overall energy consumption in the operation stage.

The most important process to which most of the environmental burdens for producing potable water are traced is the generation of electricity. This process dominates all environmental impact categories for the operation stage, for both methods considered. Because of the predominance of the operation stage it dominates the entire life cycle for the waterworks. The focusing capacities of this environmental tool are highlighted by these results, LCA being able

to identify major environmental contributors in a complex, interconnected system. By targeting these major contributors, the overall environmental performance of the system can be improved in the most efficient manner.

When comparing the environmental scores for the two methods of producing potable water, the figures involved are of the same magnitude and therefore, from an environmental point of view, the two methods are comparable.

The sensitivity analyses performed proved that the exclusion of transport at the beginning of the study was a valid assumption for both methods investigated. The exclusion of filtration nozzels for the conventional method was also proven to be valid.

When comparing the results of this study with those of similar international studies, a common pattern can be observed. The operational stage is the dominant stage of a waterworks and energy (or electricity) consumption in this stage is seen as having a major contribution to the environmental burdens of the overall water treatment processes.

In this study the main difficulties were experienced in the data gathering stage and they have been overcome by employing overseas data and by using calculations. These difficulties were related to the lack of availability of local data; however, with more demand for LCA studies in South Africa more data will become available and further LCA studies should be easier to undertake. There is a strong movement within the LCA community towards simplification of the LCA methodology. This will make LCA studies more accessible for South African companies and more LCA studies will be initiated. In creating this demand and increasing awareness about LCA as an environmental tool, the Pollution Research Group and this study play an important role through the educational outcomes of this project. As a result of this study, to date, two companies have introduced LCA. Natal Portland Cement are updating and completing the initial calculations done for them in 1999 during the data collection for cement production. The results will be presented in the Cement and Concrete Institute newsletter, which is due to be published in October 2001. Umgeni Water will take over this study and they plan to replicate and expand it for other waterworks under their control.

Finally, it must be emphasised that LCA studies will not solve the environmental problems that face an organisation or the country as a whole. However, these studies have the capacity to give focus to environmental efforts, and this is important for South Africa where financial resources for the environment are limited and it is crucial to obtain the best returns on environmental investments.

6.2 Recommendation

There are two types of recommendations pertinent to this study, namely recommendations for environmental improvement based on the results obtained and recommendations for further research in the field.

6.2.1 Recommendations for Environmental Improvement

The majority of environmental burdens for producing potable water are traced back to the consumption of electricity for the operation of waterworks. Therefore, the main recommendation emerging from this study is the need to increase electricity efficiency during operation.

For Wiggins Waterworks, a first step towards better use of electricity would be monitoring and targeting electricity consumption. This can be achieved on the site by installing simple electricity measuring devices (starting with high consumers of the electricity) and by keeping record of consumption values. The next step would be to optimise all processes (starting with the most electricity consuming ones) and make them more energy efficient.

For the membrane plant, choosing a design option which has the lowest electricity consumption is the most important step which should be undertaken. Efficiency of pumping is an issue which should be followed, since it impacts the most on the overall electricity consumption. Further research applications of membrane processes in the production of potable water should be encouraged, as the membrane processes involved in this study compare favorably with conventional water treatment processes.

6.2.2 Recommendations for Further Research

Further research is needed to make the impact assessment of the LCA more relevant to the local environmental conditions. As mentioned in the methodology chapter, there is a need to develop environmental impact categories to reflect local environmental problems, such as scarcity of water and salination. Therefore, the recommendations in this area focus on an array of measures aimed to develop these impact categories in a similar fashion to the ones already established in the LCA methodology (e.g. global warming, acidification and eutrophication). With regard to the scarcity of water, the measurement of water consumed by processes may be used as an initial rough assessment of the water intensity of processes. However, one must be aware that imported goods may be manufactured in countries where water is plentiful, therefore a

geographical distinction between the water consumed may prove important. For salinity, however, existing research needs to be reviewed and the chemical species contributing to this environmental problem have to be identified. In a next step characterisation (or equivalency) factors should be developed.

A last remark with regard to future research is about the use of LCA tools (in this case the GaBi 3 tool) in modelling water treatment processes. LCA tools aggregate a large number of data to produce environmental scores. When constructing the model for aggregation one must be very careful because this model will influence the way the results may be de-aggregated and interpreted. Useful research would be the investigation of how different ways of aggregation influence the interpretation of the results for the same water treatment method.

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APPENDIX 1

METHODOLOGICAL FRAMEWORK FOR LCA A REVIEW OF THE ISO 14040 STANDARDS

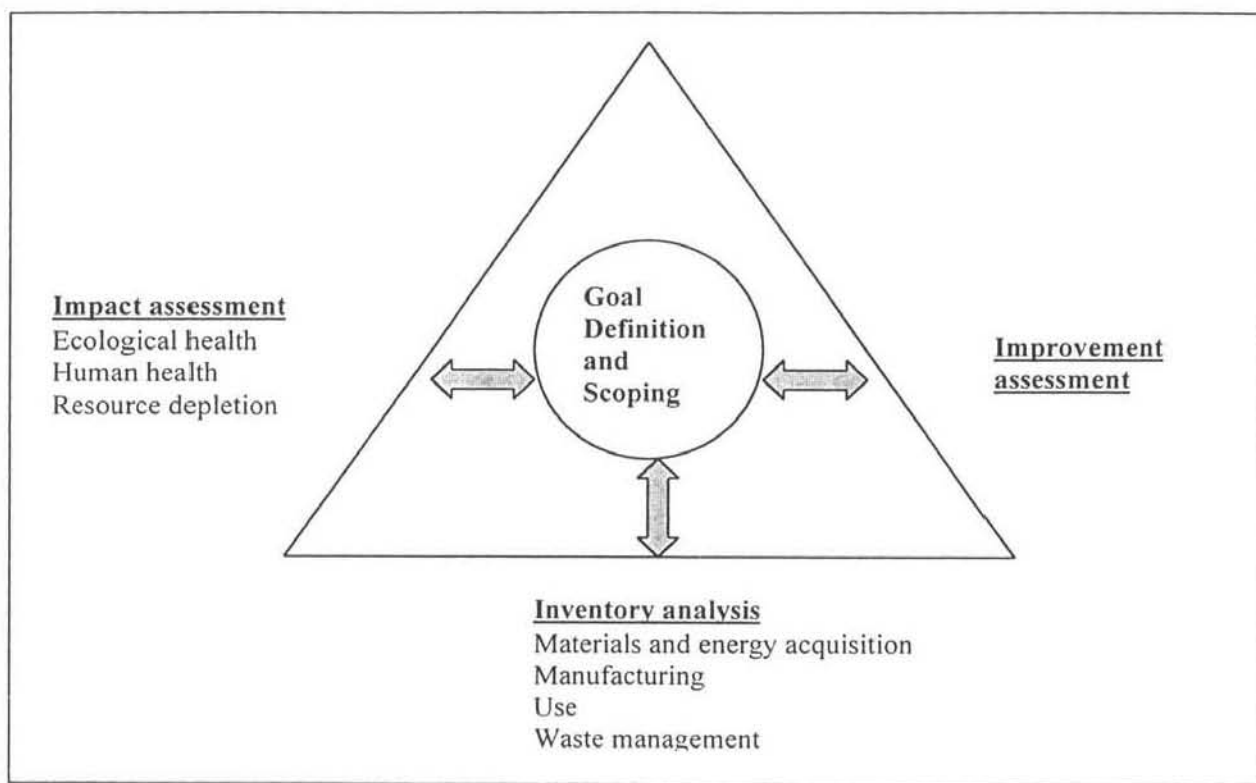
METHODOLOGICAL FRAMEWORK FOR LIFE CYCLE ASSESSMENT – REVIEW OF THE ISO 14040 STANDARDS

The development of methods for conducting LCA parallels the historical evolution of this tool as presented in **Section 2.4.2** and a series of guidelines have been developed. These guidelines and methodologies aimed to develop a consistent approach in an emerging field like LCA. This consistent approach was further consolidated with the work of the ISO LCA committee which developed a series of standards on how to conduct an LCA. Another historically important guideline which preceded the ISO standards and which set the scene for such developments is the SETAC's guideline. The SETAC guideline will be presented briefly, since it played an important role in the development of LCA methodology, and it still is one of the most accepted guidelines to date. The methodological framework for this LCA is centered around the ISO documents because these documents are based on widespread consensus within the LCA fraternity.

A1.1 The SETAC Guideline

Most of the LCA methodologies are based on a common framework first introduced by SETAC (1991 and 1992) and which gained consensus in 1993 at the SETAC workshop held in Sesimbra, Portugal. This workshop resulted in a widely accepted conceptual framework and terminology for LCAs. This framework was later changed through the ISO work; however, many important aspects have been adopted by the ISO standards. According to the SETAC framework there are four important components in the structure of an LCA: goal definition and scoping, inventory analysis, impact assessment and improvement assessment. The goal definition and scoping is the first phase in an LCA and consists of defining the study purpose, its scope, establishing the functional unit, and establishing a procedure for quality assurance of the study (Consoli et al., 1993). The inventory analysis is the second phase in an LCA and involves the compilation of all inputs and outputs of the system under study. Inputs should be traced down to the extraction of raw materials from the earth and outputs should be followed to the release into the environment. The impact assessment stage is a technical, quantitative, and/or qualitative process to characterise and assess the effects of the environmental burdens identified in the inventory component (Consoli et al., 1993). According to this framework, the impact assessment involves three steps: classification, characterisation, and valuation. Some authors include a fourth step: the normalisation. More details on these steps will be presented in the next section. The last component of an LCA is the improvement assessment phase, which deals with the identification, evaluation, and selection of options for environmental

improvements (Consoli et al., 1993, 26). The interrelationship of these four phases has been presented as follows by the SETAC workshop:



(Source: Consoli et al., 1993)

Figure A1.1: Technical Framework for Life-Cycle Assessment

At that stage (1993), the state of the methodological development for these four steps of an LCA were assessed as presented in **Table A1.1**.

From this table it can be seen that some phases (or components) of the LCA methodology were better developed than others. The early LCA studies have *focused on the quantification of energy and materials used and wastes released into the environment* (Consoli et al., 1993, 10). Therefore, the methodologies associated with the inventory are more advanced and established than those associated with impact assessments, which are relatively new. Since 1993 progress has been made on almost all outstanding issues, however, the presented pattern is still valid and the impact and improvement assessment phases are the LCA components which most need further research efforts.

Table A1.1. The State of Development of LCA Methodology (1993)

LCA Components or Phases	State-of-the-Art of Written Documents
Goal Definition and Scoping	Defined
Inventory Analysis	Defined and understood; needs some further work.
Impact Assessment	
• Classification	Defined; requires further work
• Characterisation	Conceptually defined and partially developed
• Valuation	Conceptually defined; different methods and approaches currently being used.
Improvement Assessment	Not yet documented.

(Source: Consoli et al., 1993)

As early as 1993 it was clear that there is no single way to LCA and that different degrees of sophistication in LCA studies require different applications of the available techniques. This, together with the fact that the impact and improvement assessment phases of the LCA are still under development, are the impediments against the definition of rigid methodological rules. Therefore, the SETAC framework is not a detailed methodological reference and it underlines that for valuation there are different approaches and methods. However, it lays out the general principles and a framework for the conduct, review, presentation, and use of LCA findings (Consoli et al., 1993.). The ISO series of standards follow the same loose approach and do not prescribe rigid methodologies.

A1.2 The ISO Methodological Framework

Another important series of guidelines in setting a common framework for LCA methodology are the ISO LCA standards. These are as follows:

ISO 14040 – Environmental management – Life cycle assessment – Principles and framework (1997),

ISO 14041 – Environmental management – Life cycle assessment – Goal and scope definition and inventory analysis (1999)

ISO 14042 – Environmental management – Life cycle assessment – Life cycle impact assessment (2000)

The four components of LCA according to ISO are goal and scope definition, inventory analysis, impact assessment and interpretation. As can be seen from the titles of the ISO documents for each of the phases presented above, there are further standardised guidelines and a defined terminology. The phases of an LCA as defined by ISO are slightly different to those of SETAC. The main difference is that an improvement stage is left out and instead an interpretation stage is included.

The interrelationships between the ISO LCA phases are presented graphically in **Figure A1.2**:

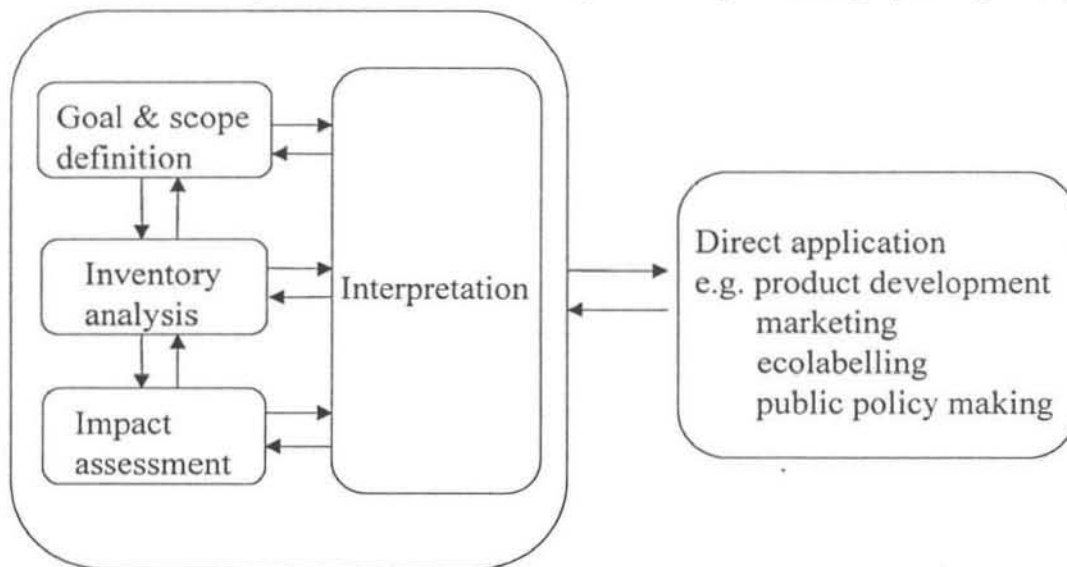


Figure A1.2: The General Framework of Life Cycle Assessment According to ISO 14040.

The ISO standards do not directly prescribe a step by step procedure, but as is the case with the SETAC guidelines, steps can be derived from the ISO documents (Guinee, 1998). Therefore, in presenting this methodological framework, a sequential (stepwise) approach will be used for each of the four phases of LCA.

A1.2.1 Goal and Scope Definition

There is no formal definition in the ISO standards for this first phase of an LCA. Guinee (1998) proposes the following definition as deriving from the ISO work: the *Goal and Scope Definition* is the first phase of an LCA stating the reasons for performing the LCA and stating the functional unit,

the system alternatives considered, and the breadth and depth of an LCA study in relation to the stated reasons for performing the study (Guinee, 1998).

For the first phase of the ISO LCA methodology, the following succession of procedures are presented in Chapter 5 of ISO 14040: defining the goal of the study and defining the scope of the study, taking into account a series of listed issues.

A1.2.1.1 Goal Definition

The ISO 14040 document states that *the goal of any LCA 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* (ISO 14040, 1997, 5) and this is seen as one single step. Wenzel et al. (1997) also distinguish one single step for goal definition. They believe that the goal definition fixes the objectives of an LCA and therefore *determines the use to which the environmental analysis will be put and at the same time assessing what it can and cannot be used for* (Wenzel et al., 1997). However, Heijungs et al. (1992) in the guideline which formed the core of the CML method, subdivide the goal definition step into two main sub-steps, each with a number of other sub-steps:

- determining the application
 - defining the goal
 - defining the target group
 - defining the initiator
- defining the subject of the study
 - defining the product group
 - defining spatial representativeness
 - defining temporal representativeness
 - defining the functional unit
 - defining the product or products

Lindfors et al. (1995) also distinguishes two steps under the heading **Goal Definition** but these steps are different to the previous ones:

- planning of LCA
 - improving credibility through reference panels, validation or external critical review
- case specific goals
 - purpose and intended applications

- function(s) of the studied system(s).

In addition, Guinee (1998) mentions the *marginal-average discussion* and its reason for inclusion in the goal definition phase. He argues that at the goal definition stage it is important to distinguish between descriptive and change-oriented applications, because these applications require different modes of analysis and hence different methodologies for the following LCA phases. Some of the issues mentioned by different authors under goal definition are included by the ISO documents under the heading of *Scope Definition* and the boundaries between these two steps shift from author to author.

A1.2.1.2 Definition of the Scope

The scope of the study should be *sufficiently well defined to ensure that the breadth, the depth and the detail of the study are compatible and sufficient to address the stated goal* (ISO 14040, 1997). Furthermore, according to the same document, under the scope of the study the following list of items should be considered and clearly defined.

- The function of the product system, or, in the case of comparative studies, the systems.
- The functional unit.
- The product system to be studied.
- The product systems boundaries.
- Allocation procedures.
- Types of impact and methodology of impact assessment, and subsequent interpretation to be used.
- Data requirements.
- Assumptions.
- Limitations.
- Initial data quality requirements.
- Type of critical review, if any.
- Type and format of the report required for the study.

According to Lindfors et al., 1995, the scope definition should include following items:

- product group or type of service,
- studied alternatives,

- system boundaries (technical system) i.e. a schematic process tree describing the whole system, independently of whether or not all flows will be quantified,
- impact assessment boundaries, and
- data quality goals.

Wenzel et al. (1997) believe that scope definition should include the following list of items.

- Defining the object of the study and expressing it as the service it provides, including defining the functional unit.
- Selecting one or more reference products or reference systems to represent the object of the study.
- Designating the environmental assessment parameters which are important for the goal of the LCA.
- Identifying the environmentally significant processes in the product system, paying respect to the goal of the LCA; setting up a model for the product system on the basis of the references selected, which will include the most significant and exclude other processes; determining the geographic framework for the product system.
- Defining the time horizon for which the decisions based on the LCA are to apply, including defining the technological level which should be represented in the product system which is assessed; projecting the LCA of the reference product(s) to apply to the relevant time period; defining the time horizon under which the environmental impact should be seen.
- Allocating the environmental exchanges occurring in the product system between the object studied and other users' services to which the product system's process contribute, because they also are part of other product systems.

When looking at the different ways to define the scope of an LCA study, it is clear that the issues considered by the different research groups are quite different and that the ISO documents compromise all the aspects involved. Because of that, some authors consider that the ISO documents are not yet clear and precise enough with respect to:

- *issues and/or possible steps which should be distinguished in the scope definition,*
- *what should be stated about these issues and/or steps in the scope definition and what in the inventory analysis and impact assessment* (Guinee, 1998).

The depth of the study as mentioned in the ISO documents represents the different degrees of sophistication to which the LCA techniques can be applied, and it ranges from streamlined or scanning LCA studies to the very detailed ones. According to Guinee (1998) the scope definition

step should *comprise both the choice between a scanning or a detailed LCA, and a first, short review of all principle choices, assumptions and limitations for each methodological step* (Guinee, 1998) including all three other phases of LCA (inventory, impact assessment and interpretation).

A1.2.1.3 Functional Unit

Defining the functional unit is one of the most important steps in performing an LCA because the *functional unit sets the scale for comparison of two or more products (systems) including improvement on one product (system)* (Jensen et al., 1997). The functional unit is used to relate all data collected in the inventory phase to one or more functions of the system under consideration. It has particular importance in comparative LCA studies where products or systems fulfilling the same function are evaluated against each other. The ISO 14041 document states:

The functional unit defines the quantification of the identified functions. The functional unit shall be consistent with the goal and scope of the study. One of the primary purposes of a functional unit is to provide a reference to which the input and output data are normalised (in a mathematical sense). Therefore the functional unit should be clearly defined and measurable. Having defined the functional unit, the amount of product which is necessary to fulfill the function shall be quantified. The result of this quantification is the reference flow. The reference flow is then used to calculate the inputs and outputs of the system. Comparisons between systems shall be made on the basis of the same function, quantified by the same functional unit in the form of their reference flow (ISO 14041, 1998).

In addition to these issues Lindfors et al. (1995) highlight three other aspects which have to be taken into account when defining the functional unit. These aspects are the efficiency of the product, the durability of the product and the performance quality standard. Wenzel et al. (1997) and Guinee (1998) introduce two more dimensions to the functional unit i.e. the duration (or temporal context) and the geographical location (or spatial context). The duration of a service or function is considered to be very important especially for comparisons of alternatives. Some examples of functional units as given by Wenzel et al. (1997) are presented in **Table A1.2**.

Table A1.2: Examples of Functional Units

Product	Quantity	Duration	Qualities
Egg tray	Egg packing equivalent to the average consumption of eggs per inhabitant in Denmark	1 y	Average maximum broken eggs
Television	Reception of TV programs in colour on a 28" screen	6 / d for 10 y	Sharpness of image, quality of sound, number of channels, remote control
Pump	Delivering 5 m ³ water per hour with an output pressure of 1.5 bar, or a similar combination according to the pump characteristics	5 000 h of operation during 10 y	Dry running protection and self-priming
Refrigerator	200 l volume cooled to 5 °C with an ambient temperature of 25 °C	13 y	Accuracy in temperature control, re-evaporation of melt water from defrosting, shelves, boxes, etc.
Electrohydraulic control unit for a hydraulic valve	Controlling a hydraulic proportional valve in a hydraulic plant	5 y	Error monitoring, response time, accuracy in control
Paint	Protection of 1 m ² fir surface on an outdoor façade, facing west and exposed to sun and rain	10 y	Non-dripping, colour, durability in closed container

Source: Wenzel et al., 1997

With regard to the functional unit Lindfors et al. (1995) warn against introducing a *fuzzy* denominator in the definition of a functional unit. He gives the example of a functional unit for washing powder, specified as *1 kg of white washed clothes*. Because the term white is not strictly defined, using such a functional unit may introduce variability in the results.

A1.2.1.4 System Boundaries

In a detailed LCA study all input flows should be traced back to the extraction from the environment for inputs and to the discharge into the environment for outputs. However, this approach could lead to endless regression since some inputs could be the result of several processes and the products and by-products of a system may be used as inputs for another series of processes. Therefore, it is important to define the boundaries of a system. The system boundaries specify which of the processes contributing towards a system will be included within an LCA study of that system. According to ISO 14040 *several factors determine the system boundaries, including the intended application of the study, the assumptions made, cut-off criteria, data and cost constraints, and the intended audience. Also the criteria used in establishing the system boundaries shall be identified and justified in the scope of the study* (ISO 14040, 1997).

Some authors like Heijungs et al. (1992) and Guinee (1998) include a separate preliminary step called *drawing up the initial process tree* in the definition of boundaries. Their argument for including this step is that a process tree gives an overview of the system in which *the processes are directly linked to each other: each input into a process comes either from another process or directly from the environment and similarly each process output flows either to another process or to the environment* (Heijungs et al. 1992). The ISO 14041 document only states that *it is helpful to describe the system using a process flow diagram showing the unit processes and their interrelationships*.

Lindfors et al. (1995) acknowledge that the definition of the system boundaries is a subjective process and the following boundaries should be considered: geographical boundaries (i.e. the area for which the study should be representative), life cycle boundaries (i.e. limitations in the life cycle due to cut-off) and boundaries between the technosphere and biosphere. Three different principles are stated for up-stream cut-offs: a certain fixed up-stream stage, a fixed mass fraction for each individual process and a certain percentage of product flows from up-stream subsystems. All of these cut-off rules include a certain degree of subjectivity. Because subjectivity is a major concern, it is important to ensure transparency of the boundaries defining process and to state all the assumptions made. Therefore, the following two paragraphs from ISO 14041 (1999) summarise very well the issues, including transparency, associated with boundaries definition.

The initial system boundary defines the unit processes which will be included in the system to be modelled. Ideally, the product system should be modelled in such a manner that the inputs and outputs at its boundaries are elementary flows. However, as a practical matter, there typically will not be sufficient time, data or resources to conduct such a comprehensive study. Decisions must be made regarding which unit processes will be modelled by the study and the level of detail to which these unit processes will be studied. Resources need not to be expended on the quantification of minor or negligible inputs and outputs that will not significantly change the overall conclusions of the study. Decisions must also be made regarding which releases to the environment will be evaluated and the level of detail of this evaluation. The decision rules used to assist in the choice of inputs and outputs should be clearly understood and described.

Any omissions of life cycle stages, processes or data needs should be clearly stated and justified. Ultimately, the sole criterion used in setting the system boundaries is the degree of confidence that the results of the study have not been compromised and that the goal of a given study has been met.

A1.2.1.5 Data Quality

Data quality is an important issue in LCA studies, since the quality of the data used is reflected in the quality of the results obtained. However, Guinee (1998) argues that even when the quality of the data is high, it can still lead to erroneous results if these data are used to answer questions for which these data are irrelevant. Therefore, the representativeness of the data for a particular study is equally important. The ISO 14040 (1997) document states that data quality requirements should be defined to enable the goals and scope of the LCA study to be met. The data quality requirements should address:

- time-related coverage;
- geographical coverage;
- technology coverage;
- precision, completeness and representativeness of the data;
- consistency and reproducibility of the methods used throughout the LCA;
- sources of the data and their representativeness;
- uncertainty of the information.

ISO 14041 (1999) elaborates on each of the data quality requirements presented above and states that *where a study is used to support a comparative assertion that is disclosed to the public, all data quality requirements described shall be included in the study*. Similar data quality requirements are mentioned by Lindfors and his colleagues from the Nordic Council (LCA Nordic Technical Report

No. 5, 1994) and by Wenzel et al. (1997). Furthermore, Weidema (1997) proposes the use of data quality indicators in the form of a pedigree matrix. He uses a scale from 1 to 5, where 1 is the highest quality and 5 the lowest and the following assessment issues: reliability, completeness, temporal correlation, geographical correlation and technical correlation. An example of such a matrix is presented in **Appendix 9**.

Jensen et al. (1997) point out that the methodology to describe data quality systematically is quite new and in the process of being further developed.

A1.2.1.6 Critical Review Consideration

The aim of a critical review process is to ensure the quality of an LCA, facilitate understanding and enhance the credibility of LCA studies. ISO 14040 (1997) defines it as *a technique to verify whether an LCA study has met the requirements of this International Standard for methodology, data and reporting*. It also specifies that whether and how to conduct a critical review, as well as who conducts the review, shall be defined in the scope of the study. The review can be internal, external or it may involve interested parties and the ISO 14040 (1997) document gives more specifications for each of these types as well as for the whole review process.

Jensen et al. (1997) distinguish two types of critical review processes. The in-process critical review is that type of critical review, which is undertaken in parallel to the LCA study, and corrections can be made continuously. The end-of-process critical review is the critical review on the final draft which gives the possibility to make corrections before finishing the report. The same authors suggest that in some cases it may be relevant to publish the critical review report along with the LCA study.

A1.2.2 Inventory Analysis

The inventory analysis is the second phase of an LCA study and it involves data collection and calculation procedures to quantify relevant inputs and outputs of the system studied. Usually the inventory produced in this phase is used as input for the next phases of the life cycle impact assessment. There are some simplified LCA studies where an inventory analysis is enough to draw conclusions, however, this has to be specified in the goal and scope of the study.

Jensen et al. (1997) distinguish six main issues to be considered for this phase: data collection, refining system boundaries, calculation, validation of data, relating data to the specific system and allocation of inputs and outputs when more than one product results from a process. Lindfors et al. (1995) believe that the *inventory analysis phase comprises a detailed description of the product system (functions and boundaries), data collection and calculations as well as sensitivity and uncertainty assessment* (Lindfors et al., 1995, 40). It is obvious that different authors include different issues under the heading of **Inventory Analysis**. Therefore, the ISO 14041 document becomes important since it presents a detailed and stepwise procedure as shown in **Figure A2.2**.

The first procedure of the inventory analysis is to prepare for data collection. From the goal and scope phase at the beginning of the study, an initial set of unit processes and associated data can be defined. The ISO 14041 sets five steps for this procedure as follows:

- *Drawing of specific process diagrams that outline all unit processes to be modelled, including interrelationships,*
- *Description of each unit process in detail and listing of data categories associated with each unit process*
- *Development of a list that specifies the units of measurement*
- *Description of data collection techniques and calculation techniques for each data category, to assist personnel at the reporting locations to understand what information is needed for the LCA study; and*
- *Provision of instructions to reporting locations to document clearly any special cases, irregularities or other items associated with the data provided* (ISO 14041, 1999).

Data collection is the next step and this step requires good knowledge about each process included in the system, since inputs and outputs for each process have to be collected. In most cases this step is the most work intensive part of the whole LCA study. In accordance to the goal and scope of the study, different data from different sources should be collected. These data can be quantitative (preferably) and qualitative (when quantitative data are not available) and site specific or general. Site specific data, i.e. data from a specific company, area or country are needed for very detailed studies. More average or general data can be obtained from trade organisations, public surveys, manufacturers associations, etc. In reality most of the studies published so far use a combination of site specific and general data. Jensen et al. (1997) suggest that average data can be used in the conceptual or simplified LCA to get a first impression of the potential inputs and outputs from producing specific materials. The ISO 14041 (1999) document recommends to avoid double counting or gaps, a description of each unit process shall be recorded. This involves the quantitative

and qualitative description of the inputs and outputs needed to determine where the process starts and ends, and the function of the unit process. Where the unit process has multiple inputs (e.g. multiple effluent streams into a water treatment plant) or multiple outputs, data relevant for allocation procedures shall be documented and reported. Energy inputs and outputs shall be quantified in energy units. Where applicable the mass and volume of the fuel should also be recorded.

In the last few years a series of academic and commercial databases have been developed (see **Appendix 3** for a list). In addition to input and output data for a series of processes unique to each database, all these databases do have calculation facilities for the next phases of an LCA - the inventory analysis and the impact assessment. Therefore, it may be appropriate to refer to them as LCA tools. Wenzel et al. (1997) underline the importance of data checks when electronic databases are used. In the Environmental Design of Industrial Products (EDIP) method which they developed, a distinction is made between the different types of processes on the basis of the possible suppliers of data like:

- raw material extraction and material production – associations of material producers and private companies,
- product manufacturing processes and use processes – private companies,
- disposal processes – authorities, research institutes, and
- transport processes and energy systems – specialised information centers.

The same authors stress the need to move from static databases to data networks, in which each individual expert body must update the data entered for their product system. This would be viable if each participant has a commercial interest in taking part in such networks.

The third step according to **Figure A2.2** is data validation and this may involve mass balances, energy balances and/or comparative analysis of emission factors. In case of obvious anomalies alternative data values have to be collected in order to fulfill the data quality requirements established. With regard to missing data, the ISO 14041 (1999) document specifies as follows:

For each data category and for each reporting location where missing data is identified, the treatment of the missing data and data gaps should result in:

- a "non-zero" data value which is justified,
- a "zero" data value if justified, or
- a calculated value based on the reported values from unit processes employing similar technology.

Two steps follow the validation of data: relating data to a unit process and relating data to the functional unit. Usually these steps involve simple mathematical calculations. Firstly, to relate data to a unit process a reference flow is established for each unit process and the inputs and outputs for that particular process are calculated in relation to that reference flow. Usually mass or energy units are used like, for example, input (and output) per kg (or ton) of material or input (and output) per MJ of energy. Relating data to the functional unit involves normalising the flows of all unit processes in the system to the functional unit. For this step the flow chart of the system is important, since it shows how the different unit processes are interconnected. Finally, all the normalised values for inputs and outputs for all unit processes involved in the system are aggregated in an inventory table.

Refining the system boundaries is the last step in an inventory analysis and at this stage all the unit processes of the system are reviewed in light of the information collected. This refining process may entail exclusion of unit processes or material flows considered unimportant, or inclusion of new unit processes which have become significant. These exclusion or inclusion processes are based on sensitivity analysis. The ISO 14041 makes the following statement with regard to this issue.

Reflecting the iterative nature of LCA, decisions regarding the data to be included shall be based on a sensitivity analysis to determine their significance, thereby verifying the initial analysis (...). The initial product system boundaries shall be revised as appropriate in accordance with the cut-off criteria established in the scope definition. This sensitivity analysis may result in:

- *exclusion of life cycle stages or unit processes when lack of significance can be shown by the sensitivity analysis;*
- *exclusion of inputs and outputs which lack significance to the results of the study;*
- *inclusion of new unit processes, inputs and outputs that are shown to be significant in the sensitivity analysis.*

The results of this refining process and the sensitivity analysis shall be documented. This analysis serves to limit the subsequent data handling to those input and output data which are determined to be significant to the goal of the LCA study (ISO 14041, 1999).

In Curran (1996) it is argued that an historical review of a few LCI studies shows that the basic system approach to LCI methodology has remained consistent for the past 20 years. Most of these methodologies are based on material and energy balances for each of the processes making up the system and this LCA phase is considered to be one of the most established with regard to LCA

methodologies employed and developed. In spite of this consistency there are three areas where variability of the methodology was reported and these are:

- allocation of inputs and outputs from an industrial operation to the various products that are produced,
- analysis of recycling systems, and
- reporting of energy that is embodied in products entering or exiting the LCI system (Curran, 1996).

Allocation is the process of splitting the environmental burdens (inputs and outputs) for a process, which besides the main product also has one or more co-products of economical value. Allocation is defined by the Nordic Council (1994) as the act of partitioning (in some proportionate shares) the responsibility for environmental impacts caused by processes in the life cycle and it is recognised that it is a traditional problem in LCA. They distinguish two situations with regard to allocation:

- multi input/output processes – e.g. processes with coproducts of economic value and
- open-loop recycling – e.g. products with no value for the producer but used as a raw material in another product system.

The same group suggests that allocation should be based on three guiding principles to be applied in the given descending order of priority:

- natural causality
- economic/social causality – for example expected gain or gross sales value
- physical parameters (allocation parameters) such as mass, energy content, exergy content, volume, molar content or even an arbitrary fraction like the 50/50 allocation.

The 50/50 allocation rule is recommended for simplified LCAs because this method of allocation ensures that information on key issues is not lost (Lindfors (1995) and Jensen (1997)).

The ISO 14041 document states that most industrial processes yield more than one product and they recycle intermediate or discarded products as raw materials. Therefore, the material and energy flows as well as associated environmental releases shall be allocated to the different products according to clearly defined procedures (ISO 14041, 1998, 11). This standard states three principles for allocation.

1. *The study shall identify the process shared with other product systems and deal with them according to the procedures presented;*

2. *The sum of the allocated inputs and outputs of a unit process shall equal the unallocated inputs and outputs of the unit process;*
3. *Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach.*

For the actual allocation procedures, the ISO 14041 standard suggests the following stepwise succession.

1. *Whenever possible allocation should be avoided by:*
 - *dividing the unit processes to be allocated into two or more subprocesses and collecting the input and output data related to these subprocesses*
 - *expanding the product system to include the additional functions related to coproducts, taking into account the requirements of the functional unit of the system*
2. *Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical relationship between them; i.e. they shall reflect the way in which the inputs and the outputs are changed by quantitative changes in the products or functions delivered by the system. The resulting allocation will not necessarily be in proportion to any simple measurements, such as the mass or molar flow of coproducts.*
3. *Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way which reflect other relationships between them. For example, input and output data might be allocated between coproducts in proportion to the economic value of the products.*

In Curran (1996) two main scenarios with regard to allocation are emphasised: coproduct allocation and recycling. For coproduct allocation the main methods are on a mass basis; however, in some cases other methods like stoichiometry (preferred for complex chemical reactions) or heat of reaction (preferred for the manufacture of hydrocarbons) may be more appropriate. Allocation on basis of economical value is discouraged, since economical value is not a physical parameter. With regard to recycling, two types are distinguished: industrial scrap and trim recycling and post consumer waste recycling. For both of these types of recycling there are two variations as presented in **Table A1.3**.

Table A1.3: Allocation for the Different Types of Recycling

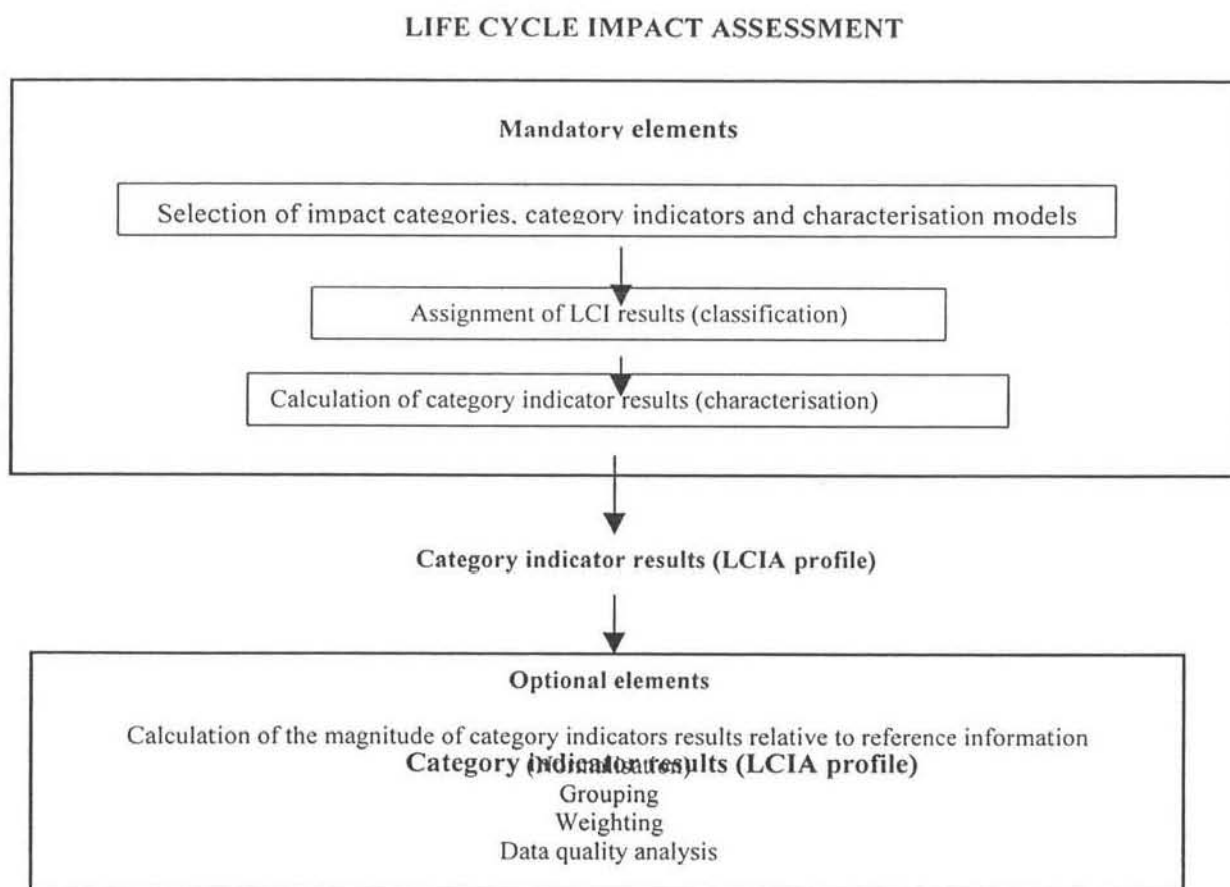
Type of Recycling	Allocation	Comments
Industrial scrap and/or trim	Incremental system approach	Assumes that the scrap/trim is waste None of the inputs/outputs to make this scrap are included
	Allocation system approach	Scrap/trim is viewed as a coproduct and allocation is made Inputs/outputs considered may be higher than virgin material due to additional (re)processing and transport.
Post consumer recycling	Closed loop recycling	Assumes permanent recycling and reuse, therefore permanently diverting materials from disposal and because of that the burdens of the initial virgin material used becomes negligible. In reality there is no 100% recycling.
	Open loop recycling	Two possible scenarios are considered: <ul style="list-style-type: none">• Materials recovered through recycling are used to manufacture a new product which is not recycled• Materials recovered through recycling are considered to be waste and no burdens are attached to them.

According to Curran (1996) embodied energy can be defined in two ways in an inventory. The one option takes into consideration the energies of material resources as the energy content (higher heating value) of raw materials entering the system that are also commercial fuel sources for that specific area. The other option defines embodied energy as the energy content of raw materials entering the system regardless of whether the materials are commercial fuel sources.

In summary, for the inventory analysis phase of an LCA study, methodologies have been established and are used. Standards have been set through the ISO 14041 document on the procedures of an LCA inventory analysis.

A1.2.3 The Life Cycle Impact Assessment (LCIA)

The impact assessment is the third phase of an LCA study and it has been defined as the phase of the LCA aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis (ISO 14040, 1997). The life cycle impact assessment uses selected environmental issues (defined as impact categories) and indicators for each of these issues to model the data from the inventory. In general, this process involves associating inventory data with specific environmental impacts and attempting to understand those impacts (ISO 14040, 1997). In most of the LCA studies published so far the impact assessment phase had four steps: category definition, classification, characterisation and valuation (or weighting) (see **Figure A1.3**).



Source: ISO 14042, 2000

Figure A1.3: Elements of the Life Cycle Impact Assessment Phase

As seen in the above figure the ISO 14042 document describes procedures and not specific methodologies or models for the life-cycle impact assessment phase. Therefore, all the impact assessment methods and methodologies are acceptable as long as they meet the ISO procedural

requirements. In the literature there are different methods which have been proposed for undertaking the characterisation and the valuation steps. With regard to characterisation there is consensus on the methods used for some of the impact categories developed. However, for valuation there are about 24 different methods which have been developed so far. Some authors include a fifth step called normalisation in their impact assessment, which usually takes place between the characterisation and the valuation step. The ISO documents also consider normalisation as an optional element.

The methodology developed by the Center for Environmental Science, Leiden University in The Netherlands (also known as the CML methodology) is one of the methodologies most used in Europe. This methodology is employed in this study and more practical details are presented in **Chapter 4**. This chapter includes information about impact categories, category indicator and characterisation models as well as about the mandatory and the optional elements used in this study.

Selection of impact categories, category indicators and classification models

Selection of impact categories, category indicators and classification models is the first mandatory step required. The impact categories are selected in order to describe the impacts caused by the inputs and outputs of the studied product system, and this step should be a follow up of the decisions made in the goal and scope definition stage. Since several categories have been developed so far in the literature, there is very little need for developing new categories. An exception are the environmental issues which are important at a regional or local level, like salination and water shortage in South Africa. Therefore, this step is an exercise to best match the scope and goal of the study with the data collected and the categories available.

ISO 14042 (2000) sets the a list of requirements for this step.

- *The selection of impact categories, category indicators and characterisation models shall be consistent with the goal and the scope of the study*
- *The sources of impact categories, category indicators and characterisation models shall be referenced*
- *The selection of impact categories, category indicators and characterisation models shall be justified*
- *Accurate and descriptive names shall be provided for the impact categories and category indicators*
- *The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope in consideration*
- *The environmental mechanism and characterisation model which relate the LCI results to the category indicator and provide a basis for characterisation factors shall be described*

- *The appropriateness of the characterisation model used for deriving the category indicator in the context of the goal and scope of the study shall be described.*

In addition the following recommendations apply for the selection of impact categories, category indicators and characterisation models:

- *the impact categories, category indicators and characterisation models should be internationally accepted, i.e. based on an international agreement or approved by a competent international body*
- *the impact categories should represent the aggregated emissions or resource use of the product system on the category endpoint(s) through the category indicators*
- *value choices and assumptions made during the selection of impact categories, category indicators and characterisation models should be minimised*
- *the impact categories, category indicators and characterisation models should avoid double counting unless required by the goal and scope definition, for example, when the study includes both human health and carcinogenicity*
- *the characterisation model for each category indicator should be scientifically and technically valid, and based upon a distinct identifiable environmental mechanism and/or reproducible empirical observation*
- *the extent to which the characterisation model and the characterisation factors are scientifically and technically valid should be identified*
- *the category indicators should be environmentally relevant.*

The impact categories considered are: abiotic resources, biotic resources, global warming, stratospheric ozone depletion, acidification, eutrophication, photochemical oxidant formation, ecotoxicological impacts, human toxicological impacts, land use and work environment. Some of these impact categories are presented in more detail in **Chapter 4**.

In addition to the ISO requirements and recommendations, Lindfors et al (1995) suggest other issues to be considered when performing this step. These are enumerated as follows: completeness (all problems of relevance should be covered), practicality (the list should not contain an excessive number of categories), independence (double counting should be avoided by choosing mutually independent categories) and relation to characterisation step.

For some of the impact categories enumerated above, there is general consensus about the impact categories, their category indicators and characterisation models. Such categories are global warming, acidification and stratospheric ozone depletion. However, for other categories there are

differences and different research groups have developed unique category indicators and characterisation models. Such an example are the ecotoxicological impacts.

Classification

Classification is the process by which inventory results are assigned to the impact categories chosen in the previous step. This is a qualitative step based on a scientific analysis of the relevant environmental processes. This scientific analysis makes up the characterisation model and determines the category indicator as in the ISO terminology. ISO 14042 states:

When LCI results are assigned to impact categories, environmental issues associated with the LCI can be highlighted.

Assignment of LCI results to impact categories should consider the following, unless other wise required by the goal and scope:

- *assignment of LCI results which are exclusive to one impact category*
- *identification of LCI results which relate to more than one impact category, including*
- *distinction between parallel mechanisms, e.g. SO₂ is allocated between the impact categories of human health and acidification, and*
- *allocation among serial mechanisms, e.g. NO_x may be assigned to both ground level ozone formation and acidification.*

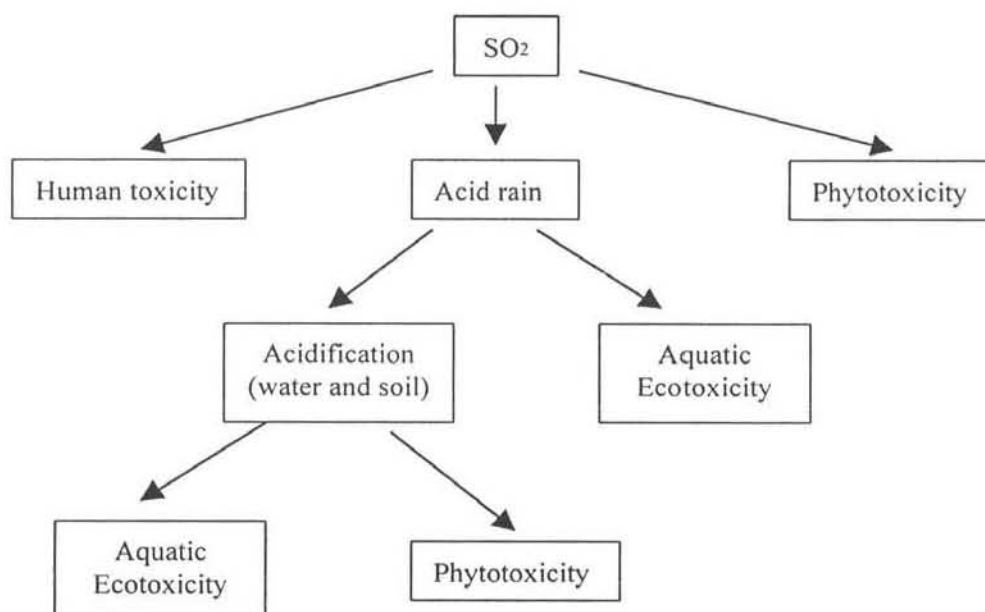
If LCI results are unavailable or of insufficient data quality for the LCIA to achieve the goal and scope of the study, either an iterative data collection or an adjustment of the goal and scope is required.

Lindfors et al. (1995), Udo de Haes (1996), Wenzel et al. (1997) and Guinee (1998) draw attention to the problems associated with multiple impacts and they give some examples:

- parallel impacts; e.g. the toxic and the acidifying impacts of sulphur dioxide,
- serial impacts; e.g. heavy metals which first cause ecotoxicological impacts followed by impacts on human health,
- indirect impacts; e.g. aluminium toxicity induced by acidification,
- combined impacts; e.g. synergistic or antagonistic impacts of toxic substances.

In dealing with these types of impacts two approaches are used. For parallel impacts, double counting is avoided by a division in the intervention, i.e. sulphur dioxide will contribute either towards acidification or towards toxicity. However, there are no guidelines on how this division should be performed. For the serial and indirect impacts it is advised to consider all serial impact categories to the full extent (Guinee, 1998, 65), that means worst case scenarios for all of the impacts involved.

One of the latest proposals for further development of the classification stage is forwarded by Chevalier and Rousseaux (1999) and it consists of building a coherent family of environmental criteria based on multicriterial decision-making tools. It is suggested that *the classification stage is not just a sorting of impacts into categories, but the assignment of inventory flows to impact categories which will form a coherent family of criteria* (Chevalier and Rousseaux, 1999). They also introduce the concept of a cascade of effects to deal with parallel and indirect impacts and the example they present for sulphur dioxide is as follows:



Source: Chevalier and Rousseaux, 1999

Figure A1.4: Part of the Sulphur Dioxide Cascade of Effects

Characterisation or calculation of category indicator results

This is the third mandatory step according to the ISO procedures, and it involves the conversion of LCI results to common units and the aggregation of the converted results within an impact category. The result is one score for each impact category taken into consideration, a score which should reflect the loading for that particular category. In order to perform the conversion, characterisation (or equivalency) factors are used. The characterisation factors used in this study, for each of the impact categories are presented in more detail in the methodology section (see **Chapter 4**) and in **Appendices 10 to 15**. With regard to this step ISO 14042 specifies the following.

The method for calculating indicator results shall be identified and documented, including the value-choices and assumptions used.

The usefulness of the indicator results for a given goal and scope depends on the accuracy, validity and characteristics of the characterisation models and characterisation factors. The number and kind of simplifying assumptions and value-choices used in the characterisation model for the category indicator also vary between impact categories. A trade-off often exists between characterisation model simplicity and accuracy. Variation in the quality of category indicators among impact categories may influence the overall accuracy of the LCA study, for example:

- *the complexity of the environmental mechanism between the system boundary and the category endpoint*
- *the spatial and temporal characteristics, for example, the persistence of a substance in the environment, and*
- *the dose-response characteristics*

Calculation of indicator results involves two steps:

- *selection and use of characterisation factors to convert the assigned LCI results to common units;*
- *aggregation of the converted LCI results into the indicator result.*

For some of the impact categories, there is consensus regarding the characterisation factors or equivalency factors to be used. Such categories are global warming, acidification and ozone depletion. However, for other impact categories, like human and ecological toxicity, biotic resources or land use, there is no consensus about characterisation factors and different methods have been used.

As can be seen from **Figure A1.3**, characterisation, classification and selection of impact categories (with indicators and models) are the three mandatory steps according to ISO 14042. In addition to these mandatory steps this standard presents a series of optional steps, specifically normalisation, grouping, weighting and data quality analysis (gravity analysis, uncertainty analysis and sensitivity analysis). The following paragraphs briefly introduce these optional elements.

Normalisation

The normalisation step is the procedure by which the indicator (or score) for each impact category is compared in relation to baseline and/or reference information. ISO 14042 states that:

This procedure transforms an indicator result by dividing it by a selected reference value. Some examples of reference values are

- *the total emissions or resource use for a given area, which may be global, regional, national or local,*
- *the total emissions or resource use for a given area on a per capita basis or similar measurements, and*
- *a baseline scenario, such as given alternative product systems.*

The selection of the reference system should consider the consistency of the spatial and temporal scales of the enrichment mechanism and the reference value.

The normalisation of the indicator results changes the outcome of the mandatory elements of the LCIA phase. It may be desirable to use several reference systems to show the consequences on the outcome of mandatory elements of the LCIA phase. A sensitivity analysis may provide additional information about the choice of reference. The collection of normalised indicator results represents a normalised LCIA profile.

Grouping

Grouping is the process by which impact categories are assigned together in one set. According to ISO 14042:

Grouping is an optional element with two possible procedures:

- *to sort the impact categories on a nominal basis, e.g. by characteristics such as emissions and resources or global, regional and local spatial scales;*
- *to rank the impact categories in a given hierarchy, e.g. high, medium, and low priority.*

Ranking is based on value-choices.

The application and use of grouping methods shall be consistent with the goal and scope of the LCA study and it shall be fully transparent.

Different individuals, organisations, and societies may have different preferences, therefore it is possible that different parties will reach different ranking results based on the same indicator results or normalised indicator results.

Weighting

In order to deduce the relative importance of the indicator results or scores obtained for each of the impact categories another optional element, the weighting or valuation step, is introduced. This step is seldom based on natural science but on political or ethical values. ISO 14042 states the following regarding this step.

Weighting is an optional element with two possible procedures:

- 1. to convert the indicator results or normalised results with selected weighting factors;*
- 2. to possibly aggregate these converted indicator results or normalised results across impact categories.*

Weighting steps are based on value-choices and are not based on natural science.

The application and use of weighting methods shall be consistent with the goal and scope of the LCA study and it shall be fully transparent. Different individuals, organisations and societies may have different preferences, therefore it is possible that different parties will reach different weighting results based on the same indicator results or normalised indicator results. In an LCA study it may be desirable to use several different weighting factors and weighting methods, and to conduct sensitivity analysis to assess the consequences of different value-choices and weighting methods.

All weighting methods and operations used shall be documented to provide transparency. Data and indicator results or normalised indicator results reached prior to weighting should be made available together with the weighting results. This ensures that:

- trade-off and other information remain available to decision-makers and to others, and*
- users can appreciate the full extent and ramifications of the results.*

Different research groups developed different methods for weighting (or valuation). Lindeijer (1996) differentiated five different principles on which about 24 different methodologies are based. These are: proxy approach, technology abatement approach, monetarisation, authorised goals or standards (also called “distance to target”) approach and authoritative panels (also called “societal”) approach.

A1.2.4 Interpretation

The interpretation is the fourth phase in life cycle assessment. The aim of this phase is to reduce the number of quantitative and qualitative data gathered during an LCA study to a number of key

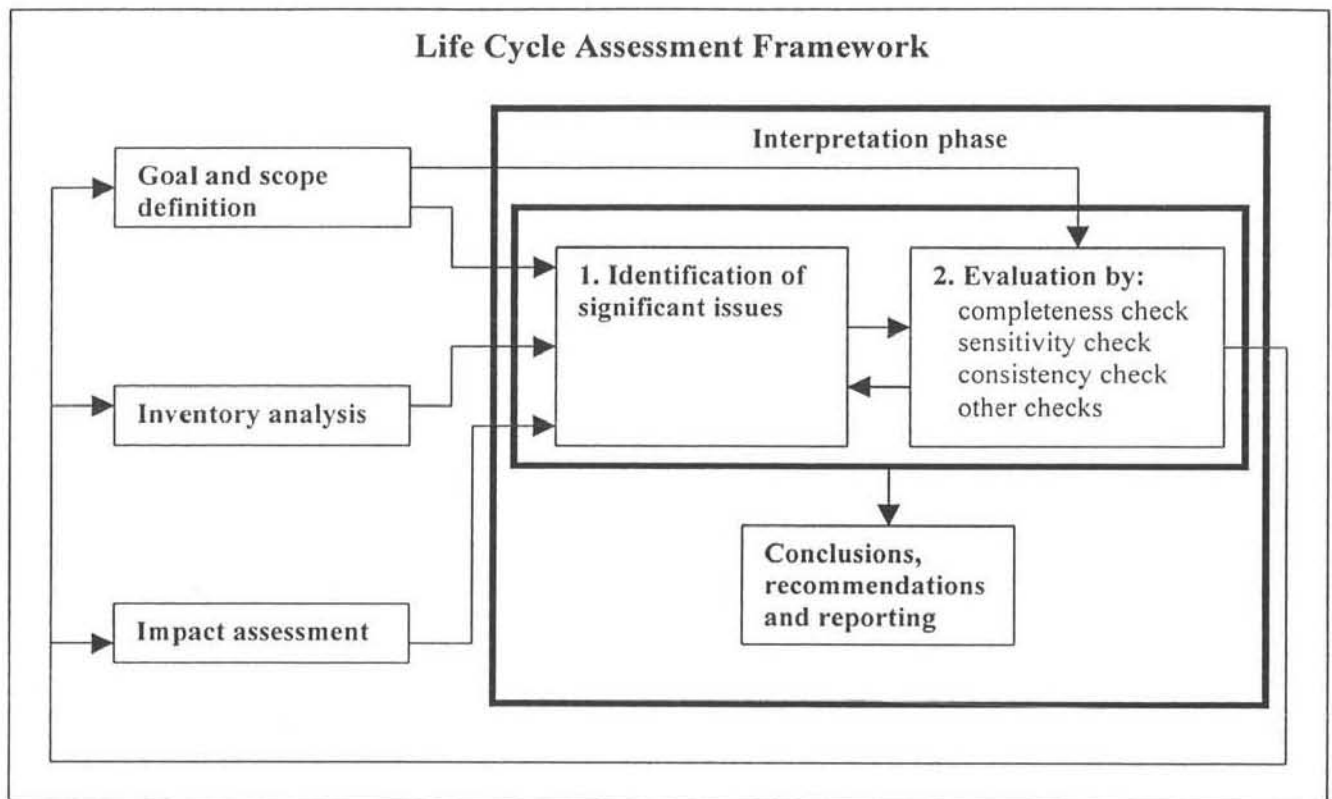
issues, which will be usable in a decision-making process. However, this reduction should give an acceptable coverage and representation of the previous phases in an LCA.

The objectives of life cycle interpretation are to analyse results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA or LCI study and to report the results of the life cycle interpretation in a transparent manner.

Life cycle interpretation is also intended to provide a readily understandable, complete and consistent presentation of the results of an LCA or LCI study, in accordance with the goal and scope of the study (ISO 14043, 2000, 2).

As illustrated in **Figure A1.2**, interpretation is performed in interaction with the three other phases of the LCA. If the results of these previous phases are not good enough to match the goal and scope as set at the beginning of the study, then improvements are needed. This includes improving the inventory analysis by e.g. further data collection, changing the boundaries or improving the quality of data. As a result, the impact assessment would have to be repeated. These iterative processes must be repeated until the *requirements in the goal and scoping phase are fulfilled* (Jenssen et al., 1997) as described by the interpretation steps. The three principal steps of the interpretation according to the ISO 14043 standard are: identification of the significant issues based on the LCI and LCIA phases of the LCA, evaluation (completeness, sensitivity and consistency checks) and conclusions, recommendations and reporting. The interrelationship between these steps, the interpretation phase and the other phases is presented in Figure A1.5:

Significant issues to be identified include inventory data categories (energy, emissions, waste, etc.), impact categories (global warming potential, acidification potential, etc) or essential contributions from life cycle stages such as individual unit processes or groups of processes (e.g. transportation or energy production).



Source: modified after ISO 14043

Figure A1.5: Relationships of the Elements within the Interpretation Phase with the Other Phases of LCA

The sensitivity check is a scientific procedure by which the effects of variations in the different parameters of the study are calculated. The objective of such a check is to assess the reliability of the final results and conclusions by determining whether they are affected by uncertainties in the data, allocation methods or calculation of category indicator results, etc. (ISO 14042, 2000). Different “what if” scenarios are used in sensitivity analysis.

The consistency check is a qualitative procedure determining “whether the assumptions, methods and data are consistent with the goal and scope” (ISO 14043, 2000, 6). Four main questions must be asked with regard to checking for consistency, and these are:

1. *Are differences in data quality along a product system life cycle and between different product systems consistent with the goal and scope of the study?*
2. *Have the regional and/or temporal differences, if any, been consistently applied?*
3. *Have the allocation rules and the system boundaries been consistently applied to all product systems?*
4. *Have the elements of impact assessment been consistently applied? (ISO 14043, 2000)*

In addition to completeness, sensitivity and consistency checks other checks like uncertainty analysis and data quality assessments may be performed.

The final steps of the interpretation phase are the conclusions, recommendations and reporting. These steps are more or less similar to the traditional concluding and recommending part of a scientific and technical assessment or investigation (Jensen et al., 1997). Lindfors et al. (1997) give strict requirements on the information that should be included in a LCA report. Furthermore, they give a list of headings and the content for what each heading should include.

A1.4 Conclusion

The main conclusion to this section is that there is no single correct way to conduct a LCA and to develop a consistent approach in the emerging field of LCA several guidelines have been developed. Two of the initiatives which gained widespread consensus in the LCA fraternity are the SETAC guideline produced in the early 1990s and more recently the LCA ISO series of standards. These guidelines do not prescribe rigid methodologies but a series of procedures to follow in order to cover all areas considered important.

APPENDIX 2

UMGENI WATER GUIDELINES FOR WATER QUALITY

Table A2.1: Physical, organoleptic and chemical requirements

Determinands		Upper Limit and Ranges		
	Units	Class O (Ideal)	Class 1 (Acceptable)	Class II (Max allowable)
Physical and organoleptic requirement				
Colour	mg/L	15	20	50
Conductivity	mS/m	70	150	370
Dissolved solids	mg/L	450	1 000	24 00
Odour	Ton	1	5	10
pH value	pH units	6.0 - 9.0	5.0 – 9.5	4.0 – 10.0
Taste	FNT	1	5	10
Turbidity	NTU	0.1	1	10
Chemical requirements : macro-determinands				
Ammonia as N	mg/L	0.2	1.0	2.0
Calcium as Ca	mg/L	80	150	300
Chloride as Cl	mg/L	100	200	600
Fluoride as F	mg/L	0.7	1.0	1.5
Magnesium as Mg	mg/L	30	70	100
Nitrate and nitrite as N	mg/L	6.0	10.0	20.0
Potassium as K	mg/L	25	50	100
Sodium as Na	mg/L	100	200	400
Sulfate as SO ₄	mg/L	200	400	600
Zinc as Zn	mg/L	3.0	5.0	10.0
Chemical requirements : micro-determinands				
Aluminium as Al	µg/L	150	300	500
Antimony as Sb	µg/L	5	10	50
Arsenic as As	µg/L	10	50	200
Cadmium as Cd	µg/L	3	5	20
Chromium as Cr	µg/L	50	100	500
Cobalt as Co	µg/L	250	500	1 000
Copper as Cu	µg/L	500	1 000	2 000
Cyanide (free) as CN	µg/L	70	70	70
Cyanide (recoverable) as CN	µg/L	70	200	300
Iron as Fe	µg/L	10	200	2 000
Lead as Pb	µg/L	10	50	100
Manganese as Mn	µg/L	50	100	1 000
Mercury as Hg	µg/L	1	2	5
Nickel as Ni	µg/L	50	150	350
Selenium as Se	µg/L	10	20	50
Vanadium as V	µg/L	100	200	500
Chemical requirements: organic determinands				
Dissolved organic carbon as C	mg/L	5	10	20
Total trihalomethanes	µg/L	100	200	300
Phenols	µg/L	1	10	70
NOTE – The limits for iron are based on aesthetic aspects				

Table A2.2: Microbiological requirements

Determinands	Units	Allowable compliance contribution		
		95 % min.	4 % max.	1 % max.
		UPPER LIMITS		
Heterotrophic plate count	Count/mL	100	1 000	10 000
Total coliform	Count/100 mL	Not detected	10	100
Faecal coliform	Count/100 mL	Not detected	1	10
Somatic coliphages	Count/10 mL	Not detected	1	10
Enteric viruses	Count/100 mL	Not detected	1	10
Protozoan parasites (Giardia/Cryptosporidium)	Count/100 mL	Not detected	1	10
<p>* The allowable compliance contribution shall be at least 95 % to the limits indicated in column 3, with a maximum of 4 % and 1 % respectively, to the limits indicated in columns 4 and 5</p> <p>The objective of disinfection should, nevertheless, be to attain 100 % compliance to the limits indicated in column 3.</p>				

APPENDIX 3

LIST OF LCA SOFTWARE

LIST OF LCA SOFTWARE AVAILABLE IN 1999

Name	Vendor	Version	Cost, \$K	Data Location
1. Boustead	Boustead Phone : +44 403 864 561 Fax : +44 403 865 284	2	24	Europe
2. CLEAN	EPRI Phone : +1 415 960 5918 Fax : +1 415 960 5965	2	14	U.S.
3. CUMPAN	University of Hohenheim	Unknown	Unknown	Germany
4. EcoAssessor	PIRA	Unknown	Unknown	UK
5. EcoManager	Franklin Associates, Ltd. Phone : +1 913 649 2225 Fax : +1 913 649 6494	1	10	Europe / U.S.
6. ECONTROL	Oekoscience	Unknown	Unknown	Switzerland
7. EcoPack2000	Max Bolliger	2.2	5.8	Switzerland
8. EcoPro	EMPA Phone : +41 71 300101 Fax : +41 71 300199	1	Unknown	Switzerland
9. EcoSys	Sandia / DOE	Prototype	Unknown	U.S.
10. EDIP	Inst. For Prod. Devel. Phone : +45 4295 2522	Prototype	Unknown	Denmark
11. EMIS	Carbotech	Unknown	Unknown	Switzerland
12. EPS	IVL Fax: +46 314 82180	1	Unknown	Sweden
13. GaBi	IPTS Phone : +49 7021 942 660 Fax : +49 7021 942 661	2	10	Germany
14. Heraklit	Fraunhofer Inst. Phone : +49 89 149009 89 Fax : +49 89 149009 80	Unknown	Unknown	Germany
15. IDEA	IIASA (A) / VTT (SF) Phone : +358 (0) 465 6538	Unknown	Unknown	Europe
16. KCL/ECO	Finnish Paper Inst. Phone : +358 9 43 711 Fax : +358 9 464 305	1	3.6	Finland
17. LCA1	P&G / ETH	1	Not avail.	Europe
18. LCAD	Battelle / DOE	Prototype	< 1	U.S.
19. LCAIT	Chalmers Industriteknik Phone : + 46 31 772 4237 Fax : + 46 31 82 7421	2.0	3.5	Sweden
20. LCASys	Philips / ORIGIN	Unknown	Unknown	Netherlands
21. LIMS	Chem Systems Phone : +1 914 631 2828 Fax : +1 941 631 8851	1	25	U.S.
22. LMS Eco-Inv. Tool	Christoph Machner	1	Unknown	Austria
23. Oeko-Base II	Peter Meier Phone : +41 1 277 3076 Fax : +41 1 277 3088	Unknown	5.5	Switzerland
24. PEMS	PIRA Phone : +44 0 1372 02000 Fax : +44 0 1372 802238	3.1	9.1	Ave. European

Name	Vendor	Version	Cost, \$K	Data Location
25. PIA	BMI / TME Phone : +31 70 346 4422 Fax : +31 70 362 3469	1.2	1.4	Europe
26. PIUSSOECOS	PSI AG	Unknown	Unknown	Germany
27. PLA	Visionik ApS Fax : +45 3313 4240	Unknown	Unknown	Denmark
28. REGIS	Sinum Gmbh Phone : +41 51 37 61	Unknown	Unknown	Switzerland
29. REPAQ	Franklin Associates, Ltd. Phone : +1 913 649 2225 Fax : +1 913 649 6494	2	10	U.S.
30. SimaPro	Pre Consulting Phone : + 31 33 461 1046 Fax : +31 33 465 2853	3.1	3	Netherlands
31. Sima Tool	Leiden Univ.	Prototype	Unknown	Netherlands
32. Simbox	EAWAG	Unknown	Unknown	Switzerland
33. TEAM	Ecobalance Phone : +1 301 548 1750 Fax : +1 301 548 1760	1.15 & 2.0	10	Europe / U.S.
34. TEMIS	Oko-Institut Phone : +49 761 473130 Fax : +49 761 475437	2	0.3	Europe
35. TetraSolver	TetraPak	Unknown	Unknown	Europe
36. Umberto	IFEU Phone : +49 40 462033 Fax : +49 40 462034	Unknown	Unknown	Germany
37. Umcon	Particip Gmbh	Unknown	Unknown	Germany
38. Oekobilanz von Packstoffen	BUWAL	EXCEL-files	0.25	Switzerland

APPENDIX 4

VALUATION (WEIGHTING) METHODS

VALUATION METHODS

Lindeijer (1996) reviews the different valuation methods as follows.

Method	Methodology	Characteristics / comments	Reference
Energy requirement	Equal energy requirement	Proxy	Franklin
MIPS	Equal material displacement	Proxy	Schmidt-Bleek (1994)*
SPI	Equal space consumption	Proxy, Technology	
Abatement energy	Equal space consumption including energy for abatement of environmental burden	Technology	Cramer <i>et al.</i> (1993)
Abatement cost	Equal modelled costs for abating emissions according to national goals	Technology, monetarisation, authorized targets	Kroon <i>et al.</i> (1994)
Abatement cost / The Tellus system	Equal costs for abating emissions. Most human toxic emissions abatement costs extrapolated from characterization factors via lead (combining carcinogenic and non-carcinogenic substances via PEL values)	Monetarisation, authorized standards	Tellus Institute (1992)
DESC	Equal projected generic costs for abatement of burden according to national goals derived per impact category	Technology, monetarisation, authorized targets	Krozer (1992)
The EPS system	The EPS system is based on "willingness to pay" to restore the concerned effect to their normal status. The concerned effects are biodiversity, production, human health, resources and aesthetic values	Monetarisation, technology. The willingness to pay / the weighting will be different from country to country	Steen & Ryding (1992); Bostrom & Steen (1994)
The "Molar" method	Equal critical volume scores, the volume of each medium weighted according to their mole density	Authorized standards	Schaltegger & Sturm (1991)
The "Critical volume" method	Equal critical volume scores weighted subjectively	Authorized standards	Kohlert & Thalmann (1992)
The "Critical surface time" method	Equal critical immissions volumes weighted subjectively	Authorized standards	Jolliet (1994a)
The "Ecoscarcity" approach	Equal scores over proportional distances to political targets	Authorized standards	Ahbe <i>et al.</i> (1990)
The "Effect category" method	-	-	Baumann <i>et al.</i> (1993)
Distance to target	Equal scores of distances to political targets optionally additionally weighted subjectively	Authorized targets	Corten <i>et al.</i> (1994)
NSAEL	Equal scores of overshoots of sustainable targets optionally weighted subjectively	Authorized targets	Kortman <i>et al.</i> (1994)
The "Eco-indicator 95" method	Equal scores of distances to science-political targets contributing to the equally weighted safeguard subjects 1 on a million human lives, 95 % of ecosystems and human health complaints due to smog	Authorized targets	Goedkoop (1995)
Iso-utility functions	Equal panel scores on relative (negative) utilities of actual impact scores	Panel	Tukker (1994)
Iso-preference approach	Equal pannel preferences for elasticities in relative impact scenarios	Panel	Heijungs (1994)
Delphi technique	Equal expert panel scores on actual impacts	Panel	Wilson & Jones (1994)
Questionnaire	Equal industry / science panel scores on impact categories	Panel	Nagata <i>et al.</i> (1995)
Panel questionnaire	Equal societal group panel scores on impact categories	Panel	Kortman <i>et al.</i> (1994)
Structured dialogue	Panel agreement on weights based on argumentation	Panel	Weidema (1994a)
Argumentative evaluation	Societal group consensus on the interpretation of product systems comparison with inputs from normalisation, environmental problem weights by a political panel and a sensitivity analysis	Panel	Schmitz <i>et al.</i> (1994)
Export panel prioritisation	Equal interpretation of product systems comparison using a qualitative valuation of normalisation data and expert panel scores on the criteria time, space and hazard	Panel	Volkwein <i>et al.</i> (1996)

* The references presented are from Lindeijer (1996)

APPENDIX 5

**TECHNICAL SPECIFICATION SHEETS FOR
ULTRAFILTRATION MODULES**

TECHNICAL SPECIFICATION SHEETS FOR ULTRAFILTRATION MODULES

1. Module specification: 250mm OD, length 1250 mm, flux 50 L/m²h, 4 740 modules

Dimensions

Number of capillaries per module	10350
Diameter of capillary	0.0012 m
Filtration length of capillary (excludes epoxy moulded part)	1.025 m
Filtration area per capillary	0.0040 m ²
Filtration area per module	42.12 m ²
Cross-sectional flow area per capillary	1.13E-06 m ²
Cross-sectional flow area per module	0.0117 m ²

Conditions for ideal filtration

Crossflow velocity through capillary	1 m/s
Feed pressure	1.5 Bar max
Assumed flux	50 L/m ² h
Assumed water recovery	95 %

Flowrates and Cleaning in Place (CIP)

Permeate / Product flowrate per module	1998.69 L/h
Raw feed flowrate per module	2103.88 L/h
Reject flowrate per module	105.19 L/h
Backflush flowrate per module*	105.19 L/h
Downtime duration per CIP	6 h
Assumed no. of CIP's over a 30 day period	2
Other downtime per 30 day period	10 h
Downtime per day	0.73 h
Vol. of water required per module for CIP	400 L/CIP
Vol. of water per module per CIP per day	26.6 L/CIP/d

Backflush Conditions

Duration	60 s
Cycle time	600 s
Flowrate	1.5 times permeation flow
No. of filtration and backflushes per day	127 cycles

Volumes of water per day

Water volume used for backflushes	222.5 L/d/module
Total water produced per module during filtration	42275.3 L/d/module
Net volume produced (Net Vol = Tot Vol - (Vol _{BF} + Vol _{CIP}))	42026.1 L/d/module

***Observation: reject flow equals backflush flow for dead end filtration**

2. Module specification: 250mm OD, length 1250 mm, flux 100 L/m²h, 2 370 modules

Dimensions

Number of capillaries per module	10350
Diameter of capillary	0.0012 m
Filtration length of capillary (excludes epoxy moulded part)	1.025 m
Filtration area per capillary	0.0040 m ²
Filtration area per module	42.12 m ²
Cross-sectional flow area per capillary	1.13E-06 m ²
Cross-sectional flow area per module	0.0117 m ²

Conditions for ideal filtration

Crossflow velocity through capillary	1 m/s
Feed pressure	1.5 Bar max
Assumed flux	100 L/m ² h
Assumed water recovery	95 %

Flowrates and Cleaning in Place (CIP)

Permeate / Product flowrate per module	3997.38 L/h
Raw feed flowrate per module	4207.77 L/h
Reject flowrate per module	210.39 L/h
Backflush flowrate per module*	210.39 L/h
Downtime duration per CIP	6 h
Assumed no. of CIP's over a 30 day period	2
Other downtime per 30 day period	10 h
Downtime per day	0.73 h
Vol. of water required per module for CIP	400 L/CIP
Vol. of water per module per CIP per day	26.6 L/CIP/d

Backflush Conditions

Duration	60 s
Cycle time	600 s
Flowrate	1.5 times permeation flow
No. of filtration and backflushes per day	127 cycles

Volumes of water per day

Water volume used for backflushes	445.0 L/d/module
Total water produced per module during filtration	84550.6 L/d/module
Net volume produced (Net Vol = Tot Vol - (Vol _{BF} + Vol _{CIP}))	84079.0 L/d/module

3. Module specification: 250mm OD, length 1670 mm, flux 50 L/m²h, 3 240 modules

Dimensions

Number of capillaries per module	10350
Diameter of capillary	0.0012 m
Filtration length of capillary (excludes epoxy moulded part)	1.50 m
Filtration area per capillary	0.0057 m ²
Filtration area per module	58.50 m ²
Cross-sectional flow area per capillary	1.13E-06 m ²
Cross-sectional flow area per module	0.0117 m ²

Conditions for ideal filtration

Crossflow velocity through capillary	1 m/s
Feed pressure	1.5 Bar max
Assumed flux	50 L/m ² h
Assumed water recovery	95 %

Flowrates and Cleaning in Place (CIP)

Permeate / Product flowrate per module	2924.91 L/h
Raw feed flowrate per module	3078.85 L/h
Reject flowrate per module	153.94 L/h
Backflush flowrate per module*	153.94 L/h
Downtime duration per CIP	6 h
Assumed no. of CIP's over a 30 day period	2
Other downtime per 30 day period	10 h
Downtime per day	0.73 h
Vol. of water required per module for CIP	581.4 L/CIP
Vol. of water per module per CIP per day	38.8 L/CIP/d

Backflush Conditions

Duration	60 s
Cycle time	600 s
Flowrate	1.5 times permeation flow
No. of filtration and backflushes per day	127 cycles

Volumes of water per day

Water volume used for backflushes	325.6 L/d/module
Total water produced per module during filtration	61866.3 L/d/module
Net volume produced (Net Vol = Tot Vol - (Vol _{BF} + Vol _{CIP}))	61501.9 L/d/module

4. Module specification: 250mm OD, length 1670 mm, flux 100 LMH, 1 620 modules

Dimensions

Number of capillaries per module	10350
Diameter of capillary	0.0012 m
Filtration length of capillary (excludes epoxy moulded part)	1.50 m
Filtration area per capillary	0.0057 m ²
Filtration area per module	58.50 m ²
Cross-sectional flow area per capillary	1.13E-06 m ²
Cross-sectional flow area per module	0.0117 m ²

Conditions for ideal filtration

Crossflow velocity through capillary	1 m/s
Feed pressure	1.5 Bar max
Assumed flux	100 L/m ² h
Assumed water recovery	95 %

Flowrates and Cleaning in Place (CIP)

Permeate / Product flowrate per module	5849.82 L/h
Raw feed flowrate per module	6157.70 L/h
Reject flowrate per module	307.89 L/h
Backflush flowrate per module*	307.89 L/h
Downtime duration per CIP	6 h
Assumed no. of CIP's over a 30 day period	2
Other downtime per 30 day period	10 h
Downtime per day	0.73 h
Vol. of water required per module for CIP	581.4 L/CIP
Vol. of water per module per CIP per day	38.8 L/CIP/d

Backflush Conditions

Duration	60 s
Cycle time	600 s
Flowrate	1.5 times permeation flow
No. of filtration and backflushes per day	127 cycles

Volumes of water per day

Water volume used for backflushes	651.2 L/d/module
Total water produced per module during filtration	123732.6 L/d/module
Net volume produced (Net Vol = Tot Vol - (Vol _{BF} + Vol _{CIP}))	123042.6 L/d/module

APPENDIX 6

CALCULATION SHEETS FOR PUMPS AND PIPES INVOLVED IN THE CONSTRUCTION OF THE MEMBRANE FLTRATION PLANT

SAMPLE CALCULATION FOR THE PUMPS NEEDED FOR SCENARIO 3A (WORST CASE SCENARIO) PERMEATE LINE

This sample calculation is an explanation on how the values presented in the calculation sheet entitled **Pumps Needed** have been obtained. This calculation sheet is referred to as pumps sheet in this section. The permeate flowrate as presented in the technical specification for this type of module (see **Appendix 5**, part 3) expressed in L/h was divided by a factor of 3600 to obtain the flowrate per module in L/s ($2924.91 : 3600 = 0.81$ L/s). This value was multiplied by 30, the number of modules per bank for this scenario ($0.81 * 30 = 24.30$ L/h) and this is the value presented in the second column in the pumps sheet for scenario 3A, permeate line. The name of this column in the pumps sheet is *Flow/bank*, since this is the permeate flow in the pipe collecting the permeate for the 30 modules for one bank. The pressure head needed for this line is 10 m (equivalent to 1 Bar, see assumptions pumps sheet). Knowing the flux and the pressure head, the size of the pump required was established as in the following figure.

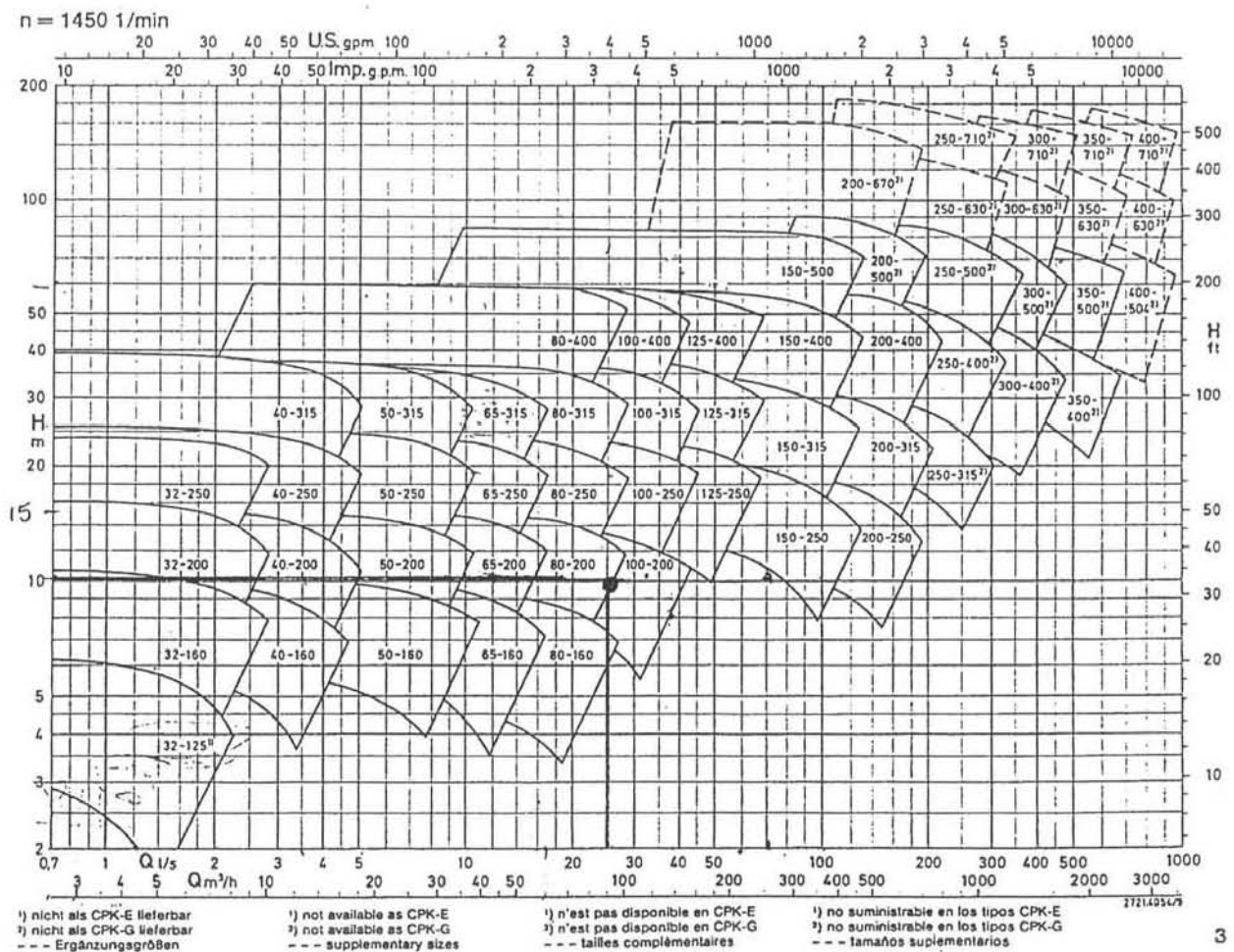
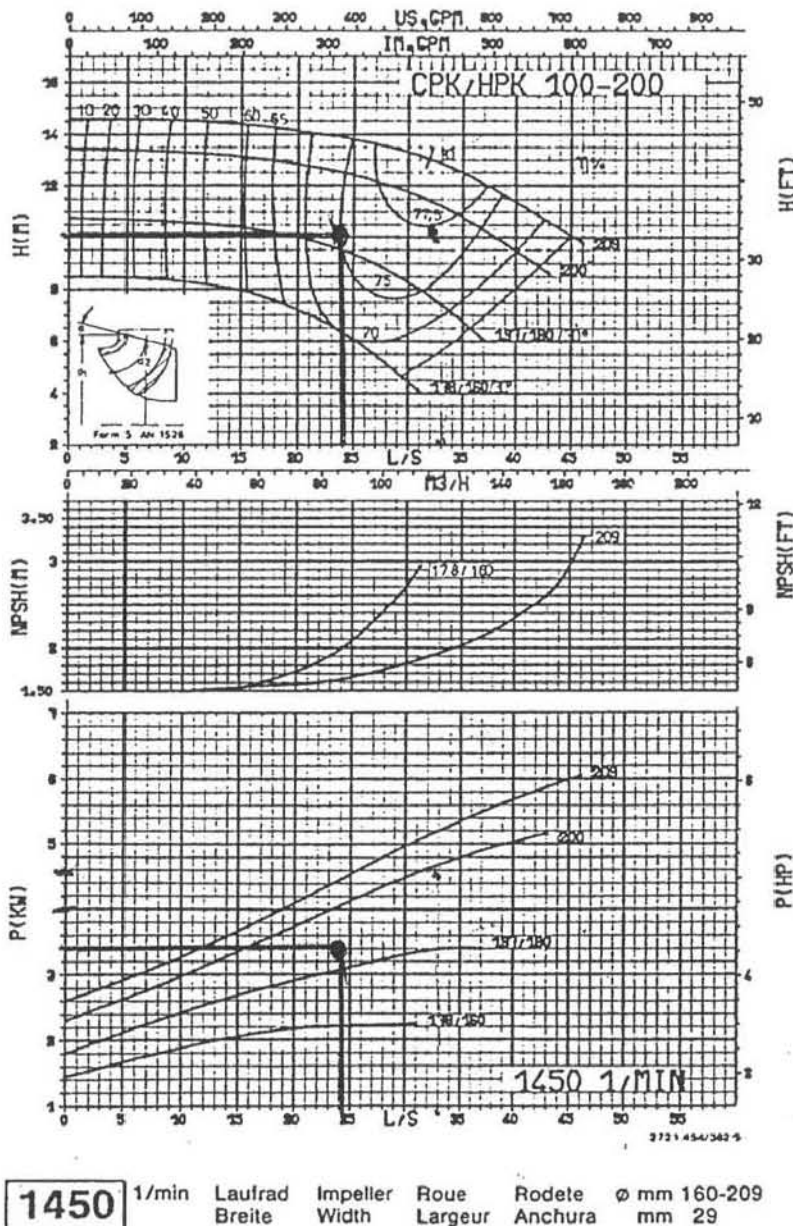


Figure A6.1: Selection of Pumps

As can be seen from the above figure in the case where the point resulting from the two parameters (flow and pressure head) was between two pump sizes, the higher pump was chosen. In this case it is a 100-200 size pump and the size is presented in the third column (named *Pump Size*) of the pumps calculation sheet. Once the size of the pump is known and its rotational speed ($n=1450$ 1/min), pumps performance curves have been used to determine the power needed and the efficiency of the pump (see **Figure A6.2**). By using the flow and the pressure head, the first graph shows the efficiency (75 %) and impeller diameter (ca. 184 mm).



1st Graph

2nd Graph

3rd Graph

Figure A6.2: Pump Performance Curves

In the third graph, by using the impeller diameter and the flow (L/s) the power needed was established (3.4 kW). Since this pump has an efficiency of 75 % the real power needed was calculated ($3.4 : 0.75 = 4.53$ kW, rounded up to 4.6 kW). This value is presented in column number six (named *P Power*) in the pumps sheet. In column number seven (named *Motor E*) the final value for the power needed is presented and this value was calculated by taking into account an efficiency of 85 % needed by the motor ($4.6 : 0.85 = 5.41$ kW). The motor efficiency values were been obtained from FEMCO, a local manufacturer of electric motors and pumps. To obtain the total value for power consumption for this line the power needed for each bank of modules (5.41 kW) was multiplied by the number of banks (or batches), in this case 108 and by the time a pump is in action (21.82 h)¹ during a day. For scenario 3A, the scenario of this sample calculation, this gives a value of 12 751.395 kWh/d. This is the value presented in column eleven (named *Total power per day*) in the pumps calculation sheet. For this scenario the power needed by all 4 lines is added and the result is 38 062.20 kWh/d. To obtain the power needed for 1 kL of potable water this total value is divided by the amount of potable water produced in a day expressed in kL ($38\,062.20 : 198\,670 = 0.192$ kWh/kL).

In addition to calculations for power consumption, the pumps sheet contains information about the motor size (column number eight named *Motor*) and about the material consumption for pumps and motors. Column number nine, named *Weight*, presents the weight of the pump and motor needed for one bank of modules and column ten, named *T weight*, presents the total weight for the pumps and the motors needed for that scenario. The total weight was obtained by multiplying the weight needed for one bank by the number of banks needed by the scenario.

* The time used in this calculation was obtained by subtracting downtime due to CIP and general downtime ($12 \text{ h/month} + 10 \text{ h/month} = 22 \text{ h/month}$; 22 h/month divided by 30 days = 0.73 h/d downtime) and backflush (1.45 h/d). The calculations are: $24 - 0.73 - 1.45 = 21.82$.

PUMPS NEEDED

Assumptions: for each line (permeate, raw feed, backflush and reject) a pump will service a bank of 30 or 60 modules

Assumptions with regard to pressures:

Filtration pressure	1.5 Bar	} 1.9 Bar
Pressure loss	0.4 Bar	
B/F pressure	2.2 Bar	
Permeate pressure	1 Bar	

SUMMARY

	<u>A: 30 Modules per bank</u>			<u>B: 60 Modules per bank</u>		
TOTAL FOR THE OPTIONS	Weight (kg)	Power/d (kWh)	kWh/kL	Weight (kg)	Power/d (kWh)	kWh/kL
1. 250/1025mm, low flux	23700	28339.76	0.143	18565	27841.79	0.140
2. 250/1025mm, high flux	18565	27841.79	0.140	18800	35508.23	0.179
3. 250/1500mm, low flux	25380	38062.2	0.192 worst	17226	29381.92	0.148
4. 250/1500mm, high flux	17226	29381.92	0.148	12933	25953.87	0.131 best

SCENARIOS

30 Modules

1A. 250/1025mm, low flux, 4725 modules

	Flow/batch	Head	Pump Size	No	P Power	Motor E	Motor	Weight	T. weight	Time/24 h	Total power per day
Permeate / Product	16.66 L/s	10	80-200	158	2.50	3.13	3.00	38	6004	21.82	10772.14
Raw feed	17.53 L/s	19	80-250	158	3.80	4.52	5.50	68	10744	21.82	15593.96
Reject	0.88 L/s	10	32-200	158	0.31	0.46	0.55	17	2686	23.27	1676.12
Backflush	0.88 L/s	22	32-250	158	1.00	1.30	1.50	27	4266	1.45	297.53
(158 banks - 4740 modules rounded)									23700		28339.76

2A. 250/1025mm, high flux, 2357 modules

	Flow/batch	Head	Pump Size	No	P Power	Motor E	Motor	Weight	T. weight	Time/24 h	Total power per day
Permeate / Product	33.31 L/s	10	100-200	79	4.60	5.41	5.50	68	5372	21.82	9327.41
Raw feed	35.06 L/s	19	100-250	79	9.00	10.17	11.00	123	9717	21.82	17527.56
Reject	1.75 L/s	10	32-200	79	0.31	0.46	0.55	17	1343	23.27	838.06
Backflush	1.75 L/s	22	32-250	79	1.00	1.30	1.50	27	2133	1.45	148.77
(79 banks - 2370 modules rounded)									18565		27841.79

3A. 250/1500mm, low flux, 3229 modules

	Flow/batch	Head	Pump Size	No	P Power	Motor E	Motor	Weight	T. weight	Time/24 h	Total power per day
Permeate / Product	24.37 L/s	10	100-200	108	4.60	5.41	5.50	68	7344	21.82	12751.39
Raw feed	25.66 L/s	19	100-250	108	9.00	10.17	11.00	123	13284	21.82	23961.72
Reject	1.28 L/s	10	32-200	108	0.31	0.46	0.55	17	1836	23.27	1145.71
Backflush	1.28 L/s	22	32-250	108	1.00	1.30	1.50	27	2916	1.45	203.38
(108 banks - 3240 modules rounded)									25380		38062.20

4A. 250/1500mm, high flux, 1615 mod.

	Flow/batch	Head	Pump Size	No	P Power	Motor E	Motor	Weight	T. weight	Time/24 h	Total power per day
Permeate / Product	48.75 L/s	10	125-250	54	9.00	10.17	11.00	123	6642	21.82	11980.86
Raw feed	51.31 L/s	19	125-250	54	12.50	13.97	15.00	144	7776	21.82	16454.16
Reject	2.57 L/s	10	40-200	54	0.46	0.63	0.75	18	972	23.27	797.28
Backflush	2.57 L/s	22	40-250	54	1.50	1.91	2.20	34	1836	1.45	149.62
(54 banks - 1620 modules rounded)									17226		29381.92

60 Modules

1B. 250/1025mm, low flux, 4725 modules

	Flow/batch	Head	Pump Size	No	P Power	Motor E	Motor	Weight	T weight	Time/24 h	Total power per day
Permeate / Product	33.311 L/s	10	100-200	79	4.60	5.41	5.50	68	5372	21.82	9327.41
Raw feed	35.065 L/s	19	100-250	79	9.00	10.17	11.00	123	9717	21.82	17527.56
Reject	1.7532 L/s	10	32-200	79	0.31	0.46	0.55	17	1343	23.27	838.06
Backflush	1.7532 L/s	22	32-250	79	1.00	1.30	1.50	27	2133	1.45	148.77
*Reject equals backflush for dead end filtration									18565		27841.79
79 banks											

2B. 250/1025mm, high flux, 2357 modules

Permeate / Product	66.623 L/s	10	150-250	40	10.00	11.30	15.00	144	5760	21.82	9860.79
Raw feed	70.129 L/s	19	150-315	40	26.00	28.26	30.00	270	10800	21.82	24662.70
Reject	3.5065 L/s	10	40-200	40	0.70	0.93	1.10	22	880	23.27	868.75
Backflush	3.5065 L/s	22	40-250	40	1.60	2.00	2.20	34	1360	1.45	116.00
40 banks									18800		35508.23

3B. 250/1500mm, low flux, 3229 modules

	Flow/batch	Head	Pump Size	No	P Power	Motor E	Motor	Weight	T weight	Time/24 h	Total power per day
Permeate / Product	48.749 L/s	10	125-250	54	9.00	10.17	11.00	123	6642	21.82	11980.86
Raw feed	51.314 L/s	19	125-250	54	12.50	13.97	15.00	144	7776	21.82	16454.16
Reject	2.5657 L/s	10	40-200	54	0.46	0.63	0.75	18	972	23.27	797.28
Backflush	2.5657 L/s	22	40-250	54	1.50	1.91	2.20	34	1836	1.45	149.62
54 banks									17226		29381.92

4B. 250/1500mm, high flux, 1615 modules

Permeate / Product	97.497 L/s	10	150-250	27	13.00	14.53	15.00	144	3888	21.82	8556.16
Raw feed	102.63 L/s	19	150-315	27	26.00	28.14	30.00	270	7290	21.82	16575.25
Reject	5.1314 L/s	10	50-200	27	0.90	1.17	1.50	27	729	23.27	734.36
Backflush	5.1314 L/s	22	50-250	27	1.80	2.25	3.00	38	1026	1.45	88.09
27 banks									12933		25953.87

SAMPLE CALCULATION FOR THE PIPES NEEDED FOR SCENARIO 3A (WORST CASE SCENARIO) PERMEATE LINE

This sample calculation is an explanation of how the values presented in the following calculation sheets entitled *Small Pipes*, *Intermediate Pipes* and *Large Pipes* have been obtained. The small pipes and the large pipes are the same regardless of how many modules are arranged in a bank, and therefore, are presented as common for a scenario (i.e. they will be the same for scenario 1A and 1B). The intermediate pipes are influenced by how many modules are arranged in a bank and therefore the pipes needed are presented separately for each scenario.

In the calculation sheet entitled *Small Pipes* the flow rate for scenario 3 (common for A and B) for the permeate line was expressed in L/s by employing the same calculation as in the sample calculation for pumps. By using this value the outer diameter (OD) was calculated by using the formula presented in the sheet ($OD = \sqrt[4]{\frac{area \times 4}{\pi}}$), where $area = \frac{flow (m^3/s)}{velocity (m/s)}$, the velocity was assumed to be 2.5 m/s). The calculated OD, together with the pressure in the line, determined the size of the pipes by using standardised pipe schedules obtained from Natal Plastics, the pipe manufacturers (see **Figure A6.3**).

OUTSIDE DIAMETER	SIZE	CLASS 4		CLASS 6		CLASS 9		CLASS 12		CLASS 16	
mm	inch	mm	kg	mm	kg	mm	kg	mm	kg	mm	kg
20	3/8									1.5	0.81
25	1/4							1.5	1.03	1.9	1.29
32	1					1.5	1.34	1.8	1.59	2.4	2.08
40	1 1/4			1.5	1.70	1.8	2.02	2.3	2.53	3.0	3.25
50	1 1/2	1.5	2.17	1.8	2.58	2.2	3.13	2.8	3.96	3.7	5.13
63	2	1.5	2.67	1.9	3.46	2.7	4.87	3.6	6.40	4.7	8.23
75	2 1/4	1.5	3.30	2.2	4.78	3.2	6.87	4.3	9.11	5.6	11.66
90	3	1.8	4.74	2.7	7.04	3.9	10.05	5.1	12.96	6.7	16.75
110	3 1/2	2.2	7.08	3.2	10.22	4.7	14.85	6.3	18.58	8.2	25.11
125	4	2.5	9.16	3.7	13.41	5.4	19.36	7.1	25.12	9.3	32.37
140	5	2.8	11.49	4.1	16.67	6.0	24.13	7.9	31.40	10.4	40.64
160	6	3.2	15.03	4.7	21.92	6.9	31.78	9.1	41.34	11.9	53.26
200	8	3.9	23.02	5.9	34.46	8.6	49.64	11.3	64.40	14.7	82.10

→ small pipes for scenario 3A

→ intermediate pipe for scenario 3A

This table shows the minimum wall thickness and mass per 6 m pipe for each size and class currently manufactured. (For standard pipe only)

Figure A6.3: Pipe Schedules for PVC Pipes for the Permeate Line for Scenario 3

The calculations for the intermediate pipes proceeded in a similar fashion as the ones done for the small pipes. The only difference is that different sizes of pipes have been calculated for different module arrangements. For scenario 3A the permeate flow associated with one module was multiplied by the number of modules in a bank ($0.81 * 30 = 24.3$ L/s), giving the flow in an intermediate pipe for this scenario. This flow was used to calculate the OD of the pipe needed, and by using the OD the pipe size was established with the help of the standardised pipe schedules used before, since it was assumed they are made out of PVC.

A similar calculation was employed for large pipes. The only difference is that in calculating the OD, the flow per line was used. This flow was obtained by multiplying the flow per module by the number of modules used for that scenario. In the case of scenario 3 the calculation done was as follows: $0.81 * 3\ 240 = 2\ 632.42$ L/s. Since this flow is too large for the largest standard steel pipe manufactured, two steel pipes have been assumed, each carrying half of this flow. Therefore, in calculating the OD (by the same formula as for small pipes) a flow of $1\ 316.21$ L/s was used. A similar pipe schedule (see **Figure A6.3**) was used for steel pipe calculations. This schedule was obtained from Process Pipe (Tel. 031-481211), a steel pipe distributor.

Small Pipes

Formula for OD: $\text{sqroot from } (\text{area} \cdot 4/\pi)$, $\text{area} = \text{flow}(\text{m}^3/\text{s})/\text{velocity}(\text{m/s})$, $\text{velocity} = 2.5 \text{ m/s}$

			Pipes
	Flow	Calc. OD (mm)	Size
1. 250/1025mm, low flux, 4725 mod.			
Permeate / Product	0.56 L/s	16.8	3/8"
Raw feed	0.58 L/s	17.3	1/2"
Reject	0.03 L/s	3.9	1/8" Smallest available
Backflush	0.03 L/s	3.9	1/8" Smallest available
*Reject equals backflush for dead end filtration (4740 modules rounded)			
2. 250/1025mm, high flux, 2357 mod.			
Permeate / Product	1.11 L/s	23.8	1"
Raw feed	1.17 L/s	24.4	1"
Reject	0.06 L/s	5.5	1/8" Smallest available
Backflush	0.06 L/s	5.5	1/8" Smallest available
(2370 modules rounded)			
3. 250/1500mm, low flux, 3229 mod.			
Permeate / Product	0.81 L/s	20.3	3/4"
Raw feed	0.86 L/s	20.9	3/4"
Reject	0.04 L/s	4.7	1/8" Smallest available
Backflush	0.04 L/s	4.7	1/8" Smallest available
(3240 modules rounded)			
4. 250/1500mm, high flux, 1615 mod.			
Permeate / Product	1.62 L/s	28.8	1 1/4"
Raw feed	1.71 L/s	29.5	1 1/4"
Reject	0.09 L/s	6.6	1/8" Smallest available
Backflush flowrate per module	0.09 L/s	6.6	1/8" Smallest available

Intermediate Pipes

Formula for OD: $\text{sqroot from } (\text{area} \times 4 / \pi)$, $\text{area} = \text{flow}(\text{m}^3/\text{s}) / \text{velocity}(\text{m}/\text{s})$, $\text{velocity} = 2.5 \text{ m/s}$

		<u>A. Batches of 30 modules</u>			<u>B. Batches of 60 modules</u>		
1. 250/1025mm, low flux, 4725 mod.		A. Pipes			B. Pipes		
	Flow/mod.	Flow/bank	Calc. OD (mm)	Size	Flow/bank	Calc. OD (mm)	Size
Permeate / Product	0.56 L/s	16.66	92.1	3 1/2"	33.31	130.3	5"
Raw feed	0.58 L/s	17.53	94.5	4"	35.06	133.6	6"
Reject	0.03 L/s	0.88	21.1	3/4"	1.75	29.9	1 1/4"
Backflush	0.03 L/s	0.88	21.1	3/4"	1.75	29.9	1 1/4"
*Reject equals backflush for dead end filtration (158 banks)				79 banks			
2. 250/1025mm, high flux, 2357 mod.							
Permeate / Product	1.11 L/s	33.31	130.3	5"	66.62	184.2	8"
Raw feed	1.17 L/s	35.06	133.6	6"	70.13	189.0	8"
Reject	0.06 L/s	1.75	29.9	1 1/4"	3.51	42.3	1 1/2"
Backflush	0.06 L/s	1.75	29.9	1 1/4"	3.51	42.3	1 1/2"
(79 banks)				40 banks			
3. 250/1500mm, low flux, 3229 mod.							
Permeate / Product	0.81 L/s	24.37	111.4	5"	48.75	157.6	6"
Raw feed	0.86 L/s	25.66	114.3	5"	51.31	161.7	6"
Reject flowrate	0.04 L/s	1.28	25.6	1"	2.57	36.1	1 1/2"
Backflush	0.04 L/s	1.28	25.6	1"	2.57	36.1	1 1/2"
(108 banks)				54 banks			
4. 250/1500mm, high flux, 1615 mod.							
Permeate / Product	1.62 L/s	48.75	157.6	6"	97.50	222.8	10"
Raw feed	1.71 L/s	51.31	161.7	6"	102.63	228.6	10"
Reject	0.09 L/s	2.57	36.1	1 1/2"	5.13	51.1	2"
Backflush	0.09 L/s	2.57	36.1	1 1/2"	5.13	51.1	2"
(54 banks)				27 banks			

Large Pipes

Formula for OD: $\text{sqroot from } (\text{area} \cdot 4 / \pi)$, $\text{area} = \text{flow}(\text{m}^3/\text{s}) / \text{velocity}(\text{m/s})$, $\text{velocity} = 2.5 \text{ m/s}$

1. 250/1025mm, low flux, 4725 modules

	Flow/mod.	Flow/bank	Flow/line	Calc. OD (mm)	Pipe Size	Number of Pipes
Permeate / Product	0.56 L/s	16.66	1315.80	818.6	34"	2
Raw feed	0.58 L/s	17.53	1385.06	839.9	34"	2
Reject	0.03 L/s	0.88	138.51	265.6	12"	
Backflush	0.03 L/s	0.88	138.51	265.6	12"	

*Reject equals backflush for dead end filtration
(4740 modules rounded)

2. 250/1025mm, high flux, 2357 modules

Permeate / Product	1.11 L/s	33.31	2631.61	1157.7	34"	2
Raw feed	1.17 L/s	35.06	2770.11	1187.8	34"	2
Reject	0.06 L/s	1.75	138.51	265.6	12"	
Backflush	0.06 L/s	1.75	138.51	265.6	12"	

(2370 mod. rounded)

3. 250/1500mm, low flux, 3229 modules

Permeate / Product	0.81 L/s	24.37	2632.42	1157.9	34"	2
Raw feed	0.86 L/s	25.66	2770.97	1188.0	34"	2
Reject	0.04 L/s	1.28	138.55	265.6	12"	
Backflush	0.04 L/s	1.28	138.55	265.6	12"	

(3240 modules rounded)

4. 250/1500mm, high flux, 1615 modules

Permeate / Product	1.62 L/s	48.75	2632.42	1157.9	34"	2
Raw feed	1.71 L/s	51.31	2770.97	1188.0	34"	2
Reject	0.09 L/s	2.57	138.55	265.6	12"	
Backflush	0.09 L/s	2.57	138.55	265.6	12"	

(1620 modules rounded)

Material consumption associated with pipes

Assumptions: each module needs about 28 cm around, between batches the distance is 1 m, the width of one batch is about 1,5m.

All pipes are of plastic with the exception of the largest pipes which are out of steel (see large pipes)

Batches of:																		
30 mod																		
60 mod																		
Pipes	Length	Weight	Tot. weight	A.Pipes	Length	Weight	Tot. weight	B.Pipes	Length	Weight	Tot. weight	Pipes	Length	Weight	Tot. weight	Observations		
Small	m	kg/m	kg	Intermediate	m	kg/m	kg	Intermediate	m	kg/m	kg	Large	m	kg/m	kg			
1. 250/1025mm, low flux, 4725 mod.																		
Permeate / Product flowrate per module	3/8"	0.2	0.135	0.027	3 1/2"	7.5	4.19	31.39	5"	15	6.80	102.00	34"	200	200.59	80236 "2		
Raw feed flowrate per module	1/2"	0.2	0.135	0.027	4"	7.5	4.19	31.39	6"	15	6.80	102.00	34"	200	200.59	80236 "2 - These are steel pipes		
Reject flowrate per module	1/8"	0.2	0.135	0.027	3/4"	7.5	0.22	1.61	1 1/4"	15	0.14	2.03	12"	200	26.92	5384 160472 Total Steel Pipe Large		
Backflush flowrate per module	1/8"	0.2	0.135	0.027	3/4"	7.5	0.22	1.61	1 1/4"	15	0.14	2.03	12"	200	26.92	5384 107680 Total Plastic Pipe Large		
*Reject equals backflush for dead end filtration (158 Batches - 4740 modules rounded)			Smallest a	0.108		158 batches		66.00	79 Batches		208.05		for 158 batches					
				511.92				10428.00			16435.95							
2. 250/1025mm, high flux, 2357 mod.																		
Permeate / Product flowrate per module	1"	0.2	0.215	0.043	5"	7.5	6.80	51.00	8"	15	13.68	205.20	34"	100	200.59	40118 "2		
Raw feed flowrate per module	1"	0.2	0.215	0.043	6"	7.5	6.80	51.00	8"	15	13.68	205.20	34"	100	200.59	40118 "2		
Reject flowrate per module	1/8"	0.2	0.135	0.027	1 1/4"	7.5	0.14	1.01	1 1/2"	15	0.54	8.10	12"	100	26.92	2692 80236 Total Steel Pipe Large		
Backflush flowrate per module	1/8"	0.2	0.135	0.027	1 1/4"	7.5	0.14	1.01	1 1/2"	15	0.54	8.10	12"	100	26.92	2692 5384 Total Plastic Pipe Large		
(79 Batches - 2370 mod. rounded)				0.14		79 batches		104.03	40 batches		426.60		for 79 batches					
				331.8				8217.98			17064.00							
3. 250/1500mm, low flux, 3229 mod.																		
Permeate / Product flowrate per module	3/4"	0.2	0.215	0.043	5"	7.5	6.80	51.00	6"	15	6.80	102.00	34"	140	200.59	56165 "2		
Raw feed flowrate per module	3/4"	0.2	0.215	0.043	5"	7.5	6.80	51.00	6"	15	6.80	102.00	34"	140	200.59	56165 "2		
Reject flowrate per module	1/8"	0.2	0.135	0.027	1"	7.5	0.22	1.61	1 1/2"	15	0.54	8.10	12"	140	26.92	3768 112330.4 Total Steel Pipe Large		
Backflush flowrate per module	1/8"	0.2	0.135	0.027	1"	7.5	0.22	1.61	1 1/2"	15	0.54	8.10	12"	140	26.92	3768 7537.6 Total Plastic Pipe Large		
(108 Batches - 3240 modules rounded)				0.14		108 batches		105.23	54 batches		220.20		for 108 batches					
				453.6				11364.30			11890.80							
4. 250/1500mm, high flux, 1615 mod.																		
Permeate / Product flowrate per module	1 1/4"	0.2	0.347	0.0694	6"	7.5	6.80	51.00	10"	15	16.97	254.55	34"	70	200.59	28082 "2		
Raw feed flowrate per module	1 1/4"	0.2	0.347	0.0694	6"	7.5	6.80	51.00	10"	15	16.97	254.55	34"	70	200.59	28082 "2		
Reject flowrate per module	1/8"	0.2	0.135	0.027	1 1/2"	7.5	0.54	4.05	2"	15	1.37	20.55	12"	70	26.92	1884 56165.2 Total Steel Pipe Large		
Backflush flowrate per module	1/8"	0.2	0.135	0.027	1 1/2"	7.5	0.54	4.05	2"	15	1.37	20.55	12"	70	26.92	1884 3768.8 Total Plastic Pipe Large		
(54 batches - 1620 modules rounded)				0.1928		54 batches		110.10	27 batches		550.20							
				312.336				5845.40			14855.40							
TOTAL FOR THE OPTIONS (kg)																		
	Small	Interm. A	Interm. B	Large Plas	Large Steel	Total PL A Total PL B												
1. 250/1025mm, low flux, 4725 mod.	511.92	10428	16435.95	10768	160472	21707.92 27715.87												
2. 250/1025mm, high flux, 2357 mod.	331.8	8217.98	17064	5384	80236	13933.78 22779.8												
3. 250/1500mm, low flux, 3229 mod.	453.6	11364.3	11890.8	7537.6	112330.4	19355.5 19882												
4. 250/1500mm, high flux, 1615 mod.	312.34	5945.4	14855.4	3768.8	56165.2	10026.54 18936.54												

APPENDIX 7

DATA QUALITY INDICATORS

DATA QUALITY INDICATORS

To assess the quality of data, a score system for data quality indicators is used. This system was developed by Weidema (1997) and the different scores are explained in the following table.

Table A7.1 Pedigree matrix with data quality indicators

SCORE	Reliability	Completeness	Correlation		
			Temporal	Geographical	Technological
1	Validated* data based on measurements**	Representative data from a sufficient sample of sites over an adequate period to level out normal fluctuations	Less than 3 years of difference to year of study	Data from area under study	Data from enterprises, processes and materials under study
2	Validated data partially based on assumptions or non-validated data based on measurements	Representative data from a smaller number of sites but for adequate periods	Less than 6 years of difference	Average data from larger area in which the area under study is included	Data from processes and materials under study but from different enterprises
3	Non-validated data partly based on assumptions	Representative data from an adequate number of sites but from shorter periods	Less than 10 years of difference	Data from area with similar production conditions	Data from processes and materials under study but from different technology
4	Qualified estimate (e.g. by industrial expert)	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Less than 15 years of difference	Data from area with slightly similar production conditions	Data on related processes and materials but same technology
5	Non-qualified estimate	Representativeness is unknown or incomplete data from a smaller number of sites and/or from shorter periods	Age of data unknown or more than 15 years of difference	Data from unknown area or area with very different production conditions	Data on related process or materials but different technology

* Validation may take place in several ways, e.g. by on-site checking, by recalculation, through mass balances or cross-checks with other sources.

** Includes calculated data (e.g. emissions calculated from inputs to a process), when the basis for calculation is measurements (e.g. measured inputs). If the calculation is based on assumptions, the score would be 2 or 3.

The purpose of such a matrix is to provide an overview with regard to data quality. Such an overview is useful to survey data more easily, to point out possibilities for improvement in data quality and to trace back sources of uncertainty. This pedigree has been applied to the two data sets collected (i.e. the data set for the conventional method and the data set for the membrane method for producing potable water) and the results are presented in **Table A7.2** and **Table A7.3**.

Table A7.2: Pedigree Matrix for the Conventional Method of Producing Potable Water

Process	Reliability Score	Completeness Score	Correlation Scores		
			Temporal	Geographical	Technological
<i>Construction Stage</i>					
Cement Production	1	1	1	1	1
Stone Production	2	2	2	2	2
Sand Production	2	2	2	2	2
Steel Production	2	2	3	4	4
Stainless Steel Production	2	2	3	4	4
Copper Production	2	2	3	4	4
Aluminium Production	2	2	3	4	4
PVC Production	2	2	3	4	4
<i>Operation Stage</i>					
Bentonite Production	3	3	5	5	5
PAC Production	4	4	4	4	4
Oxygen Production	1	2	2	2	2
Coagulant Production	3	5	5	5	3
NaOCl Production	1	1	3	3	3
Slaked Lime Production	2	2	3	3	3
Chlorine Production	2	2	3	4	4
Filtration Sand Prod.	2	2	2	2	2
Electricity Generation	2	2	3	4	4
<i>Decommissioning Stage</i>					
Recycling of Steel	2	2	3	4	4
Recycling of Copper	2	2	3	4	4
Recycling of Aluminium	2	2	3	4	4
Landfilling of PVC	4	4	4	4	4

A similar data quality matrix has been produced for the membrane methods and the scores are presented in **Table A7.3**.

Table A7.3: Pedigree Matrix for the Membrane Method of Producing Potable Water

Process	Reliability Score	Completeness Score	Correlation Scores		
			Temporal	Geographical	Technological
<i>Construction Stage</i>					
Cement Production	1	1	1	1	1
Stone Production	2	2	2	2	2
Sand Production	2	2	2	2	2
Steel Production	2	2	3	4	4
Stainless Steel Production	2	2	3	4	4
Copper Production	2	2	3	4	4
Aluminium Production	2	2	3	4	4
Membrane Production	2	5	5	4	4
Polyethylene Production	2	2	3	4	4
Epoxy Production	2	2	3	4	4
PVC Production	2	2	3	4	4
<i>Operation Stage</i>					
NaOCl Production	1	1	3	3	3
Chlorine Production	2	2	3	4	4
Filtration Sand Prod.	2	2	2	2	2
Electricity Generation	2	2	3	4	4
<i>Decommissioning Stage</i>					
Recycling of Steel	2	2	3	4	4
Recycling of Copper	2	2	3	4	4
Recycling of Aluminium	2	2	3	4	4
Landfilling of PVC	4	4	4	4	4

In the above table scores are given for the process included in **Figure 4.1** and **4.2**, and these are the processes which defined the boundaries for each case study. However, in tracing the inputs and outputs for these processes to the interface system-environment, for many substances a series of additional processes have been included. For example the production of the ultrafiltration membrane requires polysulphone, polyvinylpyrrolidone, poly(ethylene glycol) and dimethylformamide. For the production of dimethylformamide, for example, ammonia and methanol is required and the list of inputs continues for methanol and ammonia production (see **Figure 5.10** and **Appendix 9** for individual processes). The data quality scores for

substances which have a long production chain have the quality score carried forward by the weakest (worst case) data in that chain.

APPENDIX 8

INVENTORY TABLES

INVENTORY TABLES

1. Inventory Table for the Conventional Method of Producing Potable Water

Inputs

Rolling oil [Operating materials]	Mass	3.9139E-6 kg
Degreasing agent [Operating materials]	Mass	2.3128E-6 kg
Hard coal (APME) [Hard coal (resource)]	Mass	0.0021595 kg
Crude oil (APME) [Crude oil (resource)]	Mass	0.0017252 kg
Natural gas (APME) [Natural gas (resource)]	Mass	0.0021416 kg
Lignite (APME) [Lignite (resource)]	Mass	1.4529E-6 kg
Primary energy from hydro power (APME) [Renewable energy resources]	Energy (calorific value)	0.0024779 MJ
Nuclear energy (APME) [Uranium (resource)]	Energy (calorific value)	0.020327 MJ
Water for industrial use [Operating materials]	Mass	0.003076 kg
Primary energy from hydro power (BUWAL) [Renewable energy resources]	Energy (calorific value)	0.0072164 MJ
Bauxite [Non renewable resources]	Mass	0.00020719 kg
Energy unspecified (APME) [Energy resources]	Energy (calorific value)	1.113E-7 MJ
Gypsum (natural gypsum) [Non renewable resources]	Mass	0.0004245 kg
Limestone (calcium carbonate) [Non renewable resources]	Mass	0.012839 kg
Sodium chloride (rock salt) [Non renewable resources]	Mass	0.0037288 kg
Dead rock [Non renewable resources]	Mass	0.016675 kg
Wood (BUWAL) [Renewable energy resources]	Mass	0.00092491 kg
Water [Water]	Mass	0.02261 kg
Iron ore [Non renewable resources]	Mass	0.0042718 kg
Polyvinyl chloride granulate (PVC) [Plastics]	Mass	5.6134E-7 kg
Explosives [Operating materials]	Mass	4.9831E-6 kg
Process water [Operating materials]	Mass	2.9176E-5 kg
Sulphur dioxide [Inorganic intermediate products]	Mass	1.087E-6 kg
Bentonite [Non renewable resources]	Mass	0.00059054 kg
Quartz sand (silica sand; silicon dioxide) [Non renewable resources]	Mass	0.012446 kg
Heavy spar (barytes) [Non renewable resources]	Mass	2.8758E-6 kg
Fluorspar (calcium fluoride; fluorite) [Inorganic intermediate products]	Mass	1.4087E-6 kg
Alloy components [Metals]	Mass	9.251E-6 kg
Raw brown coal (BUWAL) [Lignite (resource)]	Mass	0.0011015 kg
Crude oil free wellhead [Crude oil (resource)]	Mass	0.0015071 kg
Raw hard coal (BUWAL) [Hard coal (resource)]	Mass	0.095902 kg
Uranium free ore (BUWAL) [Uranium (resource)]	Mass	6.5587E-8 kg
Raw natural gas (BUWAL) [Natural gas (resource)]	Mass	0.001069 kg
Process and cooling water [Operating materials]	Mass	4.6809E-7 kg
Insulating stone [Operating materials]	Mass	2.884E-7 kg
Insulating board [Operating materials]	Mass	1.8857E-7 kg
Flux and gas [Operating materials]	Mass	1.1092E-7 kg
Acid (unspecified) [Inorganic intermediate products]	Mass	2.2238E-5 kg
Additives (steel production) [Metals]	Mass	5.8886E-5 kg

Copper wire [Metals]	Mass	2.6334E-6 kg
Hydrogen [Inorganic intermediate products]	Mass	3.4263E-6 kg
Wood 50% water (APME) [Renewable energy resources]	Mass	8E-5 kg
Sulphur (APME) [Non renewable energy resources]	Energy (calorific value)	1.0416E-6 MJ
Iron [Non renewable elementary resources]	Mass	4.0281E-7 kg
Water (feed water) [Water]	Mass	0.0037315 kg
Dolomite [Non renewable resources]	Mass	4.1143E-9 kg
Water (river water) [Water]	Mass	0.019886 kg
Slate [Non renewable resources]	Mass	2.5715E-8 kg
Clay [Non renewable resources]	Mass	2.582E-8 kg
Water (surface water) [Water]	Mass	1002.4 kg
Air [Renewable resources]	Mass	7.3042E-5 kg
Water (well water) [Water]	Mass	7.9201E-7 kg
Nitrogen [Renewable resources]	Mass	1.4733E-5 kg
Oxygen [Renewable resources]	Mass	0.00065002 kg
Sulphur (bonded) [Non renewable resources]	Mass	5.5986E-8 kg
Sulphur [Non renewable elementary resources]	Mass	1.4075E-7 kg
Steam (MJ) [Thermal energy]	Energy (calorific value)	0.0001023 MJ
Olivine [Non renewable resources]	Mass	3.0857E-9 kg
Water (sea water) [Water]	Mass	0.064801 kg
Raw gravel [Non renewable resources]	Mass	1.0286E-9 kg
Sodium carbonate (soda) [Non renewable resources]	Mass	4.1631E-5 kg
Salt [Non renewable resources]	Mass	0.0029568 kg

Outputs

Steel scrap [Waste for recovery]	Mass	30533 kg
Chromium (unspecified) [Heavy metals into air]	Mass	2.506E-10 kg
Krypton (Kr85) [Radioactive emissions into air]	Activity	5.3251 Bq
Chromium (unspecified) [Heavy metals into water]	Mass	1.5206E-6 kg
Cathode steel [Operating materials]	Mass	3.3831E-7 kg
Carbon dioxide [Inorganic emissions into air]	Mass	0.16974 kg
Carbon monoxide [Inorganic emissions into air]	Mass	5.9039E-5 kg
Methane [Organic emissions into air (group VOC)]	Mass	0.00068956 kg
Laughing gas (dinitrogen monoxide) [Inorganic emissions into air]	Mass	9.376E-7 kg
NMVOC (unspecified) [Group NMVOC into air]	Mass	2.0491E-5 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.0004809 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.00071219 kg
Dust (unspecified) [Particles into air]	Mass	2.3601E-5 kg
Hydrogen chloride [Inorganic emissions into air]	Mass	4.6184E-5 kg
Hydrogen fluoride [Inorganic emissions into air]	Mass	4.8466E-6 kg
Chlorinated hydrocarbons (unspecified) [Halogenated organic emissions into water]	Mass	8.8129E-11 kg
Antimony [Heavy metals into air]	Mass	5.9047E-15 kg
Arsenic [Heavy metals into air]	Mass	2.6814E-13 kg
Beryllium [Inorganic emissions into air]	Mass	4.2329E-15 kg
Lead [Heavy metals into air]	Mass	3.6463E-8 kg
Cadmium [Heavy metals into air]	Mass	9.1057E-10 kg
Iron [Heavy metals into air]	Mass	5.5023E-10 kg
Cobalt [Heavy metals into air]	Mass	3.1065E-14 kg

Copper [Heavy metals into air]	Mass	4.6274E-10 kg
Lanthane [Heavy metals into air]	Mass	5.7236E-15 kg
Manganese [Heavy metals into air]	Mass	1.9849E-8 kg
Molybdenum [Heavy metals into air]	Mass	2.4369E-14 kg
Nickel [Heavy metals into air]	Mass	7.3789E-8 kg
Mercury [Heavy metals into air]	Mass	6.3675E-9 kg
Scandium [Inorganic emissions into air]	Mass	3.9848E-15 kg
Selenium [Heavy metals into air]	Mass	6.0773E-13 kg
Strontium [Inorganic emissions into air]	Mass	5.7236E-14 kg
Thallium [Heavy metals into air]	Mass	7.1165E-11 kg
Titanium [Heavy metals into air]	Mass	1.0533E-12 kg
Vanadium [Heavy metals into air]	Mass	1.7848E-11 kg
Zinc [Heavy metals into air]	Mass	5.3551E-8 kg
Tin [Heavy metals into air]	Mass	1.4666E-14 kg
Ammonia [Inorganic emissions into air]	Mass	8.8772E-7 kg
Barium compounds (unspecified; rel. to Ba) [Inorganic emissions into air]	Mass	6.9313E-13 kg
Hydrogen cyanide (prussic acid) [Inorganic emissions into air]	Mass	1.449E-16 kg
Fluoride (unspecified) [Inorganic emissions into air]	Mass	4.5808E-8 kg
Sulphuric acid [Inorganic emissions into air]	Mass	5.143E-10 kg
Hydrogen sulfide [Inorganic emissions into air]	Mass	1.8237E-8 kg
Benzo{a}pyrene [Group PAH into air]	Mass	3.2738E-12 kg
Benzene [Group NMVOC into air]	Mass	2.496E-8 kg
Formaldehyde (methanal) [Group NMVOC into air]	Mass	1.5578E-13 kg
Carbon (C14) [Radioactive emissions into air]	Activity	2.5321E-5 Bq
Plutonium (Pu alpha) [Radioactive emissions into air]	Activity	2.7481E-8 Bq
Radium (Ra226) [Radioactive emissions into air]	Activity	9.6182E-8 Bq
Radon (Rn222) [Radioactive emissions into air]	Activity	8.8305E-9 Bq
Thorium (Th230) [Radioactive emissions into air]	Activity	1.3911E-11 Bq
Uranium (U234) [Radioactive emissions into air]	Activity	2.6512E-8 Bq
Uranium (U238) [Radioactive emissions into air]	Activity	1.8147E-9 Bq
Uranium (total) [Radioactive emissions into air]	Activity	1.5894E-6 Bq
Waste water [Other emissions into water]	Mass	0.001533 kg
Adsorbable organic compounded halogenes (AOX) [Analytical values emissions into water]	Mass	1.1643E-9 kg
Biological oxygen demand (BOD) [Analytical values emissions into water]	Mass	3.5594E-7 kg
Chemical oxygen demand (COD) [Analytical values emissions into water]	Mass	1.6618E-6 kg
Aromatic hydrocarbons (unspecified) [Group NMVOC into air]	Mass	1.7785E-8 kg
Total organic bounded carbon [Analytical values emissions into water]	Mass	1.2903E-6 kg
Arsenic [Heavy metals into water]	Mass	3.0551E-7 kg
Barium [Inorganic emissions into water]	Mass	1.2267E-5 kg
Lead [Heavy metals into water]	Mass	7.5978E-7 kg
Cadmium [Heavy metals into water]	Mass	7.8741E-9 kg
Halone (1301) [Halogenated organic emissions into air]	Mass	3.5985E-10 kg
Iron [Heavy metals into water]	Mass	4.7271E-5 kg
Metals (unspecified) [Particles into air]	Mass	1.2018E-5 kg
Copper [Heavy metals into water]	Mass	7.5777E-7 kg
Nickel [Heavy metals into water]	Mass	7.6414E-7 kg

Mercury [Heavy metals into water]	Mass	7.5273E-10 kg
Zinc [Heavy metals into water]	Mass	1.5219E-6 kg
Aluminium [Inorganic emissions into water]	Mass	0.00015105 kg
Ammonium / ammonia [Inorganic emissions into water]	Mass	2.4297E-7 kg
Acid (calculated as H+) [Inorganic emissions into water]	Mass	1.2151E-6 kg
Chloride [Inorganic emissions into water]	Mass	0.0011379 kg
Cyanide [Inorganic emissions into water]	Mass	1.1224E-9 kg
Fluoride [Inorganic emissions into water]	Mass	6.5147E-10 kg
Sodium [Inorganic emissions into water]	Mass	2.5558E-5 kg
Chemicals (unspecified) [Waste for recovery]	Mass	3.4E-5 kg
Nitrate [Inorganic emissions into water]	Mass	3.5739E-6 kg
Phosphate [Inorganic emissions into water]	Mass	9.1155E-6 kg
Sulphate [Inorganic emissions into water]	Mass	0.00069759 kg
Methanol [Hydrocarbons into water]	Mass	1.8047E-12 kg
Phenol (hydroxy benzene) [Hydrocarbons into water]	Mass	1.8711E-8 kg
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - PCDD) [Halogenated organic emissions into water]	Mass	1.8113E-16 kg
Toluene (methyl benzene) [Hydrocarbons into water]	Mass	8.998E-9 kg
Carbon (C14) [Radioactive emissions into water]	Activity	7.0426E-6 Bq
Cesium (Cs137) [Radioactive emissions into water]	Activity	9.273E-5 Bq
Hydrogen (H3) [Radioactive emissions into water]	Activity	0.099649 Bq
Iodine (I129) [Radioactive emissions into water]	Activity	2.0607E-5 Bq
Plutonium (Pu alpha) [Radioactive emissions into water]	Activity	1.8889E-6 Bq
Radium (Ra226) [Radioactive emissions into water]	Activity	0.0012043 Bq
Strontium (Sr90) [Radioactive emissions into water]	Activity	4.1208E-5 Bq
Technetium (Tc99) [Radioactive emissions into water]	Activity	3.6061E-6 Bq
Thorium (Th230) [Radioactive emissions into water]	Activity	0.00022413 Bq
Uranium [Radioactive emissions into water]	Activity	0.00010895 Bq
Ash [Waste for recovery]	Mass	5.0446E-7 kg
Gypsum [Waste for recovery]	Mass	1.6166E-7 kg
Overburden [Stockpile goods]	Mass	0.00030539 kg
Ore processing residues [Stockpile goods]	Mass	1.2133E-6 kg
Aldehyde (unspecified) [Group NMVOC into air]	Mass	5.1984E-10 kg
Municipal waste [Consumer waste]	Mass	4.0395E-10 kg
Municipal similarly industrial waste [Consumer waste]	Mass	4.7715E-6 kg
Hazardous waste [Hazardous waste]	Mass	8.7753E-7 kg
Radioactive waste [Radioactive waste]	Mass	2.7843E-11 kg
CaF2 (poor radioactive) [Radioactive waste]	Mass	1.3742E-11 kg
Uranium depleted [Radioactive waste]	Mass	1.0249E-10 kg
Jacket and body material [Radioactive waste]	Mass	7.215E-12 kg
Volatile fission products (inert gases;iodine;C14) [Radioactive waste]	Mass	1.2368E-13 kg
Highly-active fission product solution [Radioactive waste]	Mass	1.2018E-11 kg
Medium and low radioactive liquid waste [Radioactive waste]	Mass	1.7175E-11 kg

Plutonium as residual product [Radioactive waste]	Mass	7.1549E-14 kg
Uranium burned out as residue [Radioactive waste]	Mass	1.6314E-11 kg
Medium and low radioactive wastes [Radioactive waste]	Mass	3.5231E-12 kg
Radioactive ore processing residues [Radioactive waste]	Mass	2.5845E-8 kg
Metals (unspecified) [Particles into water]	Mass	1.6322E-5 kg
Halogenized hydrocarbons (unspecified) [Halogenated organic emissions into air]	Mass	5.1618E-10 kg
Nitrogen [Inorganic emissions into water]	Mass	9.8725E-8 kg
Sulphide [Inorganic emissions into water]	Mass	2.4741E-9 kg
Rolling tinder [Waste for recovery]	Mass	4.9813E-5 kg
Production residues (unspecified) [Waste for recovery]	Mass	3.7041E-8 kg
Slag [Hazardous waste]	Mass	4.3443E-5 kg
Tetrafluoromethane [Halogenated organic emissions into air]	Mass	2.2184E-8 kg
Total dissolved organic bounded carbon [Analytical values emissions into water]	Mass	8.4277E-8 kg
Solids (suspended) [Particles into water]	Mass	1.3038E-5 kg
Hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	1.0342E-7 kg
Oil (unspecified) [Hydrocarbons into water]	Mass	2.1941E-6 kg
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Hydrocarbons into water]	Mass	2.354E-9 kg
Neutral salts [Inorganic emissions into water]	Mass	3.4672E-9 kg
Heavy metals into water (unspecified) [Heavy metals into water]	Mass	7.7499E-11 kg
VOC (unspecified) [Organic emissions into air (group VOC)]	Mass	2.4164E-5 kg
Dross [Waste for recovery]	Mass	6.6553E-7 kg
Nitrogen organic bounded [Inorganic emissions into water]	Mass	1.2306E-8 kg
Cathode carbon (outpouring) [Waste for recovery]	Mass	9.2065E-7 kg
Radioactive substances (unspecified) [Radioactive emissions into air]	Activity	6527.4 Bq
Inorganic salts and acids (unspecified) [Inorganic emissions into water]	Mass	0.0005305 kg
Radioactive substances (unspecified) [Radioactive emissions into water]	Activity	60.278 Bq
Aromatic hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	2.0137E-6 kg
Chromium compounds [Waste for recovery]	Mass	6.4757E-6 kg
Iron compounds (unspecified) [Waste for recovery]	Mass	3.2912E-5 kg
Slag (Iron plate production) [Waste for recovery]	Mass	0.00068671 kg
Dust, outpouring [Waste for recovery]	Mass	0.0001103 kg
Steel sheet (ECCS low grade) [Metals]	Mass	5.9242E-5 kg
Boron compounds (unspecified) [Inorganic emissions into air]	Mass	6.8134E-11 kg
Liquid hazardous waste [Hazardous waste]	Mass	5.6997E-10 kg
Polycyclic aromatic hydrocarbons (PAH) [Group PAH into air]	Mass	4.3399E-9 kg
Potassium [Inorganic emissions into water]	Mass	5.1429E-10 kg
Magnesium [Inorganic emissions into water]	Mass	5.1429E-10 kg
Energy recovery (APME) [Energy resources]	Energy (calorific value)	0.0014914 MJ
Salt [Inorganic emissions into soil]	Mass	3.15E-8 kg
Sulphur [Inorganic emissions into water]	Mass	5.1429E-10 kg

Ammonium nitrate [Inorganic emissions into air]	Mass	2.0832E-10 kg
Chlorine [Inorganic emissions into air]	Mass	6.216E-10 kg
Fluorine [Inorganic emissions into air]	Mass	5.1429E-10 kg
Inert chemicals [Consumer waste]	Mass	4.0491E-5 kg
Organic compounds (unspecified) [Organic emissions into water]	Mass	4.1143E-9 kg
Calcium [Inorganic emissions into water]	Mass	5.1429E-10 kg
Solids (dissolved) [Analytical values emissions into water]	Mass	4.1099E-7 kg
Detergent (unspecified) [Other emissions into water]	Mass	1.1325E-7 kg
Waste (unspecified) [Consumer waste]	Mass	0.0003928 kg
Demolition waste [Stockpile goods]	Mass	4.8343E-8 kg
Packaging waste (metal) [Consumer waste]	Mass	7.2001E-9 kg
Packaging waste (plastic) [Consumer waste]	Mass	1.44E-8 kg
Organic chlorine compounds [Organic emissions into air (group VOC)]	Mass	6.1845E-10 kg
Chlorine (dissolved) [Inorganic emissions into water]	Mass	5.1429E-10 kg
Organic chlorine compounds (unspecified) [Organic emissions into water]	Mass	6.1845E-10 kg
Hydrogen [Inorganic emissions into air]	Mass	6.1715E-9 kg
Carbonate [Inorganic emissions into water]	Mass	1.1314E-7 kg
Incineration good [Waste for disposal]	Mass	9.2572E-8 kg
Mercaptan [Organic emissions into air (group VOC)]	Mass	6.1845E-10 kg
Copper scrap [Waste for recovery]	Mass	633.33 kg
Polyvinyl chloride (PVC, unspecified) [Consumer waste]	Mass	2166.7 kg

2. Inventory Table for the Membrane Method of Producing Potable Water

Inputs

Rolling oil [Operating materials]	Mass	7.1988E-7 kg
Degreasing agent [Operating materials]	Mass	4.2538E-7 kg
Hard coal (APME) [Hard coal (resource)]	Mass	0.00051164 kg
Crude oil (APME) [Crude oil (resource)]	Mass	0.0003719 kg
Natural gas (APME) [Natural gas (resource)]	Mass	0.00051254 kg
Lignite (APME) [Lignite (resource)]	Mass	1.1187E-5 kg
Wood 50% water (APME) [Renewable energy resources]	Mass	8.8706E-8 kg
Primary energy from hydro power (APME) [Renewable energy resources]	Energy (calorific value)	0.0012767 MJ
Nuclear energy (APME) [Uranium (resource)]	Energy (calorific value)	0.010873 MJ
Bauxite [Inorganic intermediate products]	Mass	4.6757E-8 kg
Sulphur (APME) [Non renewable energy resources]	Energy (calorific value)	3.2628E-6 MJ
Water for industrial use [Operating materials]	Mass	0.00021534 kg
Hydrogen (APME) [Non renewable energy resources]	Energy (calorific value)	0.00015008 MJ
Primary energy from hydro power (BUWAL) [Renewable energy resources]	Energy (calorific value)	0.012861 MJ
Lead [Non renewable elementary resources]	Mass	1.7741E-10 kg
Iron [Non renewable elementary resources]	Mass	1.3351E-7 kg
Bauxite [Non renewable resources]	Mass	3.4308E-5 kg
Energy unspecified (APME) [Energy resources]	Energy (calorific value)	5.1208E-5 MJ

Water (feed water) [Water]	Mass	0.0010349 kg
Dolomite [Non renewable resources]	Mass	1.3173E-8 kg
Fluorspar (calcium fluoride; fluorite) [Non renewable resources]	Mass	1.7298E-9 kg
Gypsum (natural gypsum) [Non renewable resources]	Mass	3.4588E-5 kg
Limestone (calcium carbonate) [Non renewable resources]	Mass	0.00082806 kg
Water (river water) [Water]	Mass	0.012454 kg
Slate [Non renewable resources]	Mass	3.6613E-9 kg
Sodium chloride (rock salt) [Non renewable resources]	Mass	0.0019985 kg
Dead rock [Non renewable resources]	Mass	0.0015035 kg
Clay [Non renewable resources]	Mass	2.6289E-9 kg
Wood (BUWAL) [Renewable energy resources]	Mass	2.4988E-5 kg
Water [Water]	Mass	0.0052455 kg
Air [Renewable resources]	Mass	4.4064E-5 kg
Water (well water) [Water]	Mass	8.7029E-7 kg
Barium sulphate [Non renewable resources]	Mass	1.8185E-8 kg
Ferro manganese [Non renewable resources]	Mass	8.8706E-11 kg
Nitrogen [Renewable resources]	Mass	6.4219E-6 kg
Oxygen [Renewable resources]	Mass	4.3163E-5 kg
Sulphur (bonded) [Non renewable resources]	Mass	1.7069E-7 kg
Sulphur [Non renewable elementary resources]	Mass	3.381E-7 kg
Steel scrap [Waste for recovery]	Mass	2.9105E-5 kg
Iron ore [Non renewable resources]	Mass	0.00067999 kg
Diesel [Crude oil products]	Mass	2.8604E-5 kg
Fuel oil heavy [Crude oil products]	Mass	1.2813E-6 kg
Olivine [Non renewable resources]	Mass	1.2089E-9 kg
Explosives [Operating materials]	Mass	4.507E-7 kg
Process water [Operating materials]	Mass	5.2214E-6 kg
Sulphur dioxide [Inorganic intermediate products]	Mass	1.7987E-7 kg
Nitrile rubber (NBR) [Plastics]	Mass	2.0314E-6 kg
Potassium chloride [Non renewable resources]	Mass	1.2862E-6 kg
Bentonite [Non renewable resources]	Mass	1.3412E-8 kg
Water (sea water) [Water]	Mass	0.0076781 kg
Steam (APME) [Thermal energy]	Mass	4.9134E-5 kg
Raw gravel [Non renewable resources]	Mass	4.3252E-10 kg
Quartz sand (silica sand; silicon dioxide) [Non renewable resources]	Mass	0.0010137 kg
Heavy spar (barytes) [Non renewable resources]	Mass	5.2643E-8 kg
Fluorspar (calcium fluoride; fluorite) [Inorganic intermediate products]	Mass	2.331E-7 kg
Alloy components [Metals]	Mass	1.8599E-6 kg
Raw brown coal (BUWAL) [Lignite (resource)]	Mass	0.7098 kg
Crude oil free wellhead [Crude oil (resource)]	Mass	0.00086355 kg
Raw hard coal (BUWAL) [Hard coal (resource)]	Mass	0.0026353 kg
Uranium free ore (BUWAL) [Uranium (resource)]	Mass	1.9173E-7 kg
Raw natural gas (BUWAL) [Natural gas (resource)]	Mass	0.00054957 kg
Process and cooling water [Operating materials]	Mass	1.1053E-7 kg
Insulating stone [Operating materials]	Mass	4.7722E-8 kg
Insulating board [Operating materials]	Mass	3.1203E-8 kg
Flux and gas [Operating materials]	Mass	1.8354E-8 kg
Acid (unspecified) [Inorganic intermediate products]	Mass	4.0902E-6 kg

Additives (steel production) [Metals]	Mass	9.3638E-6 kg
Copper wire [Metals]	Mass	4.038E-6 kg
Argon [Inorganic intermediate products]	Mass	5.2744E-9 kg
Chlorine [Inorganic intermediate products]	Mass	3.0801E-9 kg
Salt [Non renewable resources]	Mass	5.5687E-6 kg
Auxiliary material [Operating materials]	Mass	5.0974E-7 kg
Sodium hydroxide (100%; caustic soda) [Inorganic intermediate products]	Mass	5.985E-7 kg
Hydrochloric acid [Inorganic intermediate products]	Mass	2.109E-7 kg
Water (surface water) [Water]	Mass	1002.1 kg
Sodium carbonate (soda) [Non renewable resources]	Mass	2.166E-8 kg

Outputs

Chromium (unspecified) [Heavy metals into air]	Mass	4.8055E-11 kg
Krypton (Kr85) [Radioactive emissions into air]	Activity	0.098199 Bq
Chromium (unspecified) [Heavy metals into water]	Mass	4.1424E-8 kg
Potassium [Inorganic emissions into water]	Mass	3.6389E-8 kg
Cathode steel [Operating materials]	Mass	5.5981E-8 kg
Carbon dioxide [Inorganic emissions into air]	Mass	0.65252 kg
Magnesium [Inorganic emissions into water]	Mass	8.1778E-10 kg
Energy recovery (APME) [Energy resources]	Energy (calorific value)	0.00041564 MJ
Methanol [Inorganic emissions into air]	Mass	1.8944E-7 kg
Amines [Hydrocarbons into water]	Mass	4.53E-6 kg
Sulphur [Inorganic emissions into water]	Mass	1.9426E-11 kg
Carbon monoxide [Inorganic emissions into air]	Mass	7.5289E-5 kg
Methane [Organic emissions into air (group VOC)]	Mass	0.00013379 kg
Laughing gas (dinitrogen monoxide) [Inorganic emissions into air]	Mass	3.2898E-6 kg
NMVOC (unspecified) [Group NMVOC into air]	Mass	1.5055E-5 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.00096801 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.0033141 kg
Dust (unspecified) [Particles into air]	Mass	0.00097704 kg
Hydrogen chloride [Inorganic emissions into air]	Mass	0.00010506 kg
Hydrogen fluoride [Inorganic emissions into air]	Mass	1.0909E-5 kg
Chlorinated hydrocarbons (unspecified) [Halogenated organic emissions into water]	Mass	6.6805E-11 kg
Antimony [Heavy metals into air]	Mass	1.0889E-16 kg
Arsenic [Heavy metals into air]	Mass	4.93E-15 kg
Beryllium [Inorganic emissions into air]	Mass	7.749E-17 kg
Lead [Heavy metals into air]	Mass	2.542E-8 kg
Cadmium [Heavy metals into air]	Mass	1.0381E-8 kg
Iron [Heavy metals into air]	Mass	6.6134E-13 kg
Cobalt [Heavy metals into air]	Mass	5.7116E-16 kg
Copper [Heavy metals into air]	Mass	9.7048E-11 kg
Lanthane [Heavy metals into air]	Mass	1.0555E-16 kg
Manganese [Heavy metals into air]	Mass	1.8969E-8 kg
Molybdenum [Heavy metals into air]	Mass	4.4824E-16 kg
Nickel [Heavy metals into air]	Mass	3.2359E-8 kg
Mercury [Heavy metals into air]	Mass	2.4094E-8 kg
Scandium [Inorganic emissions into air]	Mass	7.3482E-17 kg
Selenium [Heavy metals into air]	Mass	1.1156E-14 kg
Strontium [Inorganic emissions into air]	Mass	1.0555E-15 kg

Thallium [Heavy metals into air]	Mass	1.1316E-11 kg
Titanium [Heavy metals into air]	Mass	1.9373E-14 kg
Vanadium [Heavy metals into air]	Mass	2.83E-12 kg
Zinc [Heavy metals into air]	Mass	1.6053E-7 kg
Tin [Heavy metals into air]	Mass	2.6988E-16 kg
Ammonia [Inorganic emissions into air]	Mass	3.5348E-7 kg
Ammonium nitrate [Inorganic emissions into air]	Mass	3.1629E-11 kg
Barium compounds (unspecified; rel. to Ba) [Inorganic emissions into air]	Mass	1.2759E-14 kg
Chlorine [Inorganic emissions into air]	Mass	5.9928E-10 kg
Hydrogen cyanide (prussic acid) [Inorganic emissions into air]	Mass	2.6721E-18 kg
Fluorine [Inorganic emissions into air]	Mass	1.9426E-11 kg
Fluoride (unspecified) [Inorganic emissions into air]	Mass	7.5779E-9 kg
Sulphuric acid [Inorganic emissions into air]	Mass	1.9426E-11 kg
Hydrogen sulfide [Inorganic emissions into air]	Mass	3.1757E-9 kg
Benzo[a]pyrene [Group PAH into air]	Mass	6.0189E-14 kg
Benzene [Group NMVOC into air]	Mass	1.6736E-8 kg
Formaldehyde (methanal) [Group NMVOC into air]	Mass	2.8658E-15 kg
Methanol [Group NMVOC into air]	Mass	7.5767E-7 kg
Carbon (C14) [Radioactive emissions into air]	Activity	4.6574E-7 Bq
Plutonium (Pu alpha) [Radioactive emissions into air]	Activity	5.0569E-10 Bq
Radium (Ra226) [Radioactive emissions into air]	Activity	1.7703E-9 Bq
Radon (Rn222) [Radioactive emissions into air]	Activity	1.6233E-10 Bq
Thorium (Th230) [Radioactive emissions into air]	Activity	2.5585E-13 Bq
Uranium (U234) [Radioactive emissions into air]	Activity	4.8765E-10 Bq
Uranium (U238) [Radioactive emissions into air]	Activity	3.3401E-11 Bq
Uranium (total) [Radioactive emissions into air]	Activity	2.9259E-8 Bq
Waste water [Other emissions into water]	Mass	2.8194E-5 kg
Adsorbable organic compounded halogenes (AOX) [Analytical values emissions into water]	Mass	2.9395E-10 kg
Biological oxygen demand (BOD) [Analytical values emissions into water]	Mass	1.3056E-7 kg
Chemical oxygen demand (COD) [Analytical values emissions into water]	Mass	2.6873E-6 kg
Inert chemicals [Consumer waste]	Mass	2.1607E-5 kg
Organic compounds (unspecified) [Organic emissions into water]	Mass	2.3063E-7 kg
Aromatic hydrocarbons (unspecified) [Group NMVOC into air]	Mass	5.8912E-9 kg
Total organic bounded carbon [Analytical values emissions into water]	Mass	6.8266E-6 kg
Arsenic [Heavy metals into water]	Mass	8.0378E-9 kg
Barium [Inorganic emissions into water]	Mass	4.2254E-7 kg
Lead [Heavy metals into water]	Mass	2.3751E-8 kg
Cadmium [Heavy metals into water]	Mass	2.7357E-10 kg
Halone (1301) [Halogenated organic emissions into air]	Mass	2.0328E-10 kg
Iron [Heavy metals into water]	Mass	0.0011369 kg
Metals (unspecified) [Particles into air]	Mass	3.0073E-5 kg
Copper [Heavy metals into water]	Mass	2.0107E-8 kg
Nickel [Heavy metals into water]	Mass	2.0192E-8 kg
Mercury [Heavy metals into water]	Mass	3.7024E-11 kg
Zinc [Heavy metals into water]	Mass	4.0503E-8 kg

Aluminium [Inorganic emissions into water]	Mass	4.0057E-6 kg
Ammonium / ammonia [Inorganic emissions into water]	Mass	9.3249E-8 kg
Acid (calculated as H+) [Inorganic emissions into water]	Mass	5.4591E-7 kg
Chloride [Inorganic emissions into water]	Mass	0.00018366 kg
Cyanide [Inorganic emissions into water]	Mass	3.1446E-10 kg
Fluoride [Inorganic emissions into water]	Mass	4.7966E-11 kg
Sodium [Inorganic emissions into water]	Mass	2.1697E-5 kg
Chemicals (unspecified) [Waste for recovery]	Mass	5.4079E-6 kg
Nitrate [Inorganic emissions into water]	Mass	1.6541E-7 kg
Phosphate [Inorganic emissions into water]	Mass	2.5693E-7 kg
Calcium [Inorganic emissions into water]	Mass	2.3951E-6 kg
Sulphate [Inorganic emissions into water]	Mass	0.0024197 kg
Methanol [Hydrocarbons into water]	Mass	2.6297E-6 kg
Phenol (hydroxy benzene) [Hydrocarbons into water]	Mass	6.8346E-9 kg
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - PCDD) [Halogenated organic emissions into water]	Mass	3.3401E-18 kg
Toluene (methyl benzene) [Hydrocarbons into water]	Mass	5.1073E-9 kg
Carbon (C14) [Radioactive emissions into water]	Activity	1.2953E-7 Bq
Cesium (Cs137) [Radioactive emissions into water]	Activity	1.7055E-6 Bq
Hydrogen (H3) [Radioactive emissions into water]	Activity	0.001833 Bq
Iodine (I129) [Radioactive emissions into water]	Activity	3.7903E-7 Bq
Plutonium (Pu alpha) [Radioactive emissions into water]	Activity	3.4737E-8 Bq
Radium (Ra226) [Radioactive emissions into water]	Activity	2.2152E-5 Bq
Strontium (Sr90) [Radioactive emissions into water]	Activity	7.582E-7 Bq
Technetium (Tc99) [Radioactive emissions into water]	Activity	6.6334E-8 Bq
Thorium (Th230) [Radioactive emissions into water]	Activity	4.1224E-6 Bq
Uranium [Radioactive emissions into water]	Activity	2.0041E-6 Bq
Ash [Waste for recovery]	Mass	9.2855E-9 kg
Gypsum [Waste for recovery]	Mass	2.9727E-9 kg
Overburden [Stockpile goods]	Mass	0.00013609 kg
Ore processing residues [Stockpile goods]	Mass	2.2312E-8 kg
Aldehyde (unspecified) [Group NMVOC into air]	Mass	2.1051E-9 kg
Municipal waste [Consumer waste]	Mass	7.415E-12 kg
Municipal similarly industrial waste [Consumer waste]	Mass	5.0899E-6 kg
Hazardous waste [Hazardous waste]	Mass	1.0702E-6 kg
Radioactive waste [Radioactive waste]	Mass	5.1237E-13 kg
CaF2 (poor radioactive) [Radioactive waste]	Mass	2.5251E-13 kg
Uranium depleted [Radioactive waste]	Mass	1.8838E-12 kg
Jacket and body material [Radioactive waste]	Mass	1.3294E-13 kg
Volatile fission products (inert gases;iodine;C14) [Radioactive waste]	Mass	2.2779E-15 kg
Highly-active fission product solution [Radioactive waste]	Mass	2.2111E-13 kg
Medium and low radioactive liquid waste [Radioactive waste]	Mass	3.1597E-13 kg
Plutonium as residual product [Radioactive waste]	Mass	1.316E-15 kg
Uranium burned out as residue [Radioactive waste]	Mass	2.9994E-13 kg
Medium and low radioactive wastes [Radioactive waste]	Mass	6.4798E-14 kg

Radioactive ore processing residues [Radioactive waste]	Mass	4.7563E-10 kg
Power [Power, electrical energy]	Energy (calorific value)	0.9971 MJ
Metals (unspecified) [Particles into water]	Mass	8.7926E-7 kg
Solids (dissolved) [Analytical values emissions into water]	Mass	9.2343E-7 kg
Detergent (unspecified) [Other emissions into water]	Mass	5.213E-9 kg
Waste (unspecified) [Consumer waste]	Mass	6.2672E-5 kg
Demolition waste [Stockpile goods]	Mass	2.6237E-9 kg
Packaging waste (metal) [Consumer waste]	Mass	9.4275E-10 kg
Packaging waste (plastic) [Consumer waste]	Mass	1.9091E-8 kg
Organic waste [Consumer waste]	Mass	8.8706E-10 kg
Halogenized hydrocarbons (unspecified) [Halogenated organic emissions into air]	Mass	3.793E-10 kg
Organic chlorine compounds [Organic emissions into air (group VOC)]	Mass	1.0777E-7 kg
Nitrogen [Inorganic emissions into water]	Mass	6.0139E-8 kg
Sulphide [Inorganic emissions into water]	Mass	1.5163E-9 kg
Chlorine (dissolved) [Inorganic emissions into water]	Mass	1.0839E-9 kg
Organic chlorine compounds (unspecified) [Organic emissions into water]	Mass	4.7182E-9 kg
Organic compounds (dissolved) [Organic emissions into water]	Mass	7.7702E-11 kg
Hydrogen [Inorganic emissions into air]	Mass	9.3195E-7 kg
Rolling tinder [Waste for recovery]	Mass	7.921E-6 kg
Carbonate [Inorganic emissions into water]	Mass	6.7229E-7 kg
Production residues (unspecified) [Waste for recovery]	Mass	5.6334E-7 kg
Incineration good [Waste for disposal]	Mass	2.7162E-7 kg
Slag [Hazardous waste]	Mass	2.8304E-5 kg
Toxic chemicals (unspecified) [Hazardous waste for disposal]	Mass	8.1558E-11 kg
Tetrafluoromethane [Halogenated organic emissions into air]	Mass	3.6709E-9 kg
Total dissolved organic bounded carbon [Analytical values emissions into water]	Mass	1.8288E-7 kg
Solids (suspended) [Particles into water]	Mass	1.0488E-5 kg
Hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	8.8998E-9 kg
Oil (unspecified) [Hydrocarbons into water]	Mass	1.161E-6 kg
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Hydrocarbons into water]	Mass	7.1946E-10 kg
Neutral salts [Inorganic emissions into water]	Mass	6.3796E-11 kg
Heavy metals into water (unspecified) [Heavy metals into water]	Mass	1.4229E-12 kg
VOC (unspecified) [Organic emissions into air (group VOC)]	Mass	1.3533E-5 kg
Inert chemicals [Hazardous waste]	Mass	1.2189E-8 kg
Mercaptan [Organic emissions into air (group VOC)]	Mass	3.524E-11 kg
Ammonium [Inorganic emissions into air]	Mass	2.6923E-7 kg
Dross [Waste for recovery]	Mass	4.5303E-7 kg
Nitrogen organic bounded [Inorganic emissions into water]	Mass	8.3547E-9 kg
Cathode carbon (outpouring) [Waste for recovery]	Mass	1.5234E-7 kg
Radioactive substances (unspecified) [Radioactive emissions into air]	Activity	16863 Bq
Inorganic salts and acids (unspecified) [Inorganic]	Mass	0.0025224 kg

emissions into water]		
Radioactive substances (unspecified) [Radioactive emissions into water]	Activity	155.16 Bq
Aromatic hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	7.2749E-6 kg
Chromium compounds [Waste for recovery]	Mass	9.9161E-7 kg
Iron compounds (unspecified) [Waste for recovery]	Mass	5.2335E-6 kg
Slag (Iron plate production) [Waste for recovery]	Mass	0.0001092 kg
Dust, outpouring [Waste for recovery]	Mass	1.7539E-5 kg
Boron compounds (unspecified) [Inorganic emissions into air]	Mass	1.2559E-12 kg
Liquid hazardous waste [Hazardous waste]	Mass	1.0488E-11 kg
Polycyclic aromatic hydrocarbons (PAH) [Group PAH into air]	Mass	6.3851E-9 kg
Copper scrap [Waste for recovery]	Mass	3.0128E-6 kg
Aluminium secondary [Metals]	Mass	6.7104E-6 kg
Mercury [Heavy metals into soil]	Mass	4.4071E-14 kg
Cadmium [Heavy metals into soil]	Mass	1.0498E-13 kg
Lead [Heavy metals into soil]	Mass	2.3404E-14 kg
Zinc [Heavy metals into soil]	Mass	5.1188E-17 kg
Steel sheet (ECCS low grade) [Metals]	Mass	2.9521E-6 kg
Steel sheet (ECCS) [Metals]	Mass	8.8651E-5 kg
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD) [Halogenated organic emissions into air]	Mass	1.9572E-19 kg
Carbon (unspecified) [Organic emissions into soil]	Mass	1.2715E-9 kg
Nitrogen [Inorganic emissions into soil]	Mass	2.6963E-11 kg

APPENDIX 9

DATA ON INDIVIDUAL PROCESSES

DATA ON INDIVIDUAL PROCESSES

An overview of the materials used in the production of potable water at Wiggins Waterworks (conventional method) and at the membrane plant (membrane method) is given in the first part of this section. In the second part, data on the production processes for each of these input is presented.

A9.1 Materials Used for the Production of Potable Water in the Conventional Method

Construction Stage

Concrete 1.59E-05 m ³ /kL made of:	Cement	6.12 g/kL
	Sand	11.62 g/kL
	Stone	18.35 g/kL
	Water	2.63 g/kL
Reinforcement Steel	1.81 g/kL	
Steel Pipes	2.59E-2 g/kL	
Stainless Steel	1.513E-3 g/kL	
Steel used in pumps	1.63E-3 g/kL	
Aluminium used in pumps	6.38E-3 g/kL	
Copper used in pumps	2.81E-3 g/kL	
Copper used in pipes	5.79E-4 g/kL	
PVC used in pipes	1.88E-3 g/kL	

Operation Stage (i.e. Production of Potable Water)

Quicklime	2.05 g/kL		
Zetafloc	2.17 g/kL		
Sodium Hypochloride	1.51 g/kL		
Chlorine	0.77 g/kL		
Bentonite	0.60 g/kL		
Ozone	0.013 g/kL	{ Air	0.0604 g/kL
		{ Electricity	0.0125 kWh/kL
HTH	0.006 g/kL		
PAC	0.004 g/kL		
Electricity	0.085 kWh/kL (incl. electricity for ozone)		

Decommissioning Stage

- All the concrete will be left in place and the tanks will be filled and vegetated.
- All materials which can be recycled or reused (steel, copper and aluminium) will be recycled in totality.
- Old PVC pipes are landfilled.

2. Materials Used for the Production of Potable Water in the Membrane Method – Scenario 3A

Construction Stage

Concrete 1.30E-06 m ³ /kL made of:		Cement	0.50 g/kL	
		Sand	0.95 g/kL	
		Stone	1.50 g/kL	
		Water	0.22 g/kL	
Reinforcement Steel	0.14 g/kL			
Steel Pipes	8.12 E-2 g/kL			
Steel used in pumps	2.35E-2 g/kL			
Aluminium used in pumps	9.18E-3 g/kL			
Copper used in pumps	4.04E-3 g/kL			
PVC used in pipes	1.40E-2 g/kL			
Filtration module:				
Epoxy resin	4.44E-2 g/kL			
Nitrile rubber	2.03E-3 g/kL			
PVC	0.134 g/kL			
Polyethylene	2.03E-3 g/kL			
Power	1.51E-05 MJ/kL			
Polymer membrane:	0.16 g/kl	Polysulphone	3.89E-2 g/kL	
		Dimethylformamide	8.23E-2 g/kL	
		Polyvinyl pyrrolidone	2.80E-3 g/kL	
		Polyethelene glycol	7.77E-3 g/kL	
		Power	0.786 MJ/kL	

Operation Stage (i.e. Production of Potable Water)

Sodium hypochloride	2.85E-3 g/kL
Chlorine	1.50 g/kL
Electricity	0.192 kWh/kL

Decommissioning Stage

- All the concrete will be left in place and the tanks will be filled and vegetated.
- All materials which can be recycled or reused (steel, copper and aluminium) will be recycled in totality.
- Old PVC and filtration modules and pipes are landfilled.

A9.3 Data on Production Processes

This section presents data on the processes employed to manufacture the inputs used at Wiggins Waterworks.

A9.3.1 Production of Cement

Data on this process were collected from Natal Portland Cement (Mr. Ian Naidoo) and is of high quality, being validated with similar international data from Denmark. For calculating the inputs and outputs for cement production from the raw data obtained from the manufacturer the processes presented in **Figure A9.1** have been used.

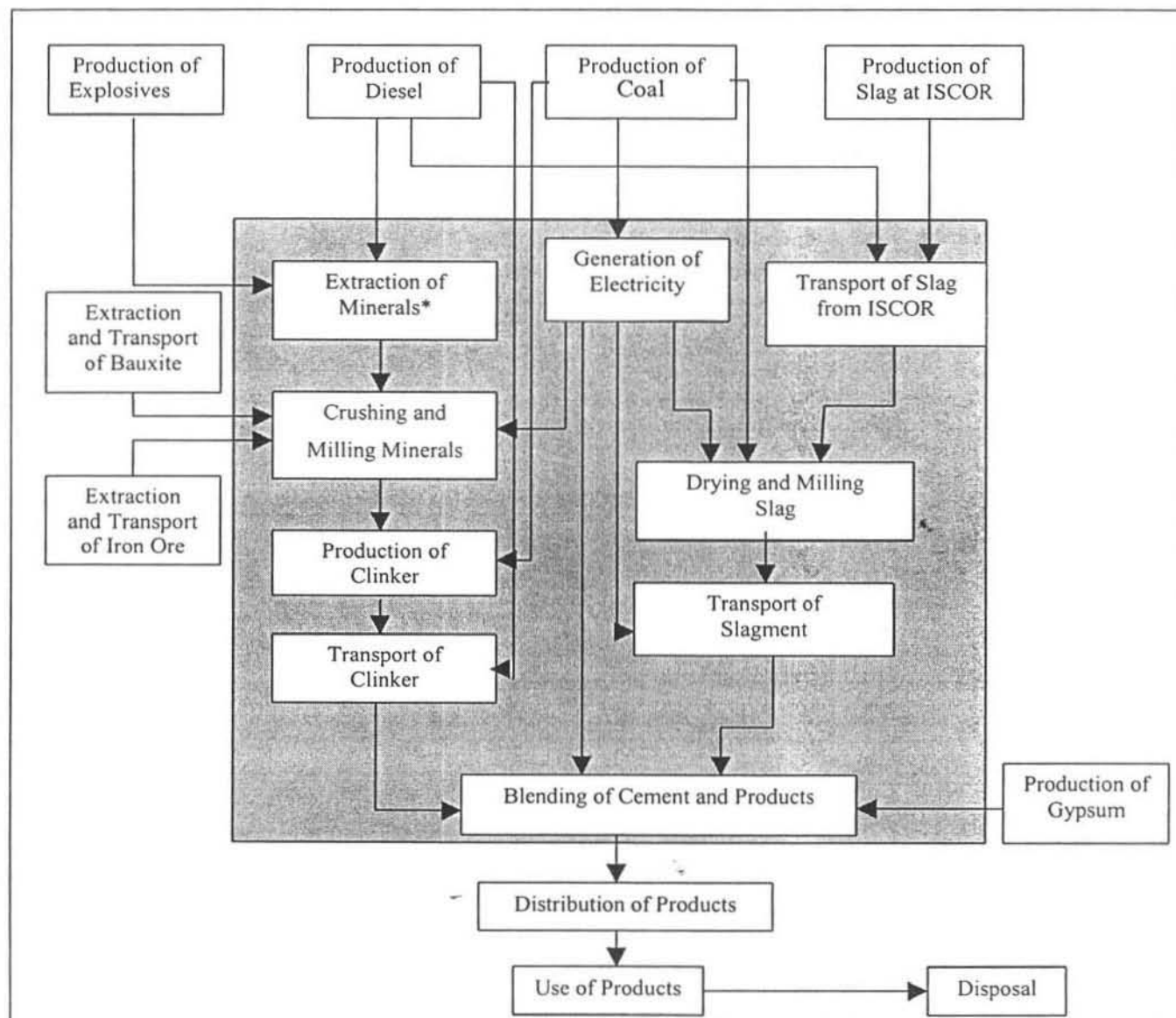


Fig A9.1: The Lifecycle of Cement and Cement Products Produced by NPC
 (*Minerals included are: limestone, argillite, dolerite, quartz schist and shale)

Inputs per kg of rapid hardened cement produced (the product with the highest environmental burdens):

Limestone	1.370 kg
Quartz minerals	0.018 kg

Other minerals	0.105 kg
Gypsum	0.069 kg
Diesel	0.005 kg
Coal	0.170 kg (includes coal needed for electricity generation)

Emissions per kg rapid hardened cement:

Carbon dioxide	0.961 kg
Sulphur dioxide	0.004 kg
Carbon monoxide	0.013 g
VOC	0.003 g
Particulates	0.40 g
Nitrogen oxide	8.50 g

A9.3.2 Production of Sand

Sand is mined through open cast mining procedures. For this study only the energy (diesel consumed) to extract and sort the sand was taken into consideration. About 0.6 g of diesel per kg of sand produced is consumed. This data was obtained from Natal Portland Cement because quartz sand is one of their inputs.

A9.3.3 Production of Stone

For the production of a similar process of open cast mining was considered and the amount of diesel consumed per kg of stone produced is the same. This figure was also validated from data obtained from Natal Portland Cement.

A9.3.4 Production of HTH (Calcium hypochlorite) (ARCH Chemicals – Mr. Marcon)

1. A solution of Ca(OH)_2 and NaOH is chlorinated (first the NaOH is chlorinated then mixed with the Ca(OH)_2 and then chlorinated again). It forms a paste which is filtered, dried and granulated. The process is exothermic and cooling is needed. For the drying process air is used and the dry product is in form of chips.
2. Raw materials (per kg product):

	1.0 kg Cl_2
	0.6 kg NaOH
	0.5 kg Ca(OH)_2
3. Electricity consumption (per t product): 1.0 kWh/kg
Also steam is used : 4 kg of steam (4 bar) / kg product
4. I.) Air emissions: hot air with some chlorine (under the legal limit of 5 ppm). There are two different routes for these emissions: one with lime (and water) scrubbers and one with caustic soda scrubbers.

II.) Water emissions: effluent containing salt and lime 3 kL / ton product. These effluents are collected and water is evaporated.

III.) Soil emissions: salt and lime left over from the evaporation of the effluent. These leftovers are not quantified and have not been entered in the GaBi 3 model.

Data on the production of the chemicals involved as inputs (NaOH and Cl_2) was used from the GaBi 3 database. For Ca(OH)_2 data collected for the manufacture of quicklime was used.

A9.3.5 Production of Oxygen (Fedgas – Mr. Grant Curich)

The raw material for the production of oxygen is air. The air is filtered and compressed at 5 bar after which it is refrigerated in a refrigeration column and compressed in a high pressure column. It is distilled in a low pressure column where at three different temperatures, oxygen, nitrogen and argon are separated. These gases are then liquified and sold. Only electricity is used as a power source in the process.

Inputs: 4643.2 kg/h of air is needed to produce 1000 kg/h of oxygen
961.6 kWh electricity is needed for 1000 kg of oxygen

A second, more precise figure, was obtained for electricity consumption from Mr. Dave Ossin – Afrox. In total 1.2 kWh is used by Afrox to produce 1 kg oxygen. 0.5 kWh are used for oxygen production and 0.7 kWh for liquifying the gas. This total of 1.2 kWh was used as input for the GaBi 3 modelling.

No direct emissions (to air, water, soil) have been considered for this process. However, the indirect emissions due to the generation of electricity used in the process have been taken into account.

A9.3.6 Production of Quicklime (Limeco Ltd. – Mr. Leon Kurter)

Limestone (CaCO_3) is mined (open cast mining), crushed and burnt in a rotary kiln (1600°C). The resulting CaO is ball-milled and air separated. The cyclone overflow resulting from this separation is dry slaked yielding $\text{Ca}(\text{OH})_2$ powder. Production data is given per ton of quicklime.

Inputs: 1.8 t Limestone
150 kg Coal
0.5 t Water (for slacking)

Outputs: 0.6 t CO_2
0.1 - 0.2 t Inert minerals (impurities)

In addition to the inputs enumerated above the energy consumed for open cast mining was included. If the open cast equipment consumes only diesel as fuel about 0.6 g of diesel is required for the mining of limestone.

A9.3.7 Production of Sodium Hypochlorite (Zetachem – Mr. Marco Bernardis)

The process involved is presented in the following diagram supplied by the producing company. The data presented below is the data supplied by the company and as it can be seen it is expressed per ton of chlorine gas (also called available chlorine – a standard practice in the chlor-alkali industry to determine chlorine strength). The calculated values per ton of sodium hypochlorite are presented in paranthesis.

Inputs:

Water	12.299 ton / ton Cl_2 (11.721)
Salt (NaCl)	2.050 ton / ton Cl_2 (1.954)
Caustic soda (50%)	0.431 ton / ton Cl_2 (0.411)
Hydrochloric acid (32%)	0.259 ton / ton Cl_2 (0.247)
Sodium carbonate	0.008 ton / ton Cl_2 (0.0076)
Sodium thiosulphate	0.002 ton / ton Cl_2 (0.0019)
Electricity	45.139 MWh / ton Cl_2 (43.017)

Outputs:

Hydrogen gas	0.028 ton / ton Cl_2 (0.027)
Effluent*	3.804 ton / ton Cl_2 (3.625)

Effluent contains mainly water, with sodium, calcium, magnesium, chlorides, carbonates, sulphates and hydroxides. These effluents are pumped to a sewage work and are not released directly in the environment. Therefore, their environmental burden has been neglected.

Data on the production of caustic soda, hydrochloric acid and sodium carbonate has been obtained from the GaBi 3 database and these substances have been followed to the point where the inputs needed to produce them have been extracted from the earth. Data on production of sodium thiosulphate are not available and this is a gap in the data for this process.

The diagram of the production process as supplied by the manufacturer (Zetachem) is presented in **Figure A9.2**.

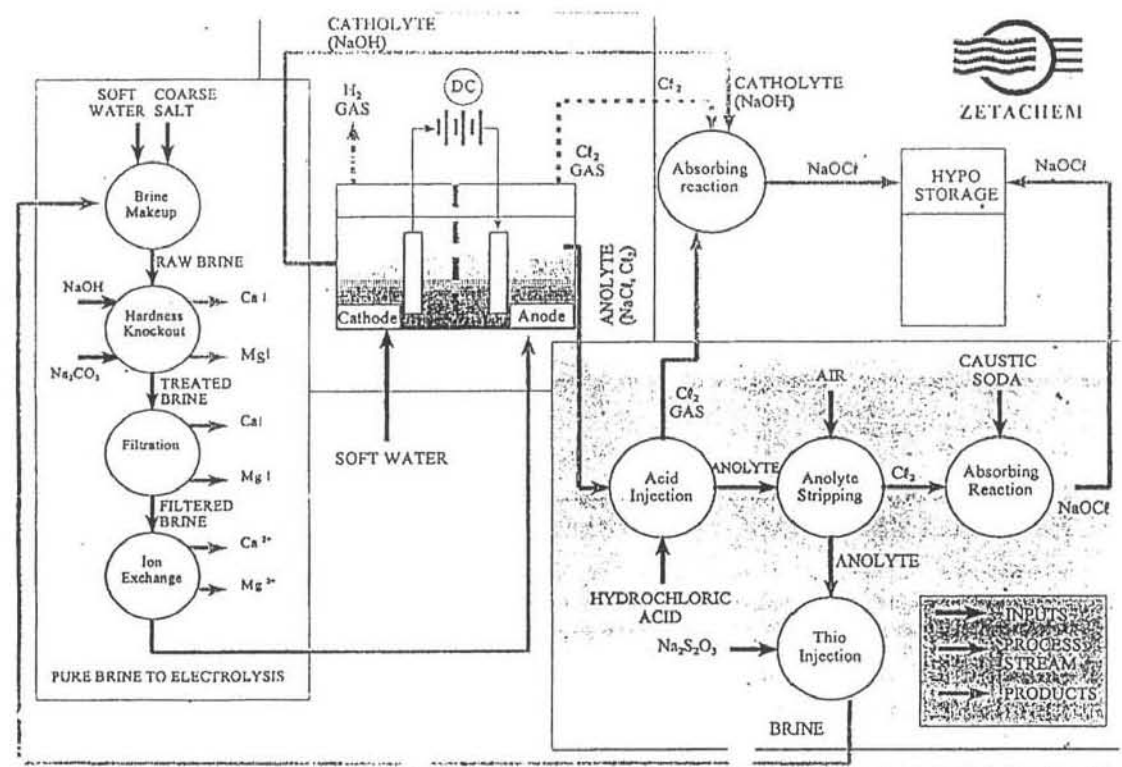


Figure A9.2: Flowsheet for the Production of NaOH

A9.3.8 Production of Powdered Activated Carbon (PAC) (Prof. Arnold - University of Natal, School of Chemical Engineering)

The PAC used by Wiggins Waterworks was imported some years ago from Brazil. It was impossible to trace the producer. Prof. Arnold head of the School of Chemical Engineering, University of Natal, was involved for several years in similar production processes for activated carbon. The method presented below is the South African way of producing activated carbon. Since the quantity involved at Wiggins Waterworks is very small (0.004 kg PAC per 1 kL potable water) it was considered acceptable to use this calculated data.

The starting material for the production of PAC was taken as being wood which undergoes firstly a process of carbonisation and secondly a process of activation. Carbonisation was done most probably in pits with part of the wood being burned to obtain the necessary energy (carbonisation occurs at about 500 to 700 °C. Activation is done with steam. For 1 kg of PAC about 5 kg of wood is needed. In calculating this figure it was taken into account that during activation half of the carbon produced is lost due to the reaction:



The efficiency of the process is about 50 %. During carbonisation water and methanol are emitted. These emissions are not quantified and have not been taken into consideration.

A9.3.9 Production of Zetafloc (Polymeric Coagulant)

Data for this chemical is of mixed origin. The initial formulation was obtained from the manufacturer under the condition of confidentiality. Therefore, in showing how calculations were done the names of the substances will be replaced with letters.

One kg of Zetafloc contains 0.650 kg of co-polymer A, 0.050 kg of co-polymer B, 0.200 kg of substance C, 0.100 kg water and 0.001 kg of hydrochloric acid (HCl). To produce the 0.650 kg of substance A, 0.181 kg of substance D and 0.616 kg of substance E is required. These amounts have been calculated by taking into account the stoichiometry of the reaction. By the same method it was found that to produce the 0.050 kg of substance B, 0.045 kg of substance F and 0.022 kg of substance D are required. To produce substance D (0.181+0.022=0.203 kg) one needs 0.077 kg ammonia and 0.289 kg methanol. To produce substance F one needs 0.038 kg substance E, 0.025 kg of HOCl, 0.021 kg of propylene and 0.035 kg molecular chlorine. To produce substance E (0.616+0.038=0.654 kg) 0.359 kg propylene and 0.606 kg molecular chlorine is needed. Therefore to produce 1 kg of Zetafloc, assuming an overall yield of 80 % (an average of the yields presented in the literature for these reactions), following inputs are needed:

Methanol	0.362 kg
Ammonia	0.096 kg
Propylene	0.474 kg
Hypochlorous acid (HOCl)	0.032 kg
Chlorine	0.801 kg
Hydrochloric acid (HCl)	0.001 kg
Aluminium chloride hydrate	0.200 kg
Water	0.100 kg

From this list of inputs data on the production of chlorine, ammonia, HCl and propylene was obtained from the GaBi 3 database and these data will be presented as individual processes in the following sections.

Data on the production of methanol was obtained from Prof. Michael Overcash, University of North Carolina. The production of methanol will also be presented as an separate process.

For the production of HOCl and aluminium chloride hydrate similar calculations, based on literature, have been employed. The inputs and outputs used for these substances are presented underneath.

The production of 1 kg of hypochlorous acid (HOCl) requires the following calculated inputs:

Chlorine [Inorganic intermediate products]	Mass	1.485 kg
Limestone (calcium carbonate) [Non renewable resources]	Mass	2.09 kg
Water (river water) [Water]	Mass	0.374 kg

The production of 1 kg of aluminium chloride hydrate requires the following calculated inputs:

Chlorine [Inorganic intermediate products]	Mass	0.445 kg
Aluminium sheet [Metals]	Mass	0.114 kg
Water [Water]	Mass	0.447 kg

A9.3.10 Production of Electricity (Hard Coal Power Plant – GaBi 3 Process)

For the production of electricity data from the GaBi 3 database was used. This data has been collected from a German plant employing similar technology as Eskom in South Africa. The inputs and the outputs for the production of 1 MJ by this process in the database are as follows:

Inputs:

Primary energy from hydro power (BUWAL) [Renewable energy resources]	Energy (calorific value)	0.007138 MJ
Wood (BUWAL) [Renewable energy resources]	Mass	1.2021E-5 kg
Raw brown coal (BUWAL) [Lignite (resource)]	Mass	0.41183kg
Crude oil free wellhead [Crude oil (resource)]	Mass	0.00046906 kg
Raw hard coal (BUWAL) [Hard coal (resource)]	Mass	0.0012256 kg
Uranium free ore (BUWAL) [Uranium (resource)]	Mass	1.1082E-7 kg
Raw natural gas (BUWAL) [Natural gas (resource)]	Mass	0.00028949 kg

Outputs:

Power [Power, electrical energy]	Energy (calorific value)	1 MJ
Carbon dioxide [Inorganic emissions into air]	Mass	0.37591kg
Carbon monoxide [Inorganic emissions into air]	Mass	3.6897E-5 kg
Methane [Organic emissions into air (group VOC)]	Mass	7.2725E-5 kg
Laughing gas (dinitrogen monoxide) [Inorganic emissions into air]	Mass	1.9069E-6 kg
NM VOC (unspecified) [Group NM VOC into air]	Mass	8.3489E-6 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.00054776 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.0019056 kg
Dust (unspecified) [Particles into air]	Mass	0.00056218 kg
Hydrogen chloride [Inorganic emissions into air]	Mass	6.0746E-5 kg
Hydrogen fluoride [Inorganic emissions into air]	Mass	6.327E-6 kg
Chlorinated hydrocarbons (unspecified) [Halogenated organic emissions into water]	Mass	2.4349E-11 kg
Lead [Heavy metals into air]	Mass	1.3728E-8 kg
Cadmium [Heavy metals into air]	Mass	6.004E-9 kg
Manganese [Heavy metals into air]	Mass	1.0628E-8 kg
Nickel [Heavy metals into air]	Mass	1.8427E-8 kg
Mercury [Heavy metals into air]	Mass	1.3965E-8 kg
Zinc [Heavy metals into air]	Mass	9.3082E-8 kg
Ammonia [Inorganic emissions into air]	Mass	1.4038E-7 kg
Benzene [Group NM VOC into air]	Mass	9.1908E-9 kg
Adsorbable organic compounded halogenes (AOX) [Analytical values emissions into water]	Mass	8.3908E-11 kg
Biological oxygen demand (BOD) [Analytical values emissions into water]	Mass	1.8309E-9 kg
Chemical oxygen demand (COD) [Analytical values emissions into water]	Mass	4.4845E-8 kg
Total organic bounded carbon [Analytical values emissions into water]	Mass	4.5425E-7 kg

Arsenic [Heavy metals into water]	Mass	3.9879E-9 kg
Barium [Inorganic emissions into water]	Mass	2.1505E-7 kg
Lead [Heavy metals into water]	Mass	1.205E-8 kg
Cadmium [Heavy metals into water]	Mass	1.3487E-10 kg
Halone (1301) [Halogenated organic emissions into air]	Mass	1.1204E-10 kg
Iron [Heavy metals into water]	Mass	0.00065953 kg
Metals (unspecified) [Particles into air]	Mass	1.7441E-5 kg
Copper [Heavy metals into water]	Mass	9.8907E-9 kg
Nickel [Heavy metals into water]	Mass	9.9957E-9 kg
Mercury [Heavy metals into water]	Mass	4.8573E-12 kg
Zinc [Heavy metals into water]	Mass	2.0073E-8 kg
Aluminium [Inorganic emissions into water]	Mass	1.987E-6 kg
Ammonium / ammonia [Inorganic emissions into water]	Mass	5.1679E-8 kg
Chloride [Inorganic emissions into water]	Mass	3.4629E-5 kg
Cyanide [Inorganic emissions into water]	Mass	1.6599E-10 kg
Nitrate [Inorganic emissions into water]	Mass	6.1562E-8 kg
Phosphate [Inorganic emissions into water]	Mass	1.1735E-7 kg
Sulphate [Inorganic emissions into water]	Mass	0.0013955 kg
Phenol (hydroxy benzene) [Hydrocarbons into water]	Mass	3.3118E-9 kg
Toluene (methyl benzene) [Hydrocarbons into water]	Mass	2.8117E-9 kg
Chromium (unspecified) [Heavy metals into water]	Mass	1.9887E-8 kg
Metals (unspecified) [Particles into water]	Mass	3.5178E-7 kg
Halogenized hydrocarbons (unspecified) [Halogenated organic emissions into air]	Mass	2.8962E-12 kg
Nitrogen [Inorganic emissions into water]	Mass	3.2811E-8 kg
Sulphide [Inorganic emissions into water]	Mass	7.8512E-10 kg
Total dissolved organic bounded carbon [Analytical values emissions into water]	Mass	3.7815E-9 kg
Solids (suspended) [Particles into water]	Mass	1.8839E-6 kg
Oil (unspecified) [Hydrocarbons into water]	Mass	6.3082E-7 kg
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Hydrocarbons into water]	Mass	3.06E-10 kg
Nitrogen organic bounded [Inorganic emissions into water]	Mass	4.6317E-9 kg
Radioactive substances (unspecified) [Radioactive emissions into air]	Activity	9644.1 Bq
Inorganic salts and acids (unspecified) [Inorganic emissions into water]	Mass	0.001462 kg
Radioactive substances (unspecified) [Radioactive emissions into water]	Activity	88.732 Bq
Aromatic hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	4.2201E-6 kg
Polycyclic aromatic hydrocarbons (PAH) [Group PAH into air]	Mass	3.4866E-9 kg

A9.3.11 Production of Chlorine – GaBi 3 Process

Data for this process is used form the GaBi 3 database and it is average data from a multitude of producer. For the production of 1 kg chlorine the inputs and outputs are as presented.

Inputs

Hard coal (APME) [Hard coal (resource)]	Mass	0.23998 kg
Crude oil (APME) [Crude oil (resource)]	Mass	0.078457 kg
Natural gas (APME) [Natural gas (resource)]	Mass	0.075658 kg

Primary energy from hydro power (APME) [Renewable energy resources]	Energy (calorific value)	0.72 MJ
Nuclear energy (APME) [Uranium (resource)]	Energy (calorific value)	6.14 MJ
Limestone (calcium carbonate) [Non renewable resources]	Mass	0.0186 kg
Sodium chloride (rock salt) [Non renewable resources]	Mass	1.21 kg
Water [Water]	Mass	0.9 kg
Iron ore [Non renewable resources]	Mass	0.00065 kg
Quartz sand (silica sand; silicon dioxide) [Non renewable resources]	Mass	0.0002 kg

Outputs

Chlorine [Inorganic intermediate products]	Mass	1 kg
Carbon dioxide [Inorganic emissions into air]	Mass	1.21 kg
Carbon monoxide [Inorganic emissions into air]	Mass	0.0008 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.007 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.012 kg
Dust (unspecified) [Particles into air]	Mass	0.0035 kg
Hydrogen chloride [Inorganic emissions into air]	Mass	0.00018 kg
Biological oxygen demand (BOD) [Analytical values emissions into water]	Mass	3E-6 kg
Chemical oxygen demand (COD) [Analytical values emissions into water]	Mass	1E-5 kg
Inert chemicals [Consumer waste]	Mass	0.013 kg
Metals (unspecified) [Particles into air]	Mass	2E-6 kg
Acid (calculated as H+) [Inorganic emissions into water]	Mass	0.00034 kg
Chloride [Inorganic emissions into water]	Mass	0.042 kg
Sodium [Inorganic emissions into water]	Mass	0.0028 kg
Sulphate [Inorganic emissions into water]	Mass	0.0072 kg
Overburden [Stockpile goods]	Mass	0.072 kg
Municipal similarly industrial waste [Consumer waste]	Mass	0.001 kg
Hazardous waste [Hazardous waste]	Mass	2E-5 kg
Metals (unspecified) [Particles into water]	Mass	9E-5 kg
Solids (dissolved) [Analytical values emissions into water]	Mass	5E-5 kg
Slag [Hazardous waste]	Mass	0.013 kg
Solids (suspended) [Particles into water]	Mass	0.002 kg
VOC (unspecified) [Organic emissions into air (group VOC)]	Mass	6 kg

A9.3.12 Production of Steel – GaBi 3 Process

For 1 kg of steel sheet the inputs and the outputs are as presented.

Inputs:

Steel scrap [Waste for recovery]	Mass	0.122 kg
Degreasing agent [Operating materials]	Mass	0.0013 kg
Primary energy from hydro power (BUWAL) [Renewable energy resources]	Energy (calorific value)	0.339 MJ
Limestone (calcium carbonate) [Non renewable resources]	Mass	0.283 kg
Wood (BUWAL) [Renewable energy resources]	Mass	0.0143 kg
Rolling oil [Operating materials]	Mass	0.0022 kg
Iron ore [Non renewable resources]	Mass	2.4 kg
Process water [Operating materials]	Mass	0.0164 kg

Alloy components [Metals]	Mass	0.0052 kg
Raw brown coal (BUWAL) [Lignite (resource)]	Mass	0.106 kg
Crude oil free wellhead [Crude oil (resource)]	Mass	0.0868 kg
Raw hard coal (BUWAL) [Hard coal (resource)]	Mass	1.19 kg
Uranium free ore (BUWAL) [Uranium (resource)]	Mass	5.36E-9 kg
Raw natural gas (BUWAL) [Natural gas (resource)]	Mass	0.104 kg
Chromium compounds [Waste for recovery]	Mass	0.00086 kg
Acid (unspecified) [Inorganic intermediate products]	Mass	0.0125 kg
Additives (steel production) [Metals]	Mass	0.0331 kg

Outputs:

Steel sheet (ECCS low grade) [Metals]	Mass	0.0333 kg
Steel sheet (ECCS) [Metals]	Mass	1 kg
Carbon dioxide [Inorganic emissions into air]	Mass	2.95 kg
Carbon monoxide [Inorganic emissions into air]	Mass	0.0185 kg
Methane [Organic emissions into air (group VOC)]	Mass	0.0108 kg
Laughing gas (dinitrogen monoxide) [Inorganic emissions into air]	Mass	9.52E-6 kg
NM VOC (unspecified) [Group NM VOC into air]	Mass	0.001 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.00454 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.00618 kg
Dust (unspecified) [Particles into air]	Mass	0.00141 kg
Hydrogen chloride [Inorganic emissions into air]	Mass	8.63E-5 kg
Hydrogen fluoride [Inorganic emissions into air]	Mass	1.1E-5 kg
Chlorinated hydrocarbons (unspecified)	Mass	5.8E-9 kg
[Halogenated organic emissions into water]		
Lead [Heavy metals into air]	Mass	4.58E-6 kg
Cadmium [Heavy metals into air]	Mass	1.07E-7 kg
Copper [Heavy metals into air]	Mass	2.6E-7 kg
Manganese [Heavy metals into air]	Mass	1.74E-6 kg
Nickel [Heavy metals into air]	Mass	1.76E-6 kg
Mercury [Heavy metals into air]	Mass	1.57E-8 kg
Thallium [Heavy metals into air]	Mass	4E-8 kg
Vanadium [Heavy metals into air]	Mass	1E-8 kg
Zinc [Heavy metals into air]	Mass	2.66E-7 kg
Ammonia [Inorganic emissions into air]	Mass	1.97E-6 kg
Hydrogen sulfide [Inorganic emissions into air]	Mass	9.9E-6 kg
Benzene [Group NM VOC into air]	Mass	2.27E-6 kg
Adsorbable organic compounded halogenes (AOX)	Mass	5.16E-7 kg
[Analytical values emissions into water]		
Biological oxygen demand (BOD)	Mass	0.00017 kg
[Analytical values emissions into water]		
Chemical oxygen demand (COD)	Mass	0.000465 kg
[Analytical values emissions into water]		
Aromatic hydrocarbons (unspecified) [Group NM VOC into air]	Mass	5.23E-6 kg
Total organic bounded carbon [Analytical values emissions into water]	Mass	0.000149 kg
Arsenic [Heavy metals into water]	Mass	3.85E-6 kg
Barium [Inorganic emissions into water]	Mass	0.000165 kg
Lead [Heavy metals into water]	Mass	9.74E-6 kg
Cadmium [Heavy metals into water]	Mass	1.02E-7 kg
Halone (1301) [Halogenated organic emissions into air]	Mass	2.07E-8 kg
Iron [Heavy metals into water]	Mass	0.00079 kg
Metals (unspecified) [Particles into air]	Mass	2.55E-5 kg

Copper [Heavy metals into water]	Mass	9.61E-6 kg
Nickel [Heavy metals into water]	Mass	9.69E-6 kg
Mercury [Heavy metals into water]	Mass	1.56E-8 kg
Zinc [Heavy metals into water]	Mass	1.93E-5 kg
Aluminium [Inorganic emissions into water]	Mass	0.00192 kg
Ammonium / ammonia [Inorganic emissions into water]	Mass	7.94E-6 kg
Chloride [Inorganic emissions into water]	Mass	0.0142 kg
Cyanide [Inorganic emissions into water]	Mass	2.94E-8 kg
Chemicals (unspecified) [Waste for recovery]	Mass	0.0191 kg
Nitrate [Inorganic emissions into water]	Mass	6.04E-6 kg
Phosphate [Inorganic emissions into water]	Mass	0.000146 kg
Sulphate [Inorganic emissions into water]	Mass	0.00895 kg
Phenol (hydroxy benzene) [Hydrocarbons into water]	Mass	6.45E-7 kg
Toluene (methyl benzene) [Hydrocarbons into water]	Mass	5.33E-7 kg
Metals (unspecified) [Particles into water]	Mass	0.000223 kg
Halogenized hydrocarbons (unspecified)	Mass	1E-10 kg
[Halogenated organic emissions into air]		
Nitrogen [Inorganic emissions into water]	Mass	5.52E-6 kg
Sulphide [Inorganic emissions into water]	Mass	1.38E-7 kg
Rolling tinder [Waste for recovery]	Mass	0.028 kg
Total dissolved organic bounded carbon	Mass	1.67E-6 kg
[Analytical values emissions into water]		
Solids (suspended) [Particles into water]	Mass	0.000392 kg
Oil (unspecified) [Hydrocarbons into water]	Mass	0.000119 kg
Polycyclic aromatic hydrocarbons (PAH, unspec.)	Mass	5.67E-8 kg
[Hydrocarbons into water]		
Nitrogen organic bounded [Inorganic emissions into water]	Mass	7.19E-7 kg
Radioactive substances (unspecified) [Radioactive emissions into air]	Activity	4.66E5 Bq
Inorganic salts and acids (unspecified) [Inorganic emissions into water]	Mass	0.00782 kg
Radioactive substances (unspecified)	Activity	4300 Bq
[Radioactive emissions into water]		
Aromatic hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	3.9E-6 kg
Chromium compounds [Waste for recovery]	Mass	0.0045 kg
Iron compounds (unspecified) [Waste for recovery]	Mass	0.0185 kg
Slag (Iron plate production) [Waste for recovery]	Mass	0.386 kg
Dust, outpouring [Waste for recovery]	Mass	0.062 kg
Chromium (unspecified) [Heavy metals into air]	Mass	1.4E-7 kg
Chromium (unspecified) [Heavy metals into water]	Mass	2.33E-5 kg
Polycyclic aromatic hydrocarbons (PAH) [Group PAH into air]	Mass	2.77E-8 kg

A9.3.13 Production of Aluminium – GaBi 3 Process

For the production of 1 kg of aluminium sheet following inputs and outputs are needed.

Inputs:

Primary energy from hydro power (BUWAL) [Renewable energy resources]	Energy (calorific value)	48.1 MJ
Bauxite [Non renewable resources]	Mass	3.71 kg
Limestone (calcium carbonate) [Non renewable resources]	Mass	0.174 kg
Sodium chloride (rock salt) [Non renewable resources]	Mass	0.0545 kg
Wood (BUWAL) [Renewable energy resources]	Mass	0.0158 kg
Iron ore [Non renewable resources]	Mass	4.25E-5 kg

Sulphur dioxide [Inorganic intermediate products]	Mass	0.0196 kg
Quartz sand (silica sand; silicon dioxide) [Non renewable resources]	Mass	1.85E-5 kg
Fluorspar (calcium fluoride; fluorite) [Inorganic intermediate products]	Mass	0.0254 kg
Raw brown coal (BUWAL) [Lignite (resource)]	Mass	0.217 kg
Crude oil free wellhead [Crude oil (resource)]	Mass	1.3 kg
Raw hard coal (BUWAL) [Hard coal (resource)]	Mass	1.6207 kg
Uranium free ore (BUWAL) [Uranium (resource)]	Mass	7.8E-5 kg
Raw natural gas (BUWAL) [Natural gas (resource)]	Mass	0.3608 kg
Process and cooling water [Operating materials]	Mass	0.00844 kg
Insulating stone [Operating materials]	Mass	0.0052 kg
Insulating board [Operating materials]	Mass	0.0034 kg
Flux and gas [Operating materials]	Mass	0.002 kg

Outputs:

Aluminium sheet [Metals]	Mass	1 kg
Cathode steel [Operating materials]	Mass	0.0061 kg
Carbon dioxide [Inorganic emissions into air]	Mass	8.22 kg
Carbon monoxide [Inorganic emissions into air]	Mass	0.0616 kg
Methane [Organic emissions into air (group VOC)]	Mass	0.018 kg
Laughing gas (dinitrogen monoxide) [Inorganic emissions into air]	Mass	4.57E-5 kg
NM VOC (unspecified) [Group NM VOC into air]	Mass	0.0111 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.017 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.0565 kg
Dust (unspecified) [Particles into air]	Mass	0.0216 kg
Hydrogen chloride [Inorganic emissions into air]	Mass	0.000748 kg
Hydrogen fluoride [Inorganic emissions into air]	Mass	7.79E-5 kg
Chlorinated hydrocarbons (unspecified)	Mass	6.23E-8 kg
[Halogenated organic emissions into water]		
Lead [Heavy metals into air]	Mass	1.1E-6 kg
Cadmium [Heavy metals into air]	Mass	2.71E-7 kg
Manganese [Heavy metals into air]	Mass	3.42E-7 kg
Nickel [Heavy metals into air]	Mass	8.88E-6 kg
Mercury [Heavy metals into air]	Mass	1.21E-7 kg
Zinc [Heavy metals into air]	Mass	2.29E-6 kg
Ammonia [Inorganic emissions into air]	Mass	1.45E-5 kg
Fluoride (unspecified) [Inorganic emissions into air]	Mass	0.000824 kg
Benzene [Group NM VOC into air]	Mass	1.63E-5 kg
Adsorbable organic compounded halogenes (AOX) [Analytical values emissions into water]	Mass	2.25E-7 kg
Biological oxygen demand (BOD) [Analytical values emissions into water]	Mass	3.51E-6 kg
Chemical oxygen demand (COD) [Analytical values emissions into water]	Mass	8.59E-5 kg
Aromatic hydrocarbons (unspecified) [Group NM VOC into air]	Mass	5.83E-5 kg
Total organic bounded carbon [Analytical values emissions into water]	Mass	0.000869 kg
Arsenic [Heavy metals into water]	Mass	5.18E-6 kg
Barium [Inorganic emissions into water]	Mass	0.000365 kg
Lead [Heavy metals into water]	Mass	1.41E-5 kg
Cadmium [Heavy metals into water]	Mass	2.06E-7 kg
Halone (1301) [Halogenated organic emissions into air]	Mass	3.09E-7 kg
Iron [Heavy metals into water]	Mass	0.00111 kg
Metals (unspecified) [Particles into air]	Mass	0.000236 kg

Copper [Heavy metals into water]	Mass	1.28E-5 kg
Nickel [Heavy metals into water]	Mass	1.3E-5 kg
Mercury [Heavy metals into water]	Mass	4.98E-9 kg
Zinc [Heavy metals into water]	Mass	2.62E-5 kg
Aluminium [Inorganic emissions into water]	Mass	0.00256 kg
Ammonium / ammonia [Inorganic emissions into water]	Mass	7.98E-5 kg
Acid (calculated as H+) [Inorganic emissions into water]	Mass	1.6915E-5 kg
Chloride [Inorganic emissions into water]	Mass	0.0532 kg
Cyanide [Inorganic emissions into water]	Mass	3.02E-7 kg
Fluoride [Inorganic emissions into water]	Mass	2.71E-6 kg
Nitrate [Inorganic emissions into water]	Mass	9.6E-5 kg
Phosphate [Inorganic emissions into water]	Mass	0.000153 kg
Sulphate [Inorganic emissions into water]	Mass	0.0185 kg
Phenol (hydroxy benzene) [Hydrocarbons into water]	Mass	9.37E-6 kg
Toluene (methyl benzene) [Hydrocarbons into water]	Mass	7.73E-6 kg
Aldehyde (unspecified) [Group NMVOC into air]	Mass	1E-7 kg
Metals (unspecified) [Particles into water]	Mass	0.000668 kg
Halogenized hydrocarbons (unspecified)	Mass	2.01E-9 kg
[Halogenated organic emissions into air]		
Nitrogen [Inorganic emissions into water]	Mass	6.49E-5 kg
Sulphide [Inorganic emissions into water]	Mass	2.03E-6 kg
Tetrafluoromethane [Halogenated organic emissions into air]	Mass	0.0004 kg
Total dissolved organic bounded carbon	Mass	5.35E-6 kg
[Analytical values emissions into water]		
Solids (suspended) [Particles into water]	Mass	0.00501 kg
Hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	1.7E-6 kg
Oil (unspecified) [Hydrocarbons into water]	Mass	0.00173 kg
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Hydrocarbons into water]	Mass	1.79E-5 kg
VOC (unspecified) [Organic emissions into air (group VOC)]	Mass	7.19E-5 kg
Chromium (unspecified) [Heavy metals into water]	Mass	2.6E-5 kg
Dross [Waste for recovery]	Mass	0.012 kg
Nitrogen organic bounded [Inorganic emissions into water]	Mass	6.6E-6 kg
Cathode carbon (outpouring) [Waste for recovery]	Mass	0.0166 kg
Radioactive substances (unspecified) [Radioactive emissions into air]	Activity	6.68E6 Bq
Inorganic salts and acids (unspecified) [Inorganic emissions into water]	Mass	0.0346 kg
Radioactive substances (unspecified)	Activity	61500 Bq
[Radioactive emissions into water]		
Aromatic hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	5.58E-5 kg
Polycyclic aromatic hydrocarbons (PAH) [Group PAH into air]	Mass	4E-5 kg

A9.3.14 Production of Epoxy Resin – GaBi 3 Process

Inputs:

Hard coal (APME) [Hard coal (resource)]	Mass	0.38 kg
Crude oil (APME) [Crude oil (resource)]	Mass	0.68 kg
Natural gas (APME) [Natural gas (resource)]	Mass	1.7 kg
Lignite (APME) [Lignite (resource)]	Mass	0.25 kg
Wood 50% water (APME) [Renewable energy resources]	Mass	0.002 kg
Primary energy from hydro power (APME)	Energy	1.36 MJ
[Renewable energy resources]	(calorific value)	
Nuclear energy (APME) [Uranium (resource)]	Energy	7.81 MJ

Sulphur (APME) [Non renewable energy resources]	(calorific value) Energy (calorific value)	0.07 MJ
Hydrogen (APME) [Non renewable energy resources]	Energy (calorific value)	3.34 MJ
Lead [Non renewable elementary resources]	Mass	4E-6 kg
Iron [Non renewable elementary resources]	Mass	0.0024 kg
Bauxite [Non renewable resources]	Mass	0.0024 kg
Energy unspecified (APME) [Energy resources]	Energy (calorific value)	0.03 MJ
Water (feed water) [Water]	Mass	14 kg
Dolomite [Non renewable resources]	Mass	0.00029 kg
Fluorspar (calcium fluoride; fluorite) [Non renewable resources]	Mass	3.9E-5 kg
Gypsum (natural gypsum) [Non renewable resources]	Mass	1.3E-5 kg
Limestone (calcium carbonate) [Non renewable resources]	Mass	0.71 kg
Water (river water) [Water]	Mass	280 kg
Slate [Non renewable resources]	Mass	3.7E-5 kg
Sodium chloride (rock salt) [Non renewable resources]	Mass	1.8 kg
Clay [Non renewable resources]	Mass	1.4E-5 kg
Water [Water]	Mass	42 kg
Air [Renewable resources]	Mass	0.94 kg
Water (well water) [Water]	Mass	0.019 kg
Barium sulphate [Non renewable resources]	Mass	0.00041 kg
Ferro manganese [Non renewable resources]	Mass	2E-6 kg
Nitrogen [Renewable resources]	Mass	0.12 kg
Oxygen [Renewable resources]	Mass	0.04 kg
Sulphur (bonded) [Non renewable resources]	Mass	0.0037 kg
Sulphur [Non renewable elementary resources]	Mass	0.0073 kg
Olivine [Non renewable resources]	Mass	2.2E-5 kg
Potassium chloride [Non renewable resources]	Mass	0.029 kg
Bentonite [Non renewable resources]	Mass	0.00013 kg
Water (sea water) [Water]	Mass	68 kg
Raw gravel [Non renewable resources]	Mass	8E-6 kg
Quartz sand (silica sand; silicon dioxide) [Non renewable resources]	Mass	0.0012 kg

Outputs:

Epoxy resin [Plastics]	Mass	1 kg
Potassium [Inorganic emissions into water]	Mass	0.00082 kg
Carbon dioxide [Inorganic emissions into air]	Mass	5.9 kg
Magnesium [Inorganic emissions into water]	Mass	1.8E-5 kg
Energy recovery (APME) [Energy resources]	Energy (calorific value)	7.12 MJ
Carbon monoxide [Inorganic emissions into air]	Mass	0.0023 kg
Methane [Organic emissions into air (group VOC)]	Mass	0.037 kg
NM VOC (unspecified) [Group NM VOC into air]	Mass	0.00049 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.035 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.02 kg
Dust (unspecified) [Particles into air]	Mass	0.016 kg
Hydrogen chloride [Inorganic emissions into air]	Mass	0.00039 kg
Hydrogen fluoride [Inorganic emissions into air]	Mass	8E-6 kg
Ammonia [Inorganic emissions into air]	Mass	4E-6 kg
Chlorine [Inorganic emissions into air]	Mass	6E-6 kg

Hydrogen sulfide [Inorganic emissions into air]	Mass	3E-6 kg
Biological oxygen demand (BOD)	Mass	0.0012 kg
[Analytical values emissions into water]		
Chemical oxygen demand (COD)	Mass	0.051 kg
[Analytical values emissions into water]		
Organic compounds (unspecified) [Organic emissions into water]	Mass	0.0052 kg
Aromatic hydrocarbons (unspecified) [Group NMVOC into air]	Mass	2.8E-5 kg
Iron [Heavy metals into water]	Mass	1E-6 kg
Metals (unspecified) [Particles into air]	Mass	6E-6 kg
Ammonium / ammonia [Inorganic emissions into water]	Mass	5E-6 kg
Acid (calculated as H+) [Inorganic emissions into water]	Mass	6.2E-5 kg
Chloride [Inorganic emissions into water]	Mass	0.98 kg
Sodium [Inorganic emissions into water]	Mass	0.38 kg
Nitrate [Inorganic emissions into water]	Mass	1E-6 kg
Phosphate [Inorganic emissions into water]	Mass	0.00022 kg
Calcium [Inorganic emissions into water]	Mass	0.054 kg
Sulphate [Inorganic emissions into water]	Mass	0.0081 kg
Phenol (hydroxy benzene) [Hydrocarbons into water]	Mass	1.2E-5 kg
Overburden [Stockpile goods]	Mass	0.31 kg
Aldehyde (unspecified) [Group NMVOC into air]	Mass	4.7E-5 kg
Municipal similarly industrial waste [Consumer waste]	Mass	0.073 kg
Hazardous waste [Hazardous waste]	Mass	0.019 kg
Metals (unspecified) [Particles into water]	Mass	0.00042 kg
Solids (dissolved) [Analytical values emissions into water]	Mass	0.017 kg
Detergent (unspecified) [Other emissions into water]	Mass	6.9E-5 kg
Waste (unspecified) [Consumer waste]	Mass	5.7E-5 kg
Demolition waste [Stockpile goods]	Mass	3.2E-5 kg
Packaging waste (metal) [Consumer waste]	Mass	1.6E-5 kg
Packaging waste (plastic) [Consumer waste]	Mass	0.00043 kg
Organic waste [Consumer waste]	Mass	2E-5 kg
Halogenized hydrocarbons (unspecified)	Mass	8E-6 kg
[Halogenated organic emissions into air]		
Organic chlorine compounds [Organic emissions into air (group VOC)]	Mass	1.1E-5 kg
Nitrogen [Inorganic emissions into water]	Mass	1E-5 kg
Chlorine (dissolved) [Inorganic emissions into water]	Mass	2.4E-5 kg
Organic chlorine compounds (unspecified) [Organic emissions into water]	Mass	7.2E-5 kg
Hydrogen [Inorganic emissions into air]	Mass	0.021 kg
Carbonate [Inorganic emissions into water]	Mass	0.015 kg
Production residues (unspecified) [Waste for recovery]	Mass	1.1E-5 kg
Incineration good [Waste for disposal]	Mass	0.0058 kg
Slag [Hazardous waste]	Mass	0.035 kg
Total dissolved organic bounded carbon	Mass	0.00041 kg
[Analytical values emissions into water]		
Solids (suspended) [Particles into water]	Mass	0.083 kg
Hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	8.6E-5 kg
VOC (unspecified) [Organic emissions into air (group VOC)]	Mass	0.0058 kg

A9.3.15 Production of PVC – GaBi 3 Process

For the production of 1 kg of PVC following inputs and outputs are considered.

Inputs:

Hard coal (APME) [Hard coal (resource)]	Mass	0.24672 kg
Crude oil (APME) [Crude oil (resource)]	Mass	0.50731 kg
Natural gas (APME) [Natural gas (resource)]	Mass	0.52531 kg
Primary energy from hydro power (APME) [Renewable energy resources]	Energy (calorific value)	0.84 MJ
Nuclear energy (APME) [Uranium (resource)]	Energy (calorific value)	7.87 MJ
Bauxite [Inorganic intermediate products]	Mass	0.00022 kg
Energy unspecified (APME) [Energy resources]	Energy (calorific value)	0.13 MJ
Limestone (calcium carbonate) [Non renewable resources]	Mass	0.0016 kg
Sodium chloride (rock salt) [Non renewable resources]	Mass	0.69 kg
Water [Water]	Mass	1.9 kg
Iron ore [Non renewable resources]	Mass	0.0004 kg
Quartz sand (silica sand; silicon dioxide) [Non renewable resources]	Mass	0.0012 kg

Outputs:

Polyvinyl chloride granulate (PVC) [Plastics]	Mass	1 kg
Carbon monoxide [Inorganic emissions into air]	Mass	0.0027 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.016 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.013 kg
Dust (unspecified) [Particles into air]	Mass	0.0039 kg
Hydrogen chloride [Inorganic emissions into air]	Mass	0.00023 kg
Chlorine [Inorganic emissions into air]	Mass	2E-6 kg
Biological oxygen demand (BOD) [Analytical values emissions into water]	Mass	8E-5 kg
Chemical oxygen demand (COD) [Analytical values emissions into water]	Mass	0.0011 kg
Inert chemicals [Consumer waste]	Mass	0.014 kg
Metals (unspecified) [Particles into air]	Mass	3E-6 kg
Acid (calculated as H+) [Inorganic emissions into water]	Mass	0.00011 kg
Chloride [Inorganic emissions into water]	Mass	0.04 kg
Sodium [Inorganic emissions into water]	Mass	0.0023 kg
Sulphate [Inorganic emissions into water]	Mass	0.0043 kg
Overburden [Stockpile goods]	Mass	0.066 kg
Municipal similarly industrial waste [Consumer waste]	Mass	0.0018 kg
Hazardous waste [Hazardous waste]	Mass	0.0012 kg
Metals (unspecified) [Particles into water]	Mass	0.0002 kg
Solids (dissolved) [Analytical values emissions into water]	Mass	0.0005 kg
Carbon dioxide [Inorganic emissions into air]	Mass	1.944 kg
Organic chlorine compounds [Organic emissions into air (group VOC)]	Mass	0.00072 kg
Nitrogen [Inorganic emissions into water]	Mass	3E-6 kg
Organic chlorine compounds (unspecified) [Organic emissions into water]	Mass	1E-5 kg
Slag [Hazardous waste]	Mass	0.047 kg
Total dissolved organic bounded carbon [Analytical values emissions into water]	Mass	0.001 kg

Solids (suspended) [Particles into water]	Mass	0.0024 kg
Oil (unspecified) [Hydrocarbons into water]	Mass	5E-5 kg
VOC (unspecified) [Organic emissions into air (group VOC)]	Mass	0.02 kg

A9.3.16 Production of PVC Pipes – GaBi Process

The PVC granulate from the previous processes is used to produce PVC pipes. The inputs and outputs from this process are presented as follows:

Inputs:

Polyvinyl chloride granulate (PVC) [Plastics]	Mass	1.0037 kg
Crude oil (APME) [Crude oil (resource)]	Mass	0.024601 kg
Natural gas (APME) [Natural gas (resource)]	Mass	0.054231 kg
Primary energy from hydro power (APME) [Renewable energy resources]	Energy (calorific value)	0.036 MJ
Nuclear energy (APME) [Uranium (resource)]	Energy (calorific value)	0.625 MJ
Energy unspecified (APME) [Energy resources]	Energy (calorific value)	0.199 MJ
Water [Water]	Mass	14.522 kg
Hard coal (APME) [Hard coal (resource)]	Mass	0.058596 kg

Outputs:

Polyvinyl chloride-tube (PVC) [Plastic parts]	Mass	1 kg
Carbon monoxide [Inorganic emissions into air]	Mass	0.00017 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.0031 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.0032 kg
Dust (unspecified) [Particles into air]	Mass	0.0011 kg
Hydrogen chloride [Inorganic emissions into air]	Mass	3E-5 kg
Hydrogen fluoride [Inorganic emissions into air]	Mass	1E-6 kg
Biological oxygen demand (BOD) [Analytical values emissions into water]	Mass	1E-6 kg
Chemical oxygen demand (COD) [Analytical values emissions into water]	Mass	2E-6 kg
Acid (calculated as H ⁺) [Inorganic emissions into water]	Mass	1E-6 kg
Overburden [Stockpile goods]	Mass	0.0135 kg
Production residues (unspecified) [Waste for recovery]	Mass	0.0037 kg
Slag [Hazardous waste]	Mass	0.0001 kg
Solids (suspended) [Particles into water]	Mass	2E-5 kg
Hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	1E-6 kg
VOC (unspecified) [Organic emissions into air (group VOC)]	Mass	0.0028 kg
Carbon dioxide [Inorganic emissions into air]	Mass	0.41 kg

A9.3.17 Production of Polyethylene (PE) – GaBi 3 Process

Inputs:

Hard coal (APME) [Hard coal (resource)]	Mass	0.05929 kg
Crude oil (APME) [Crude oil (resource)]	Mass	1.2173 kg
Natural gas (APME) [Natural gas (resource)]	Mass	0.40148 kg
Primary energy from hydro power (APME) [Renewable energy resources]	Energy (calorific value)	0.81 MJ

Nuclear energy (APME) [Uranium (resource)]	Energy (calorific value)	1 MJ
Bauxite [Non renewable resources]	Mass	0.0004 kg
Energy unspecified (APME) [Energy resources]	Energy (calorific value)	0.06 MJ
Limestone (calcium carbonate) [Non renewable resources]	Mass	0.0002 kg
Sodium chloride (rock salt) [Non renewable resources]	Mass	0.005 kg
Clay [Non renewable resources]	Mass	3E-5 kg
Water [Water]	Mass	3.1 kg
Iron ore [Non renewable resources]	Mass	0.0003 kg

Outputs:

Polypropylene granulate (PP) [Plastics]	Mass	1 kg
Carbon monoxide [Inorganic emissions into air]	Mass	0.0007 kg
NMVOC (unspecified) [Group NMVOC into air]	Mass	0.00025 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.01 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.011 kg
Dust (unspecified) [Particles into air]	Mass	0.002 kg
Hydrogen chloride [Inorganic emissions into air]	Mass	4E-5 kg
Hydrogen fluoride [Inorganic emissions into air]	Mass	1E-6 kg
Hydrogen sulfide [Inorganic emissions into air]	Mass	1E-5 kg
Biological oxygen demand (BOD) [Analytical values emissions into water]	Mass	6E-5 kg
Chemical oxygen demand (COD) [Analytical values emissions into water]	Mass	0.0004 kg
Metals (unspecified) [Particles into air]	Mass	5E-6 kg
Ammonium / ammonia [Inorganic emissions into water]	Mass	1E-5 kg
Acid (calculated as H ⁺) [Inorganic emissions into water]	Mass	9E-5 kg
Chloride [Inorganic emissions into water]	Mass	0.0008 kg
Nitrate [Inorganic emissions into water]	Mass	2E-5 kg
Phosphate [Inorganic emissions into water]	Mass	2E-5 kg
Overburden [Stockpile goods]	Mass	0.014 kg
Municipal similarly industrial waste [Consumer waste]	Mass	0.012 kg
Metals (unspecified) [Particles into water]	Mass	0.0003 kg
Solids (dissolved) [Analytical values emissions into water]	Mass	0.0002 kg
Carbon dioxide [Inorganic emissions into air]	Mass	1.1 kg
Nitrogen [Inorganic emissions into water]	Mass	1E-5 kg
Slag [Hazardous waste]	Mass	0.005 kg
Toxic chemicals (unspecified) [Hazardous waste for disposal]	Mass	3E-5 kg
Total dissolved organic bounded carbon [Analytical values emissions into water]	Mass	3E-5 kg
Solids (suspended) [Particles into water]	Mass	0.0002 kg
Hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	0.0003 kg
Oil (unspecified) [Hydrocarbons into water]	Mass	4E-5 kg
VOC (unspecified) [Organic emissions into air (group VOC)]	Mass	0.013 kg

A9.3.18 Production of Polyethylene Netting – GaBi 3 Process

It was assumed that the same molding process is used to produce the polyethylene netting as the production of polyethylene pipes. The inputs and outputs are as follows.

Inputs:

Polyethylene high density granulate (PE HD) [Plastics]	Mass	1.0037 kg
Crude oil (APME) [Crude oil (resource)]	Mass	0.025487 kg
Natural gas (APME) [Natural gas (resource)]	Mass	0.057463 kg
Primary energy from hydro power (APME) [Renewable energy resources]	Energy (calorific value)	0.041 MJ
Nuclear energy (APME) [Uranium (resource)]	Energy (calorific value)	0.721 MJ
Energy unspecified (APME) [Energy resources]	Energy (calorific value)	0.224 MJ
Water [Water]	Mass	25.444 kg
Hard coal (APME) [Hard coal (resource)]	Mass	0.067316 kg

Outputs:

Polyethylene-tube (PE) [Plastic parts]	Mass	1 kg
Carbon monoxide [Inorganic emissions into air]	Mass	0.00019 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.0033 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.0035 kg
Dust (unspecified) [Particles into air]	Mass	0.0012 kg
Hydrogen chloride [Inorganic emissions into air]	Mass	4E-5 kg
Hydrogen fluoride [Inorganic emissions into air]	Mass	1E-6 kg
Biological oxygen demand (BOD) [Analytical values emissions into water]	Mass	1E-6 kg
Chemical oxygen demand (COD) [Analytical values emissions into water]	Mass	2E-6 kg
Metals (unspecified) [Particles into air]	Mass	1E-6 kg
Acid (calculated as H+) [Inorganic emissions into water]	Mass	1E-6 kg
Overburden [Stockpile goods]	Mass	0.0155 kg
Municipal similarly industrial waste [Consumer waste]	Mass	0.0001 kg
Production residues (unspecified) [Waste for recovery]	Mass	0.0037 kg
Slag [Hazardous waste]	Mass	0.0048 kg
Solids (suspended) [Particles into water]	Mass	3E-5 kg
Hydrocarbons (unspecified) [Hydrocarbons into water]	Mass	1E-6 kg
VOC (unspecified) [Organic emissions into air (group VOC)]	Mass	0.0029 kg
Inert chemicals [Hazardous waste]	Mass	0.006 kg
Carbon dioxide [Inorganic emissions into air]	Mass	0.44 kg

A9.3.19 Production of Methanol

Data on the production of methanol was obtained from Prof. Overcash, University of North Carolina. It was entered manually in the GaBi 3 database and in the process plans where it was used it was linked with the production of power. The inputs and outputs for this process are presented as follows.

Inputs:

Crude oil (APME) [Crude oil (resource)]	Mass	0.31 kg
Power [Power, electrical energy]	Energy (calorific value)	1.35 MJ
Natural gas free customer (APME) [Natural gas products]	Mass	1.3 kg
Water [Water]	Mass	3.9 kg
Raw hard coal (BUWAL) [Hard coal (resource)]	Mass	1.3 kg

Outputs:

Methanol [Organic intermediate products]	Mass	1 kg
Carbon dioxide [Inorganic emissions into air]	Mass	4.01 kg
Methane [Organic emissions into air (group VOC)]	Mass	0.02 kg
Nitrogen oxides [Inorganic emissions into air]	Mass	0.008 kg
Sulphur dioxide [Inorganic emissions into air]	Mass	0.03 kg
Waste (unspecified) [Consumer waste]	Mass	0.5 kg

A9.3.20 Production of Polysulphone

Data for this process was calculated in a similar fashion as for Zetafloc, the polymeric coagulant.

Inputs:

Benzene [Organic intermediate products]	Mass	1 kg
Power [Power, electrical energy]	Energy (calorific value)	1.7453 MJ
Propene (propylene) [Organic intermediate products]	Mass	0.532 kg
Oxygen [Renewable resources]	Mass	0.404 kg

A9.3.21 Production of Dimethylformamide

This data was obtained from Prof. Overcash, University of North Carolina. The inputs and outputs for the production of 1 kg of dimethylformamide is as follows.

Input:

Methanol [Organic intermediate products]	Mass	0.0252 kg
Dimethylamine [Organic intermediate products]	Mass	0.646 kg
Power [Power, electrical energy]	Energy (calorific value)	0.961 MJ

Outputs:

Dimethyl formamide [Plastics]	Mass	1 kg
Carbon dioxide [Inorganic emissions into air]	Mass	0.00039 kg
Methanol [Inorganic emissions into air]	Mass	0.0023 kg
Amines [Hydrocarbons into water]	Mass	0.055 kg
Carbon monoxide [Inorganic emissions into air]	Mass	0.044 kg
Waste water [Other emissions into water]	Mass	4.4E-5 kg
Methanol [Hydrocarbons into water]	Mass	0.013 kg

A9.3.22 Production of N,N Dimethyl Formamide (DMA)

Data for this process was obtained from Prof. Overcash, University of North Carolina

Inputs:

Methanol [Organic intermediate products]	Mass	1.4245 kg
Ammonia [Inorganic intermediate products]	Mass	0.3931 kg
Power [Power, electrical energy]	Energy (calorific value)	3.04 MJ
Water [Water]	Mass	0.1549 kg

Outputs:

Dimethylamine [Organic intermediate products]	Mass	1 kg
Ammonia [Inorganic emissions into air]	Mass	0.00205 kg
Methanol [Group NMVOC into air]	Mass	0.01424 kg
Methanol [Hydrocarbons into water]	Mass	0.0293 kg
Ammonium [Inorganic emissions into air]	Mass	0.00506 kg

A9.3.23 Production of Poly Vinyl Pyrrolidone

Data on this process was calculated based on literature. For one kg of this substance following inputs have been considered.

Inputs:

Hydrogen [Inorganic intermediate products]	Mass	0.09 kg
Formaldehyde (37%; methanal) [Organic intermediate products]	Mass	3.649 kg
Ethene (acetylene) [Organic intermediate products]	Mass	1.171 kg
Ammonia [Inorganic intermediate products]	Mass	0.383 kg

A9.3.24 Production of Polyethylene Glycol

Data for this chemical was calculated from literature. For 1 kg of polyethylene glycol following inputs and outputs have been considered.

Inputs:

Ethene (ethylene) [Organic intermediate products]	Mass	0.908 kg
Oxygen [Renewable resources]	Mass	0.364 kg
Power [Power, electrical energy]	Energy (calorific value)	2 MJ

Outputs

Polyethylene glycol [Plastics]	Mass	1 kg
Carbon dioxide [Inorganic emissions into air]	Mass	0.4087 kg
VOC (unspecified) [Organic emissions into air (group VOC)]	Mass	0.03 kg

APPENDIX 10

EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE ENVIRONMENTAL IMPACT CATEGORY OF GLOBAL WARMING

EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE ENVIRONMENTAL IMPACT CATEGORY OF GLOBAL WARMING

CHEMICAL	FACTOR
Carbon dioxide [Inorganic emissions into air]	1
Trichloromethane (chloroform) [Halogenated organic emissions into air]	5
Dichloromethane (methylene chloride) [Halogenated organic emissions into air]	9
Methane [Organic emissions into air (group VOC)]	21
R 123 (dichlorotrifluoroethane) [Halogenated organic emissions into air]	93
Trichloroethane [Halogenated organic emissions into air]	110
R 152a (difluoroethane) [Halogenated organic emissions into air]	140
R 225ca (dichloropentafluoropropane) [Halogenated organic emissions into air]	170
R 143 (trifluoroethane) [Halogenated organic emissions into air]	290
Laughing gas (dinitrogen monoxide) [Inorganic emissions into air]	310
R 124 (chlorotetrafluoroethane) [Halogenated organic emissions into air]	480
R 225cb (dichloropentafluoropentane) [Halogenated organic emissions into air]	530
R 32 (trifluoroethane) [Halogenated organic emissions into air]	580
R 245ca (pentafluoropropane) [Halogenated organic emissions into air]	610
R 141b (dichloro-1-fluoroethane) [Halogenated organic emissions into air]	630
R 134a (tetrafluoroethane) [Halogenated organic emissions into air]	1300
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions into air]	1400
R 43-10 (decafluoropentane) [Halogenated organic emissions into air]	1600
R 22 (chlorodifluoromethane) [Halogenated organic emissions into air]	1700
R 142b (chlorodifluoroethane) [Halogenated organic emissions into air]	2000
R 125 (pentafluoroethane) [Halogenated organic emissions into air]	3200
R 227ea (septifluoropropane) [Halogenated organic emissions into air]	3300
R 11 (trichlorofluoromethane) [Halogenated organic emissions into air]	4000
R 143a (trifluoroethane) [Halogenated organic emissions into air]	4400
R 113 (trichlorofluoroethane) [Halogenated organic emissions into air]	5000
Halone (I301) [Halogenated organic emissions into air]	5600
Tetrafluoromethane [Halogenated organic emissions into air]	6300
R 236fa (hexafluoropropane) [Halogenated organic emissions into air]	8000
R 12 (dichlorodifluoromethane) [Halogenated organic emissions into air]	8500
R 114 (dichlorotetrafluoroethane) [Halogenated organic emissions into air]	9300
R 115 (chloropentafluoroethane) [Halogenated organic emissions into air]	9300
R 13 (chlorotrifluoromethane) [Halogenated organic emissions into air]	11700
R 23 (trifluoromethane) [Halogenated organic emissions into air]	12100
R 116 (hexafluoroethane) [Halogenated organic emissions into air]	12500
Sulphur hexafluoride [Inorganic emissions into air]	23900

Reference:

GaBi 3: Software and Database for Life Cycle Engineering, IKP University of Stuttgart and PE Product Engineering GmbH, April 1998.

APPENDIX 11

EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE ENVIRONMENTAL IMPACT CATEGORY OF OZONE DEPLETION

EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE ENVIRONMENTAL IMPACT CATEGORY OF OZONE DEPLETION

CHEMICAL	FACTOR
R 22 (chlorodifluoromethane) [Halogenated organic emissions into air]	0.05
R 142b (chlorodifluoroethane) [Halogenated organic emissions into air]	0.065
R 141b (dichloro-1-fluoroethane) [Halogenated organic emissions into air]	0.1
R 115 (chloropentafluoroethane) [Halogenated organic emissions into air]	0.6
Methyl bromide [Halogenated organic emissions into air]	0.7
Methyl bromide [Halogenated organic emissions into water]	0.7
R 113 (trichlorofluoroethane) [Halogenated organic emissions into air]	0.8
R 114 (dichlorotetrafluoroethane) [Halogenated organic emissions into air]	1
R 13 (chlorotrifluoromethane) [Halogenated organic emissions into air]	1
R 12 (dichlorodifluoromethane) [Halogenated organic emissions into air]	1
R 11 (trichlorfluormethane) [Halogenated organic emissions into air]	1
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions into air]	1.1
Trichloroethane [Halogenated organic emissions into air]	1.1
Halone (1211) [Halogenated organic emissions into air]	3
Halone (2404) [Halogenated organic emissions into air]	6
Halone (1301) [Halogenated organic emissions into air]	10

Reference:

GaBi 3: Software and Database for Life Cycle Engineering, IKP University of Stuttgart and PE Product Engineering GmbH, April 1998.

APPENDIX 12

EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE ENVIRONMENTAL IMPACT CATEGORY OF ACIDIFICATION

EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE ENVIRONMENTAL IMPACT CATEGORY OF ACIDIFICATION

CHEMICAL	FACTOR
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions into air]	0.19
Hydrogen bromine (hydrobromic acid) [Inorganic emissions into air]	0.396
Nitric acid [Inorganic emissions into air]	0.508
Chloromethane (methyl chloride) [Halogenated organic emissions into water]	0.634
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions into air]	0.634
Chloromethane (methyl chloride) [Halogenated organic emissions into air]	0.634
Sulphuric acid [Inorganic emissions into air]	0.653
Nitrogen oxides [Inorganic emissions into air]	0.7
Trichloroethene (isomers) [Halogenated organic emissions into water]	0.72
Trichloroethene (isomers) [Halogenated organic emissions into air]	0.72
Trichloroethane [Halogenated organic emissions into air]	0.72
Dichloromethane (methylene chloride) [Halogenated organic emissions into air]	0.744
Trichloromethane (chloroform) [Halogenated organic emissions into water]	0.803
Trichloromethane (chloroform) [Halogenated organic emissions into air]	0.803
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions into air]	0.83
Hydrogen chloride [Inorganic emissions into air]	0.88
Sulphur dioxide [Inorganic emissions into air]	1
Hydrogen cyanide (prussic acid) [Inorganic emissions into air]	1.185
Hydrogen fluoride [Inorganic emissions into air]	1.6
Hydrogen sulfide [Inorganic emissions into air]	1.88
Ammonia [Inorganic emissions into air]	1.88

Reference:

GaBi 3: Software and Database for Life Cycle Engineering, IKP University of Stuttgart and PE Product Engineering GmbH, April 1998.

APPENDIX 13

EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE ENVIRONMENTAL IMPACT CATEGORY OF EUTROPHICATION

EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE ENVIRONMENTAL IMPACT CATEGORY OF EUTROPHICATION

CHEMICAL	FACTOR
Chemical oxygen demand (COD) [Analytical values emissions into water]	0.022
Nitrogen oxides [Inorganic emissions into air]	0.13
Ammonium / ammonia [Inorganic emissions into water]	0.33
Ammonia [Inorganic emissions into air]	0.33
Nitrate [Inorganic emissions into water]	0.42
Ammonium nitrate [Inorganic emissions into air]	0.8
Phosphate [Inorganic emissions into water]	1

Reference:

GaBi 3: Software and Database for Life Cycle Engineering, IKP University of Stuttgart and PE Product Engineering GmbH, April 1998.

APPENDIX 14

EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE ENVIRONMENTAL IMPACT CATEGORY OF PHOTOCHEMICAL OXIDANT FORMATION (SMOG FORMATION)

**EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE
ENVIRONMENTAL IMPACT CATEGORY OF
PHOTOCHEMICAL OXIDANT FORMATION**

CHEMICAL	FACTOR
Trichloroethane [Halogenated organic emissions into air]	0.001
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions into air]	0.005
Methane [Organic emissions into air (group VOC)]	0.007
Dichloromethane (methylene chloride) [Halogenated organic emissions into air]	0.01
Dichloroethane (isomers) [Group NMVOC into air]	0.021
Polychlorinated dibenzo-p-furans (2,3,7,8 - TCDD) [Halogenated organic emissions into air]	0.021
Tetrafluoromethane [Halogenated organic emissions into air]	0.021
R 115 (chloropentafluoroethane) [Halogenated organic emissions into air]	0.021
Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [Halogenated organic emissions into air]	0.021
R 113 (trichlorofluoroethane) [Halogenated organic emissions into air]	0.021
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions into air]	0.021
Chlorobenzene [Halogenated organic emissions into air]	0.021
Trichloromethane (chloroform) [Halogenated organic emissions into air]	0.021
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions into air]	0.021
R 22 (chlorodifluoromethane) [Halogenated organic emissions into air]	0.021
R 141b (dichloro-1-fluoroethane) [Halogenated organic emissions into air]	0.021
Dichloroethane [Halogenated organic emissions into air]	0.021
Polychlorinated biphenyls (PCB; unspecified) [Halogenated organic emissions into air]	0.021
R 142b (chlorodifluoroethane) [Halogenated organic emissions into air]	0.021
R 134a (tetrafluoroethane) [Halogenated organic emissions into air]	0.021
R 13 (chlorotrifluoromethane) [Halogenated organic emissions into air]	0.021
R 125 (pentafluoroethane) [Halogenated organic emissions into air]	0.021
R 12 (dichlorodifluoromethane) [Halogenated organic emissions into air]	0.021
R 116 (hexafluoroethane) [Halogenated organic emissions into air]	0.021
R 114 (dichlorotetrafluoroethane) [Halogenated organic emissions into air]	0.021
Chloromethane (methyl chloride) [Halogenated organic emissions into air]	0.021
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [Halogenated organic emissions into air]	0.021
R 11 (trichlorofluoromethane) [Halogenated organic emissions into air]	0.021
Methyl acetate [Group NMVOC into air]	0.025
Carbon monoxide [Inorganic emissions into air]	0.036
Trichloroethene (isomers) [Halogenated organic emissions into air]	0.066
Ethane [Group NMVOC into air]	0.082
Methanol [Group NMVOC into air]	0.123
Ethine (acetylene) [Group NMVOC into air]	0.168
Acetone (dimethylcetone) [Group NMVOC into air]	0.178
Benzene [Group NMVOC into air]	0.189
Propanol (iso-propanol; isopropanol) [Group NMVOC into air]	0.196
Furfuryl alcohol [Group NMVOC into air]	0.196
Butylene glycol (butane diol) [Group NMVOC into air]	0.196
Cyclohexanol [Group NMVOC into air]	0.196
Propylene glycol [Group NMVOC into air]	0.196
Propyl acetate [Group NMVOC into air]	0.215
Ethylene acetate (ethyl acetate) [Group NMVOC into air]	0.218
Ethanol (ethyl alcohol) [Group NMVOC into air]	0.268
Butylacetate [Group NMVOC into air]	0.323
Pentane (n-pentane) [Group NMVOC into air]	0.408
Butane (n-butane) [Group NMVOC into air]	0.41
NMVOC (unspecified) [Group NMVOC into air]	0.416
Propane [Group NMVOC into air]	0.42
Formaldehyde (methanal) [Group NMVOC into air]	0.421
Hexane (isomers) [Group NMVOC into air]	0.421

Octane [Group NMVOC into air]	0.493
Heptane (isomers) [Group NMVOC into air]	0.529
Toluene (methyl benzene) [Group NMVOC into air]	0.563
Butyraldehyde (n-; iso-butanal) [Group NMVOC into air]	0.568
Ethyl benzene [Group NMVOC into air]	0.593
Styrene [Group NMVOC into air]	0.761
Cyclohexanone [Group NMVOC into air]	0.761
Cyclohexane (hexahydro benzene) [Group NMVOC into air]	0.761
Cyclopentanone [Group NMVOC into air]	0.761
Phenol (hydroxy benzene) [Group NMVOC into air]	0.761
Benzo{a}pyrene [Group PAH into air]	0.761
Xylene (dimethyl benzene) [Group NMVOC into air]	0.777
Butadiene [Group NMVOC into air]	0.906
Butene (vinyl acetylene) [Group NMVOC into air]	0.959
Ethene (ethylene) [Group NMVOC into air]	1
Propene (propylene) [Group NMVOC into air]	1.03

Reference:

GaBi 3: Software and Database for Life Cycle Engineering, IKP University of Stuttgart and PE Product Engineering GmbH, April 1998.

APPENDIX 15

EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE ENVIRONMENTAL IMPACT CATEGORY OF TOXICITY (HUMAN AND ECOTOXICITY)

EQUIVALENCY (OR CHARACTERISATION) FACTORS FOR THE ENVIRONMENTAL IMPACT CATEGORY OF TOXICITY

1. HUMAN TOXICITY

CHEMICAL	FACTOR
Toluene (methyl benzene) [Group NMVOC into air]	0.036
Toluene (methyl benzene) [Hydrocarbons into water]	0.053
Zinc [Heavy metals into water]	0.058
Trichloroethene (isomers) [Halogenated organic emissions into air]	0.075
Trichloroethene (isomers) [Halogenated organic emissions into water]	0.11
Sulphur dioxide [Inorganic emissions into air]	0.16
Nitrogen oxides [Inorganic emissions into air]	0.26
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [Halogenated organic emissions into air]	0.34
Chlorobenzene [Halogenated organic emissions into air]	0.34
Formaldehyde (methanal) [Hydrocarbons into water]	0.35
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [Halogenated organic emissions into water]	0.39
Chlorobenzene [Halogenated organic emissions into water]	0.39
Formaldehyde (methanal) [Group NMVOC into air]	0.42
Zinc [Heavy metals into air]	0.63
Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [Halogenated organic emissions into water]	0.74
Ammonia [Inorganic emissions into soil]	0.83
Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [Halogenated organic emissions into air]	1
Copper [Heavy metals into water]	1.1
Methyl bromide [Halogenated organic emissions into water]	1.9
Phenol (hydroxy benzene) [Group NMVOC into air]	2.2
Butadiene [Group NMVOC into air]	2.8
Polycyclic aromatic hydrocarbons (unspecified) [Organic emissions into soil]	6.3
Benzene [Organic emissions into soil]	6.3
Chromium (unspecified) [Heavy metals into water]	9.3
Chromium +III [Heavy metals into water]	9.3
Dichloromethane (methylene chloride) [Halogenated organic emissions into air]	11
Zinc [Heavy metals into soil]	12
Dichloromethane (methylene chloride) [Halogenated organic emissions into water]	12
Ammonium / ammonia [Inorganic emissions into water]	14
Ammonia [Inorganic emissions into air]	16
Vanadium [Heavy metals into water]	19
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Hydrocarbons into water]	22
Benzene [Hydrocarbons into water]	22
Benzene [Group NMVOC into air]	29
Copper [Heavy metals into soil]	30
Cobalt [Heavy metals into water]	31
Trichloromethane (chloroform) [Halogenated organic emissions into air]	32
Trichloromethane (chloroform) [Halogenated organic emissions into water]	32
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions into air]	35
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions into water]	37
Arsenic [Heavy metals into water]	51
Nickel [Heavy metals into water]	63
Dichloroethane [Halogenated organic emissions into air]	69
Dichloroethane [Halogenated organic emissions into water]	69
Acrylonitrile [Hydrocarbons into water]	120
Cadmium [Heavy metals into water]	130
Vanadium [Heavy metals into soil]	160
Lead [Heavy metals into water]	260
Chromium +III [Heavy metals into soil]	340
Lead [Heavy metals into soil]	350
Copper [Heavy metals into air]	350

Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions into water]	480
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions into air]	550
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions into water]	550
Arsenic [Heavy metals into soil]	670
Nickel [Heavy metals into soil]	800
Trichloroethane [Halogenated organic emissions into air]	1200
Cobalt [Heavy metals into soil]	1500
Benzo {a}pyrene [Hydrocarbons into water]	1700
Acrylonitrile [Group NMVOC into air]	2100
Benzo {a}pyrene [Group PAH into air]	3700
Vanadium [Heavy metals into air]	4900
Cobalt [Heavy metals into air]	7600
Benzo {a}pyrene [Organic emissions into soil]	8300
Nickel [Heavy metals into air]	9800
Mercury [Heavy metals into water]	18000
Cadmium [Heavy metals into soil]	20000
Cadmium [Heavy metals into air]	23000
Mercury [Heavy metals into air]	29000
Mercury [Heavy metals into soil]	29000
Arsenic [Heavy metals into air]	42000
Lead [Heavy metals into air]	67000
Chromium +IV [Heavy metals into water]	67000
Polychlorinated biphenyls (PCB; unspecified) [Halogenated organic emissions into water]	1.4E5
Polychlorinated biphenyls (PCB; unspecified) [Halogenated organic emissions into air]	2.4E5
Monochloroaniline [Halogenated organic emissions into water]	3.8E5
Chromium (unspecified) [Heavy metals into air]	4.9E5
Chromium +III [Heavy metals into air]	4.9E5
Chromium +IV [Heavy metals into soil]	2.5E6
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - PCDD) [Halogenated organic emissions into water]	3.2E9
Chromium +IV [Heavy metals into air]	3.5E9

2. TERRESTRIAL ECOTOXICITY

CHEMICAL	FACTOR
Cobalt [Heavy metals into water]	2E-7
Lead [Heavy metals into water]	2E-7
Arsenic [Heavy metals into water]	9.7E-6
Copper [Heavy metals into water]	1E-5
Chromium +IV [Heavy metals into water]	1.1E-5
Chromium +III [Heavy metals into water]	1.1E-5
Chromium (unspecified) [Heavy metals into water]	1.1E-5
Zinc [Heavy metals into water]	2.5E-5
Nickel [Heavy metals into water]	3.1E-5
Vanadium [Heavy metals into water]	3.4E-5
Monochloroaniline [Halogenated organic emissions into water]	0.00038
Toluene (methyl benzene) [Hydrocarbons into water]	0.022
Trichloroethene (isomers) [Halogenated organic emissions into water]	0.024
Cadmium [Heavy metals into water]	0.025
Trichloroethene (isomers) [Halogenated organic emissions into air]	0.025
Toluene (methyl benzene) [Group NMVOC into air]	0.035
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Hydrocarbons into water]	0.039
Benzene [Hydrocarbons into water]	0.039
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions into water]	0.044
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions into air]	0.045
Benzene [Group NMVOC into air]	0.063
Dichloromethane (methylene chloride) [Halogenated organic emissions into water]	0.078

Dichloromethane (methylene chloride) [Halogenated organic emissions into air]	0.078
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions into water]	0.21
Trichloroethane [Halogenated organic emissions into air]	2
Formaldehyde (methanal) [Hydrocarbons into water]	2.5
Dichloroethane [Halogenated organic emissions into water]	4.2
Dichloroethane [Halogenated organic emissions into air]	4.2
Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [Halogenated organic emissions into water]	5.1
Trichloromethane (chloroform) [Halogenated organic emissions into air]	5.2
Trichloromethane (chloroform) [Halogenated organic emissions into water]	5.2
Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [Halogenated organic emissions into air]	8.5
Polycyclic aromatic hydrocarbons (unspecified) [Organic emissions into soil]	39
Benzene [Organic emissions into soil]	39
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions into water]	110
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions into air]	110
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [Halogenated organic emissions into water]	120
Chlorobenzene [Halogenated organic emissions into air]	120
Chlorobenzene [Halogenated organic emissions into water]	120
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [Halogenated organic emissions into air]	120
Acrylonitrile [Hydrocarbons into water]	280
Acrylonitrile [Group NMVOC into air]	480
Methyl bromide [Halogenated organic emissions into water]	1700
Butadiene [Group NMVOC into air]	2600
Formaldehyde (methanal) [Group NMVOC into air]	2600
Lead [Heavy metals into air]	11000
Phenol (hydroxy benzene) [Group NMVOC into air]	11000
Cobalt [Heavy metals into air]	17000
Lead [Heavy metals into soil]	29000
Cobalt [Heavy metals into soil]	45000
Arsenic [Heavy metals into air]	72000
Benzo {a} pyrene [Hydrocarbons into water]	80998
Nickel [Heavy metals into air]	1.9E5
Arsenic [Heavy metals into soil]	2E5
Chromium +IV [Heavy metals into air]	2.2E5
Chromium (unspecified) [Heavy metals into air]	2.2E5
Chromium +III [Heavy metals into air]	2.2E5
Vanadium [Heavy metals into air]	4.5E5
Nickel [Heavy metals into soil]	5.2E5
Chromium +IV [Heavy metals into soil]	6E5
Chromium +III [Heavy metals into soil]	6E5
Zinc [Heavy metals into air]	6.6E5
Copper [Heavy metals into air]	9.1E5
Vanadium [Heavy metals into soil]	1.2E6
Zinc [Heavy metals into soil]	1.8E6
Copper [Heavy metals into soil]	2.4E6
Mercury [Heavy metals into water]	8.2E6
Mercury [Heavy metals into air]	1.3E7
Mercury [Heavy metals into soil]	1.7E7
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - PCDD) [Halogenated organic emissions into water]	2.9E7
Benzo {a} pyrene [Group PAH into air]	6.4E7
Polychlorinated biphenyls (PCB; unspecified) [Halogenated organic emissions into water]	6.8E7
Cadmium [Heavy metals into air]	1.3E8
Benzo {a} pyrene [Organic emissions into soil]	1.7E8
Polychlorinated biphenyls (PCB; unspecified) [Halogenated organic emissions into air]	1.9E8
Cadmium [Heavy metals into soil]	3.4E8

3. AQUATIC ECOTOXICITY

CHEMICAL	FACTOR
Chromium +IV [Heavy metals into soil]	1.4E-9
Chromium +III [Heavy metals into soil]	1.4E-9
Lead [Heavy metals into soil]	1.8E-9
Copper [Heavy metals into soil]	1.4E-8
Arsenic [Heavy metals into soil]	3E-8
Zinc [Heavy metals into soil]	3.9E-8
Cobalt [Heavy metals into soil]	6E-8
Vanadium [Heavy metals into soil]	8.2E-8
Nickel [Heavy metals into soil]	5.8E-7
Cadmium [Heavy metals into soil]	3.9E-6
Trichloroethene (isomers) [Halogenated organic emissions into air]	7E-5
Toluene (methyl benzene) [Group NMVOC into air]	9.7E-5
Polycyclic aromatic hydrocarbons (unspecified) [Organic emissions into soil]	0.00022
Benzene [Organic emissions into soil]	0.00022
Dichloromethane (methylene chloride) [Halogenated organic emissions into air]	0.00044
Benzene [Group NMVOC into air]	0.0013
Trichloroethane [Halogenated organic emissions into air]	0.003
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions into air]	0.0031
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions into air]	0.0033
Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [Halogenated organic emissions into air]	0.011
Dichloroethane [Halogenated organic emissions into air]	0.011
Chlorobenzene [Halogenated organic emissions into air]	0.014
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [Halogenated organic emissions into air]	0.014
Trichloromethane (chloroform) [Halogenated organic emissions into air]	0.02
Dichloromethane (methylene chloride) [Halogenated organic emissions into water]	0.021
Trichloroethene (isomers) [Halogenated organic emissions into water]	0.16
Toluene (methyl benzene) [Hydrocarbons into water]	0.33
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions into water]	0.35
Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions into water]	0.46
Dichloroethane [Halogenated organic emissions into water]	0.57
Trichloromethane (chloroform) [Halogenated organic emissions into water]	0.7
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Hydrocarbons into water]	1
Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [Halogenated organic emissions into water]	1
Benzene [Hydrocarbons into water]	1
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions into water]	1.1
Lead [Heavy metals into air]	1.2
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [Halogenated organic emissions into water]	1.6
Chlorobenzene [Halogenated organic emissions into water]	1.6
Chromium (unspecified) [Heavy metals into air]	2.5
Chromium +IV [Heavy metals into air]	2.5
Chromium +III [Heavy metals into air]	2.5
Cobalt [Heavy metals into air]	2.6
Zinc [Heavy metals into air]	2.6
Copper [Heavy metals into air]	2.9
Benzo {a} pyrene [Organic emissions into soil]	4.5
Acrylonitrile [Group NMVOC into air]	4.9
Butadiene [Group NMVOC into air]	5.3
Arsenic [Heavy metals into air]	5.6
Formaldehyde (methanal) [Group NMVOC into air]	6.1
Vanadium [Heavy metals into air]	11
Monochloroaniline [Halogenated organic emissions into water]	25
Acrylonitrile [Hydrocarbons into water]	39
Phenol (hydroxy benzene) [Group NMVOC into air]	39
Lead [Heavy metals into water]	40

Nickel [Heavy metals into air]	80
Chromium +IV [Heavy metals into water]	84
Chromium +III [Heavy metals into water]	84
Chromium (unspecified) [Heavy metals into water]	84
Zinc [Heavy metals into water]	86
Cobalt [Heavy metals into water]	88
Copper [Heavy metals into water]	96
Cadmium [Heavy metals into air]	130
Methyl bromide [Halogenated organic emissions into water]	140
Formaldehyde (methanal) [Hydrocarbons into water]	160
Arsenic [Heavy metals into water]	190
Benzo {a} pyrene [Group PAH into air]	320
Vanadium [Heavy metals into water]	380
Nickel [Heavy metals into water]	2700
Cadmium [Heavy metals into water]	4500
Benzo {a} pyrene [Hydrocarbons into water]	10000
Mercury [Heavy metals into air]	16000
Mercury [Heavy metals into soil]	16000
Polychlorinated biphenyls (PCB; unspecified) [Halogenated organic emissions into air]	49000
Mercury [Heavy metals into water]	1.3E5
Polychlorinated biphenyls (PCB; unspecified) [Halogenated organic emissions into water]	3.2E5
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - PCDD) [Halogenated organic emissions into water]	1.5E8

Reference:

GaBi 3: Software and Database for Life Cycle Engineering, IKP University of Stuttgart and PE Product Engineering GmbH, April 1998.

APPENDIX 16

**ELECTRICITY CONSUMPTION AT WIGGINS
WATERWORKS**

ELECTRICITY DATA – WIGGINS WW.

Substation B (low voltage) supplies electricity to:

Chemical House
Sludge Plant
Wash Water Recovery
Homogenisation
Pulsators MCC (multi control center)
Compressors for Pulsators
Preozonation TDU (thermal distruction unit)
Express Plant (PEF)
Workshop
PAC Plant
Res Outlets
Pre and Intermediate Chlorination

1. Electrical Devices in the Chemical House

Panel A:

- | | |
|-----------------------------|------------|
| 1. Poly Eletro Standby | |
| 2. Poly Eletro Stirrer no.1 | |
| 3. Poly Eletro Stirrer no.2 | |
| 4. Poly Eletro Dosing no.1 | |
| 5. Bentonite Stirrer no.1 | |
| 6. Bentonite Stirrer no. 2 | |
| 7. Bentonite Pump no.1 | |
| 8. Soda Ash Stirrer no. 1 | } NOT USED |
| 9. Soda Ash Stirrer no. 2 | |
| 10. Soda Ash Stirrer no. 3 | |
| 11. Saturator Lime | |
| 12. Alum Dosing Pump no.1 | |
| 13. Alum Dosing Pump no. 2 | |
| 14. Soda Ash Dosing no. 1 | |
| 15. Soda Ash Dosing no. 2 | |
| 16. Spare | |

Panel B:

Bentonite Stirrer no.3
Bentonite Pump no. 2
Poly Dosing Pump no. 1
Poly Dosing Pump no. 2
4 Spares – NOT USED

1. Electrical Devices in the Chemical House

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Bentonite Stirrer (*3)	5.2	400	1400	2.2	24	158.4
Lime Stirrer (*4)	5.2	400	1400	2.2	24	211.2
Dosing Pumps Bentonite (*2 - one on standby)	7.3	400	1400	3	24 (only 1)	72
Ch. Booster Pumps (*2)	8.6	400	1424	4	2	16
Poly Transport Pumps (*2)	2.15	400	1400	0.75	4	6
Lime Pumps (*2)	16.6	400	1435	7.5	24	360
Total						823.6

2. Electrical Devices in the Sludge Plant

1. Sand Trap Blower
2. Emergency Storage Drive (no. 1 and 2)
3. Thickend Sludge Mixers (no. 1, 2 and 3)
4. Thickened Sludge Pump (no. 1 and 2)
5. Sludge Storage Mixer (no. 1, 2 and 3)
6. Emergency Storage Pump
7. Feeder Compressor

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Gear Drive				1.5	24	36
Sand Trap Blower	10.6	400	1470	5.5	24	132
Emergency Storage D. (same as drive motor (DN))				0.18	24	4.32
Thickened Sludge Mixer (*2)	23	400	1470	11	24	528
Thickened Sludge Mixer (*1)	6.9	400	1400	3	24	72
Thickened Sludge Pumps (*2)	1.1	400	1450	5.5	24	264
Sludge Storage Mixer	20.9	400	1470	11	24	264
Emergency Storage Pump	68.6	400	1475	37	12	444
Feeder Compressor	43.5	400	1460	22	24	528
Total						2272.3

3. Electrical Devices for Wash Water Recovery

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Sand Trap Paddle	3.5	400	1405	1.5	8	12
Transfer Pumps (*4)	15.8	400	1450	7.5	4-5 each	150
Pumps (*3)	30	400	1450	15	24 all 3	1080
Total						1242

4. Electrical Devices for Homogenisation

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Mixers (*2) on the top	23	400	1400	11	24	528
Pumps (*4)	11	400	1450	5.5	24 (only 1)	132
Total						660

5. Pulsators

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Pulsators (*4)	21.0 / 12.1	360 / 660	2900 Hz	11	24	1056
Sample Pumps (*8) Clarifiers	5.1	400	1450	0.55	24 (4 of the 8)	52.8
Total						1108

6. Compressors

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Compressors (*2)	23.2	400	1455	11	24 (1 of the 2)	264

8. Sample Pumps

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Filtered Water	4	220	1500	0.55	24	13.2
Res Out (*2)	5.1	220	1430	0.55	24	26.4
Sample Pumps (*4) At the head of works	5.1	400	1450	0.55	24 (2 of the 4)	26.4
Total						66

9. Preozonation TDU

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Static Mixer	38.5	380	1465	18.5	24	444
Compressors (*2)	3.7	380	1420	1.5	24 (only 1)	36
Foam Pumps (*2)	1	380	2800	0.37	24 (only 1)	8.88
Destructor Fans (*2)	41	380	2935	22	24	1056
Total						1610.9

10. **PAC Plant** (the plant operates only about 12 days per year or 1 day/month or 0,8 h/day)

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Dosing Pumps (*2)	7.3	380	1400	3	0.8	2.4
Compressors (*2)	8.3	380	2870	4	0.8	3.2
Mixers (*3)	9.33	220	1400	2.2	0.8 (only 2)	3.52
Rotary Valves (*2)	1.65	380	1390	0.55	0.8 (only 1)	0.44
Bag Slitter (*2)	2.9/5	380/220	1420	1.1	0.8 (only 1)	0.88
Bag Slit Shaker (*5)	2.8	380	2800	1.1	0.8 (only 3)	2.64
Bag Conveyor (*2)	2.2	380	1430	0.75	0.8	1.2
Bag Extractor	1.5	380	1413	0.37	0.8	0.3
Bag Splitter Unit	904	380	1420	2.2	0.8	1.76
Total						16.34

11. Res Outlets

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Outlet Dom Water (*2)	11.6	380	2800	5.5	24 (only 1)	132
City Out CL2 Pumps (*2)	15.8	380	2445	7.5	24 (only 1)	180
Total						312

12. Sodium Hypo Pump Station (Pre- and Intermediate Chlorination)

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Pre Chlor Dosing Pump	3.8	380	1420	1.5	Not at all	N/A
Pre Chlor Dosing Pump	6.03	380	1710	1.75	Not at all	N/A
Inter Chlor Pulsator (*4)	0.4	380	1380	0.9	24 (only 2)	43.2
Past Chlor Dosing Pump (*2)	1.1	380	1410	0.37	24 (only 1)	8.88
Total						52.9

Total for substation B 8 428,04 kWh/day

Substation A supplies electricity to:

Filtration Plant (Machine Hall)
 NaOCl Plant
 Administration Building
 Yard Lighting (1 and 2)
 Small staff battery
 Ozone generators (1, 2 and 3)
 Intermediate Ozonation TDU
 Hi-Lift Pump Station

1. Machine Hall

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Air Drier / Compressor (*4)	3.7	380	1420	1.5	24 (only 1)	36
Upwash Pumps (*3)	60	380	1465	30	2.2 (only 2)	132
Site Water Pumps (*2)	43.2	380	1450	22	24 (only 1)	528
Lime Pumps (Saturate) (*2)	16.6	380	1435	7.5	24 (only 1)	180
Compressor (*2)	21.5	380	1455	11	24 (only 1)	264
Blower Motors (*2)	177	380	1430	90	1.6	288
Total						1428

2. Intermediate Ozonation TDU

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Destructor Fans (*2)	41	380	2935	22	24	1056
Foam Pumps (*2)	1	380	2800	0.37	24 (only 1)	8.88
Gen Cooling Pumps (*3)	14.2	380	1460	7.5	24 (only 2)	360
PSU Cooling Pumps (*3)	2.7	380	1385	1.1	24 (only 2)	52.8
PSU Circulating Pumps (*3)	2.65	380	2800	1.1	24 (only 2)	52.8
Total						1530.5

3. Post Clarifiers

Device	Amps	V	Rot/min	kW	Time (h)	Consump (kWh/day)
Pre Chlor Sample Pump (*4)	6	220	1425	0.55	24 (only 2)	26.4

4. Ozonators

There are three ozonators at Wiggins Waterworks, each of 50 kW capacity. Since the electricity consumed is not metered, it is assumed that one of the three will work 24 hours per day. This means that $50 \text{ kW} * 24 \text{ hrs} = 1200 \text{ kWh}$ per day.

Total for substation A 4 184.9 kWh/day.

Total for substation B 8 428,04 kWh/day

Grand Total 12 612.94 kWh/day