Environmental Life Cycle Considerations for Design-Related Decision Making in Minerals Processing

A thesis submitted to the

UNIVERSITY OF CAPE TOWN

in fulfilment of the requirements
for the Degree of

DOCTOR OF PHILOSOPHY

in the Department of Chemical Engineering

by

MARY STEWART
BSc (Chem Eng) (Wits)

September, 1999

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VOLUME 1

Thesis

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Executive Summary

The objective of this work is to inform environmental decision making in design for the environment in minerals processing. To this end an integrated decision hierarchy has been developed. This decision hierarchy incorporates technical, environmental and social considerations in the design process. Life Cycle Assessment (LCA) has been chosen as the metric whereby environmental considerations will be included in the decision making process. LCA information is augmented by information from the Environmental Impact Assessment (EIA) process in detailed design.

There are four themes in this thesis; Minerals Processing, Process Design, LCA and Decision Making. Considerations specific to process design in the minerals industry are highlighted. The use of LCA as a tool to assess the environmental performance of the minerals industry is discussed. LCA is then used to inform the decisions taken during process design.

The first development in this thesis is a methodology for flowsheet structuring and modelling. This methodology has been developed specifically for the evaluation of Life Cycle Inventories (LCIs). A number of "rules" for flowsheet structuring are presented. Essentially these rules define an acceptable level of aggregation for information in the flowsheet structure where "acceptable" is informed by the manner in which the LCIs are used in the LCA structure. There must be sufficient information detail available to support decisions made using the LCA information, at the same time the amount of information required is limited. The information sets required for modelling the structured flowsheets are defined. These information sets are discussed in the context of degrees of freedom and design variables. The equation set used to calculate LCIs from the flowsheets is presented.

An LCI for the South African minerals industry was developed on a sub-sectoral basis, *viz.*, gold, coal, base metals, platinum group metals, ferro-alloys and mineral sands. This inventory is unique in its coverage and comprehensiveness. The inventory has been verified by the industry in South Africa. The potential of these inventories to guide different decisions with different decision contexts was illustrated for the case of the South African minerals industry by way of a number of case studies.

Process design methodologies were reviewed. It was decided to base the development of design for the environment in minerals processing on a knowledge-based approach to process design, the so-called "Douglas design hierarchy" (Douglas, 1988). The reason for this is that the hierarchy is based on a flowsheeting approach to process design and thus information structure developed in this thesis could be integrated into the design hierarchy. Process synthesis and optimisation for improved environmental performance were also reviewed. It was found that, while existing methodologies are robust, they are deficient with respect to the formulation of environmental objective functions. Environmental impacts are usually aggregated into a single objective function, this requires a subjective judgement to be made as to the relative importance of the impacts. These judgements were either arbitrary or based on economic cost.

Decision analysis and decision structuring are discussed. This discussion includes a definition of decision contexts. Environmental decision making is shown to be a complex decision context. Multi-Criteria Decision Analysis (MCDA) is presented along with the mathematics of modelling complex problems. Methodologies for incorporating social values into such a complex problem structure are outlined.

The Douglas design hierarchy was extended to incorporate considerations specific to the minerals industry and its environmental performance. Including environmental considerations in the design hierarchy prompted the inclusion of a stage of decision making before initial design begins. These decisions address strategic issues. This extended hierarchy consists of a sequence of steps intended to guide decisions taken during process design. As each decision is taken, the solution space for the technologies under review becomes more constrained until the process is detailed completely. Environmental and economic objectives are included in the optimisation of the technology permutations. These objectives are informed by LCA structure. In order to guide decisions an audit trail from unit operation, through waste to impact is structured.

The tools of MCDA were used, together with a set of weights that represent social values, to inform the optimization of technology choice with respect to environmental and economic objectives. Deficiencies in the information available to design engineers were highlighted, these are with respect to:

- Information on the social values that will be used to judge the environmental performance of the project
- Information on the site-specific impacts associated with the proposed project.

This information is gathered during the EIA process. The EIA process is reviewed. However, it is not possible to conduct an EIA for a process that has not been specified. For this reason the earliest point of the design hierarchy at which it is possible to conduct an EIA was defined. In the design steps leading up to the EIA environmental and social considerations are informed by aggregated information. The design steps after the EIA are integrated into the EIA process. This divides the decision hierarchy into a further two stages.

The information structure developed forms the basis of a decision support structure for environmental decision making. This decision support structure is demonstrated within the context of process design for the minerals industry using two case studies - the design of a gold plant, and the design of a zinc refinery.

The three-stage integrated design hierarchy developed in this thesis is applicable to the minerals industry in its current form and can guide continuous improvement through innovative design. In applying this approach to environmental decision making the minerals industry will be better placed to meet their stated environmental objectives as part of their commitment to sustainability.

Acknowledgements

There are so many people who have helped and supported me in the development and writing of this thesis that to acknowledge them by name would be too much, and yet not enough. Instead I say thank you *en masse* to friends and family across the globe for all that they have done for me.

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Chamber of Mines of South Africa
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Department of Minerals and Energy
Department of National Health
Department of Environment Affairs
CSIR
Mintek
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University of the Witwatersrand
University of Durban
University of Cape Town

The important thing is not to stop questioning.
Albert Einstein (1879-1955)

This thesis is dedicated to the memory of Jean Paris Anstey in appreciation and with love.

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Variables

Functions

$V(z)$	value function
f_P	Profit objective function
f_{Ik}	Impact objective function for impact category k

Scalars

w	total number of chemical components in the inventory
p	total number of unit operations in the flowsheet
n	total number of components in the inventory, is equal to $w+2$ where the two additional “components” are energy and cost
y	total number of impact categories
l	total number of alternatives
q	total number of attributes
P	cumulative profit expressed in monetary units
L	cumulative loss expressed in monetary units
M	mass flow through the process expressed as weight per time period
C	income generated by selling the product less the total cost of producing the product expressed in monetary units
t	the time over which the process operates expressed in units of time
I_k	is the impact value for impact category k expressed in impact units
wf_k	weighting factor for impact category k
e'_k	the overall equivalency factor for impact category k which is a function of the flowsheet structure, expressed in impact units per mass unit
SI_k	impact score for impact category k
GI_k	global contribution to impact category k for the time period under consideration expressed in impact units
IR	impact ranking

Matrix Elements

x_i	mass ratios of the components in the stream
m_j	mass flow rate of the stream to unit operation *j*
$f_{j,i}$	mass flow of component i into unit operation *j*
r_j	fraction of the stream which reports to unit *j*, this is the stream split factor
a_k	alternatives in the MCDA set of alternatives
b_r	attributes in the MCDA attribute set
$c_{k,r}$	measure of how well alternative a_k meets attribute b_r
v_i	the score associated how well criterion i achieves attribute z_i
$g_{j,i}$	the impact associated with component *i* leaving unit operation *j*
$s_{j,k}$	the contribution of unit *j* to impact category *k*
u_k	total contribution of the process to impact category *k*
$h_{i,j}$	the mass flow of component *i* into unit operation *j*
$u_{j,i}$	the mass flow of unsaleable component *i* from unit operation *j*
$d_{i,k}$	contribution to impact category *k* per mass unit of input category *i*
$k_{j,k}$	contribution of the inputs to unit operation *j* to impact category *k*
$l_{j,k}$	the contribution of inputs to unit operation *j* to impact category *k*
q_k	total contribution of inputs to the process to impact category *k*
z_k	total contribution of the use of the products from the process to impact category *k*
$t_{j,k}$	total contribution of unit operation *j* to impact category *k*.
$av_{i,k}$	the value given to attribute i in the pair attribute i - attribute k
$aw_{i,k}$	the normalised weight applied to attribute i in the pair attribute i - attribute k

Vectors

$\underline{A}$	set of alternatives in MCDA
$\underline{B}$	set of all attributes in MCDA
$\underline{E}$	Equivalency vector, contains *y* components
$\underline{F}_j$	feed vector to unit operation *j*, contains *w* components
$\underline{F'}_j$	feed vector to unit operation *j*, contains *n* components
$\underline{I}_j$	vector of input to the unit operation *j*, both reagents and services, contains *w* components
$\underline{I'}_j$	vector of input to the unit operation *j*, both reagents and services, contains *n* components

O_j	vector of outputs from the unit operation *j*, these outputs could be in the form of saleable or non-saleable products, contains *w* components
O'_j	vector of outputs from the unit operation *j*, these outputs could be in the form of saleable or non-saleable products, contains *n* components
$\underline{\mathrm{P}}'_j$	saleable products from unit *j*, contain *n* components
$\underline{\mathrm{S}}_j$	the total impact vector associated with the wastes from unit operation *j*, contains *y* components
$\underline{\mathrm{U}}'_j$	unsaleable products from unit *j*, contain n components
$\underline{\mathrm{UI}}$	total waste impact vector for the process, contains *y* components
$\underline{\mathrm{D}}_i$	impact vectors associated with a single input component *i*, contains *y* components
$\underline{\mathrm{K}}_{i,j}$	impact vector associated with a single input component *i* into unit operation *j*, contains *y* components
$\underline{\mathrm{L}}_j$	impact vector associated with inputs to unit operation *j*, contains *w* components
$\underline{\mathrm{II}}$	total impact vector associated with inputs to the process, contains *y* components
$\underline{\mathrm{PI}}$	total impact vector associated with use of products from the process, contains *y* components
$\underline{\mathrm{TI}}$	total impact vector associated with the process, contains *y* components

Matrices

$\underline{\underline{\mathrm{I}}}$	matrix of inputs to the process, dimensions of *w* by *p*
$\underline{\underline{\mathrm{I}}}'$	matrix of inputs to the process, dimensions of *n* by *p*
$\underline{\underline{\mathrm{P}}}$	matrix of saleable products from the process, dimensions of *w* by *p*
$\underline{\underline{\mathrm{P}}}'$	matrix of saleable products from the process, dimensions of *n* by *p*
$\underline{\underline{\mathrm{U}}}$	matrix of unsaleable products from the process, dimensions of *w* by *p*
$\underline{\underline{\mathrm{U}}}'$	matrix of unsaleable products from the process, dimensions of *n* by *p*
$\underline{\underline{\mathrm{PT}}}$	performance table in MCDA
$\underline{\underline{\mathrm{E}}}'$	matrix of equivalency vectors which has dimensions *n* by *y*
$\underline{\underline{\mathrm{G}}}_j$	impact matrix for the impacts associated with the outputs unit operation *j*, has dimensions *n* by *y*
$\underline{\underline{\mathrm{UI}}}$	the total impact matrix associated with the unsaleable outputs, has dimensions *p* by *y*
$\underline{\underline{\mathrm{K}}}'_j$	impact associated with the inputs to unit operation *j*, has dimensions *y* by *n*
$\underline{\underline{\mathrm{II}}}$	total impact associated with the inputs, has dimension *p* by *y*

$\underline{\underline{PI}}$	total impact associated with product use, dimensions p by y
$\underline{\underline{TI}}$	total impact matrix for the process, dimensions p by y
$\underline{\underline{AV}}$	matrix containing values allocated to attributes in a relative evaluation exercise, dimensions y by y

Acronyms

AES	African Environmental Solutions, Pty Ltd, South Africa
ANC	African National Congress, political party, South Africa
AP	Acidification Potential
BATNEEC	Best Available Technology Not Entailing Excessive Cost
BOF	Basic Oxygen Furnace
BPEO	Best Practicable Environmental Option
BPEONEEC	Best Practicable Environmental Option Not Entailing Excessive Cost
CIP	Carbon in Pulp
CSIR	Council for Scientific and Industrial Research, research organisation, South Africa
CSS	Central Statistics Services, government department, South Africa
CTAM	Critical air mass
CTWM	Critical water mass
DEAT	Department of Environment Affairs and Tourism, government department, South Africa
DfE	Design for Environment
DME	Department of Minerals and Energy (changed from Department of Mineral and Energy Affairs in 1997), government department, South Africa
DMEA	Department of Mineral and Energy Affairs (changed to Department of Minerals and Energy in 1997), government department, South Africa
DNH	Department of National Health, government department, South Africa
DRI	Direct Reduction of Iron
DSS	Decision Support System
DWAF	Department of Water Affairs and Forestry, government department, South Africa
EIA	Environmental Impact Assessment
EMS	Environmental Management System
FRD	Foundation for Research and Development, research organisation, South Africa
GDP	Gross Domestic Product
GNU	Government of National Unity, first democratically elected government, South Africa
GWI	Global warming impact
HEN	Heat Exchange Network
ISO	International Standards Organisation
ISP	Imperial Smelting Process
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory

MCA	Minerals Council of Australia
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
MEN	Mass Exchange Network
mic	metals in concentration
MIPS	Material Intensity Per unit of Service
OBIA	Unilever Overall Business Impact Assessment
OECD	Organisation for Economic Co-operation and Development
POI	Photochemical oxidation impact (POI
RDP	Reconstruction and Development Programme, development policy, South Africa
ROM	Run of Mine ore
SEA	Strategic Environmental Assessment
SETAC	Society for Environmental Toxicology and Chemistry
SMD	Solid mass disposal
SME	Small and Medium sized Enterprises
SODI	Stratospheric Ozone Depletion Impact
UNEP	United Nations Environment Programme
upa	units per annum
US EPA	United States Environmental Protection Agency
WAR	Generalised Waste Reduction algorithm

1 Introduction

This thesis investigates the potential for Life Cycle Assessment (LCA) to inform environmental decision making practices for minerals processing and the design of minerals processes in South Africa. There are a number of reasons for choosing minerals processing. First of these is its economic and strategic significance. In 1996 the minerals industry contributed R30 billion to the GDP of the country (over 8%) and paid a tax bill of over R1 billion. The contribution of the industry to GDP had grown to R100 billion in 1999. Exports from the industry generate more than R50 billion a year which represents over 40% of exports for the country (DME, 1997). These figures alone demonstrate both the economic and strategic significance of the industry. In addition however, the mineral reserves of the country represent significant quantities of those available globally. South Africa has the largest known deposits of platinum, manganese and chrome ores and a majority of the known vanadium reserves. All major metals bar aluminium are represented in South African's reserves. (For complete values please see Appendices 2-3 through 2-9 of this report).

In spite of the significance of the industry, there is not much information available on the environmental performance of the industry. Two studies of waste generation in South Africa as a whole have been undertaken (FRD, 1993; CSIR, 1991). While the results of these studies demonstrated that the mining industry makes a significant contribution to the overall waste stream of the country, there is insufficient information detail contained therein to support strategic decisions in any way. These information sets are discussed in more detail in Section 2 of this thesis.

A further reason for choosing the minerals industry as a case study is the complexity of the environmental decisions to be made. [An environmental decision is any decision taken in which environmental information and objectives are included in the decision (Cowell, 1998).] The significant impacts associated with the minerals industry are, more often than not, experienced only after cessation of normal process operations. This marks the industry as decidedly different from the chemical processing industry where impacts are more immediate. The temporal and spatial dimensions of impacts associated with the minerals industry serve only to make environmental decision making within the industry even more complicated. Taking into account the time periods over which the impacts of the minerals industry are experienced, the making of "good" environmental decisions within the industry is imperative. (see the discussion below for a definition of a good decision).

Furthermore, as the trend in environmental management moves from management at site to a more global view of the management of the impacts associated with any process, its products and their disposal, attention will be focussed to a greater extent on minerals processing, which is the "cradle" of this "cradle-to-grave" accounting (Goodland, 1995). It is thus necessary to determine the environmental performance of the industry as robustly and accurately as possible.

As a result, more and more mining companies are developing environmental policies, implementing environmental management systems and striving to improve their performance. This is borne out by the increasing number of entries relating to environment to be found in company annual reports and other documentation. Selected examples of this follow:

> *Our Values*
> *-safety and health of all our people and safe guarding assets - trust and respect for all our employees - care for our environment - responsibility towards the community - wealth creation for all stakeholders - honesty in the conduct of our business*

Quote from the code of Ethics; Impala Platinum, Annual report, 1998.

> *Mining must be undertaken in an environmentally responsible fashion, with the management of environmental impacts of all mining activity built into mining plans* ab initio, *and where compatibility is achieved between wealth and job creation, on the one hand, and environmental conservation on the other.*

Keynote address at the Mining in Africa Conference: Dr JM Stewart, Mining Consultant, Chamber of Mines of South Africa, 1998.

> *Billiton acknowledges its responsibility to its people and the environments within which it operates, and is committed to managing safety, health and environmental issues effectively.*
> *...... Two ferrochrome plants have achieved ISO 14001 certification.*

Quote from Billiton Health Safety and Environment Policy, 1999.

> *The Corporation and the companies with which it is associated strive to create wealth and to contribute to sustainable development by operating their businesses with due regard for economic, social, cultural and environmental concerns..*
>
> Quote from Anglo American Environment Policy, 1999.

These quotes and extracts are not unique to the South African industry and are being echoed throughout the industry internationally. Notable environmental reports in the industry have been produced by Western Mining Company who, as industry leaders, presented their first environmental progress report in 1996, Placer Pacific, North Limited, Rio Tinto and BHP.

However, there is still little guidance on offer to the industry on how to achieve these aims. The information structure and decision support framework presented in this thesis demonstrates how it is possible to support environmental decision making within minerals processing. The application of this information structure to decision making in the minerals industry is demonstrated by a number of case studies within the South African Minerals Industry. Process design is then considered as the series of decisions which have the potential to determine the overall environmental impact of a process. For this reason the specific case of process design for the environment in minerals processing is investigated using the information structure developed.

However, quantifying environmental impact within the context of an industry analysis is not an elementary exercise. As a first step it is necessary to determine the environmental performance of a process in a transparent and objective manner. To this end, Life Cycle Assessment (LCA) has been selected as the methodology whereby the environmental impacts associated with a process can be evaluated.

By definition, LCA is intended to reflect the environmental performance of a service, process, or in its simplest form, a specific product. LCA can be thought of as a form of environmental systems analysis (Petrie and Clift, 1994). It is based on a rigorous flowsheeting approach to process modelling whereby the environmental impacts associated with resource consumption and waste generation are identified explicitly (Clift and Longley, 1995). It does this by preparing detailed waste inventories and resource consumption profiles for the process under investigation, and attempts, as far as possible, to link these inventories to recognised environmental problems in an objective manner (SETAC, 1993a).

There are four stages within LCA. The first deals with the definition of the system and its boundaries. In the LCA methodology the boundaries of a process are expanded beyond those defined by process engineers, whose terms of reference generally relate solely to manufacturing entities. The LCA system definition includes the impacts of resource extraction, the process itself, all intermediate use and re-use stages through to final disposal of the product (Clift and Longley, 1995; Welford and Gouldson, 1993; Wrisberg and Triebswetter, 1999). This expanded definition makes explicit provision for social interventions in the material chain outside of the manufacturing framework as it allows preferences or weights to be assigned to impact categories. In this way LCA recognises the oft-overlooked role of consumers in generating environmental burdens. LCA views manufacturing processes as an integral step in the provision of services valued by society (Boustead, 1993). The boundary defined within the LCA methodology is illustrated in Figure 1-1.

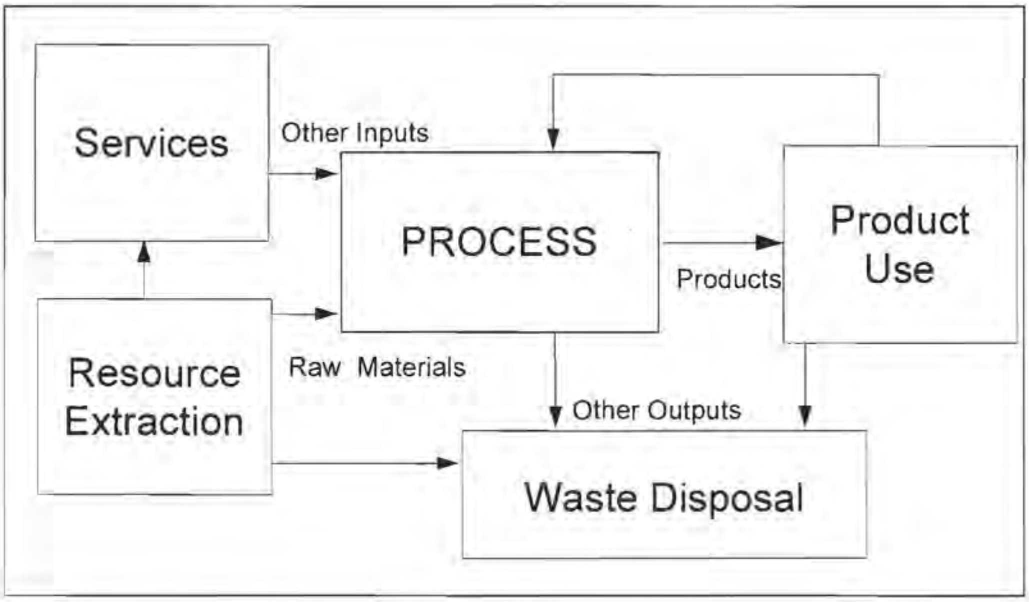


Figure 1-1 *Boundary Definition for LCA*

By expanding boundaries beyond the process itself, the goods and services provided can be placed in a global context. For example, a system under investigation could include an analysis of resource extraction economies coupled with resource consumption economies - say minerals beneficiation in a country like South Africa leading to manufacture of metal products in the service industries within OECD (Organisation for Economic Co-operation and Development) countries. In this way LCA can start to apportion the burden of environmental degradation to both the users of the service as well as to the manufacturing process or any of its sub-sets (Ayres and

Simonis, 1994; Ayres, 1989). This is not seen in any way to be a dilution of environmental responsibility. Rather, by making explicit the total impacts associated with the service, LCA provides a platform from which social intervention can be driven to effect improvement in environmental performance (Clift *et al*, 1994).

The second stage of LCA is the establishment of waste inventories. These require mass and energy balances for the service/process. This is a mainstream activity of chemical and process engineers during design. Typical LCA inventories involve large sets of data which are manipulated using customary process systems tools (Boustead, 1993; SETAC 1993b).

The third phase of LCA is the assessment stage where the relationship between waste generation and environmental impact is quantified. This is not a trivial exercise. It is not practicable to work with the many waste streams identified in a typical inventory. The LCA methodology has evolved to a point where wastes are associated with a greatly reduced number of recognised environmental problems (on a global scale). Typical of these are the thirteen categories highlighted at the Rio Earth Summit. An example of impact categories is included in Figure 1-2 below. This linking of wastes to the environmental impacts which they embody is objective and is carried out quantitatively within the current scientific understanding of the environmental effects of wastes.

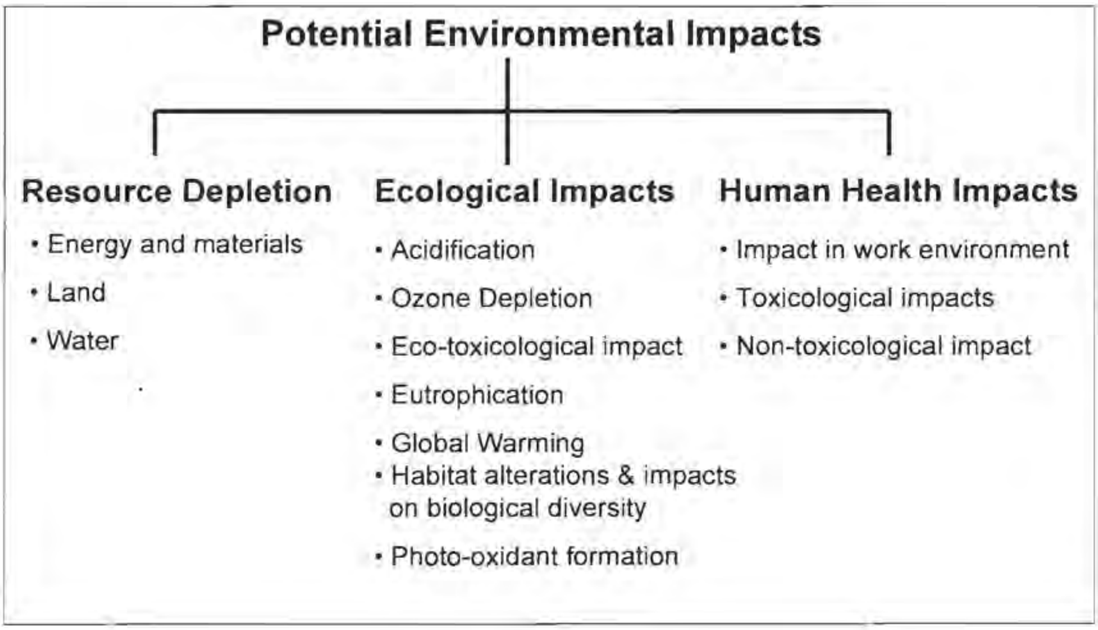


Figure 1-2 *Examples of Impact Categories (Meittinen and Hamalainen, 1997)*

How this information is interpreted requires some subjective judgement of the relative importance of these problems in a specific context. At this stage LCA does no more than link waste generation to environmental impacts in a way which allows some aggregation of information based on a specific set of priorities. This ranking exercise needs to be developed to allow for social values to be taken into consideration (de Oude, 1993; Meittinen and Hamalainen, 1997). In this thesis social values are included in the information structure as a series of values to be included in a multi-criteria decision analysis algorithm.

Up to this point LCA has been concerned with an assessment of a service/process as defined by the *status quo*. The most notable feature of LCA is the way in which it generates its environmental perspective based on rigorous process analysis. Critical impacts are identified as are the waste streams that give rise to them. Likewise the steps within the process which generate these wastes are highlighted. Consequently the fourth stage of LCA, improvement analysis, targets specific parts of the process where intervention will have the greatest effect. Improvements can thus be iterative as the benefits of process changes can be quantified and refined until the process delivers the best possible environmental performance within the constraints of the technology in place.

Significant research is underway at present on using Life Cycle Assessment as a decision support tool (Wrisberg and Triebswetter, 1999). This work is engaged in using LCA to structure information in such a manner as to allow environmental objectives to be explicitly factored into the decision making process. LCA is being used to structure environmental objectives and to ensure that sufficient information is available to the decision maker. LCA has been placed within the context of a "good" decision (Cowell, 1998), a good decision being one where the decision:

- fulfills the decision-taker's objective
- leads to actions agreed on by the constituency which responds to the decision
- is supported by the constituency which is affected by the outcomes of the decision

The role of LCA in supporting such a decision is defined in the work of Cowell (1998) and has been further expanded upon by the SETAC working group on LCA and decision making.

The significance of LCA in decision making and information structuring is further highlighted by its inclusion in the ISO 14000 series of standards. This series of standards applies to environmental management systems. The ISO 14001 decision cycle for business operational management is included in Figure 1-3 below. ISO 14041 through to ISO 14043 have been written in support of the review and planning stages of this decision cycle. These three standards are specifically centered on LCA and place LCA within the decision structure. ISO 14042 and 14043 are still in draft form at present.

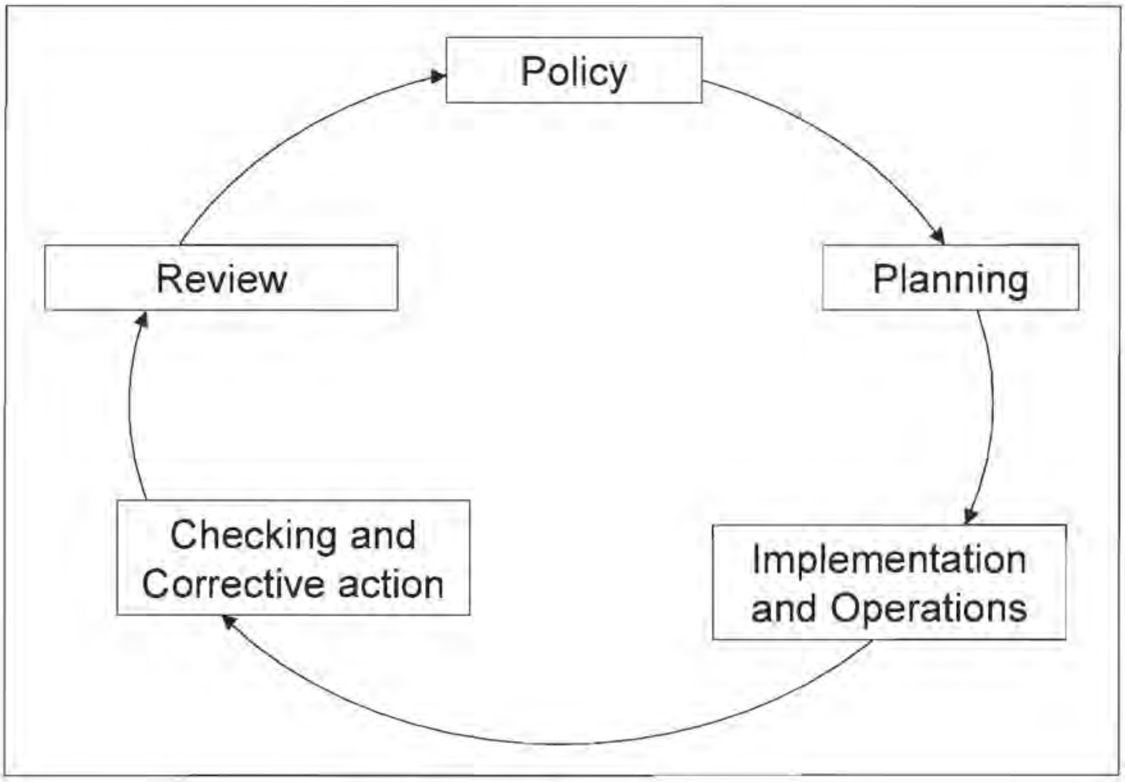


Figure 1-3 *Decision Cycle for Business Operational Decisions (ISO 14001)*

There are a number of factors which make a decision "hard" (Clemen, 1996; Rosenhead, 1989). These include:

- The complexity of the problem.
- The inherent uncertainty in the problem.
- A situation in which the decision maker is working towards a number of potentially competing objectives.
- Situations in which different perspectives lead to different conclusions.

These types of problems are also referred to as "messy" (Ackoff, 1979) - problems which are difficult to describe and even more difficult to model.

The tools of decision analysis have been developed both to structure and to enhance decision making in order to render a "good" decision. This requires an understanding of what constitutes a good decision as opposed to mere good luck. It is possible to make a decision as well-informed as possible and yet still end up with a poor outcome, i.e., one which does not meet the requirements of all groups involved in the decision process. Decision structuring will assist in ordering the available information in such as way as to ensure that all available information is used to make the *best-informed* decision. Decision structuring will also give a better understanding of the inter-connectedness of the elements within the decision which may give a different perspective on the potential outcomes. However, it must be acknowledged that the process of decision making is distinct from the outcome of the decision; no matter how well-informed a decision is it may still not be a good decision.

As important, structuring a problem will give a better understanding of the potential trade-offs and uncertainties inherent in the problem. This has the advantage of potentially eliminating decisions which have unlucky or misinformed outcomes. It is at this stage of the decision making cycle that the tools of multi-criteria decision analysis can be used to quantify the trade-offs to be made within the constraints of the model used.

Decision analysis should not however be seen as a font of wisdom. The results from an analysis should not be accepted blindly as the single possible best outcome for the problem. Rather, decision structuring should be seen as a methodology for guiding the potentially flawed thought processes natural to humans along a more effective decision path, as Bunn (1984) states: "Ultimately, it is of most value if the decision maker has actually learned something about the problem and his or her own decision-making attitude through the exercise."

An example of this within the context of the South African Minerals Industry is the Environmental Impact Assessment (EIA) carried out for the Saldhana Steel project that has been built on the West Coast of the country (AES, 1998). The social scoping exercise that formed part of the EIA introduced a complex set of stakeholder expectations into the decision making process. It can be argued that these expectations should have been brought on-board in the decision cycle earlier. This could have delivered a different decision, and potentially have addressed the social concerns of stakeholders in a more meaningful and less confrontational manner. The shortcomings in this EIA process highlighted a number of general deficiencies in the EIA decision making process with particular reference to the incorporation of social values (Campbell, 1997). As a result, the EIA process, as well as the attitude of companies embarking on EIAs in South Africa, has changed. A comparison of two minerals related EIAs that Saldhana Steel (CSIR, 1992) and the Billiton Zinc Plant proposed for the East Coast of the country (AES, 1998) will bear this assertion out.

Decision making is not easily interpreted as single algorithm. Rather it is an approach to organising information so that the outcome of the decision making process is as effective as possible within the context of the available information. Figure 1-4 overleaf illustrates the four elements inherent in structuring a decision, namely:

- Identifying the decision situation and the objectives
- Development of alternatives
- Modelling and solution of alternatives
- Determining the preferred alternative

These elements are discussed in more detail in Section 4 of this thesis.

Within this decision making structure it is necessary to adopt a structured approach to minimising the trade-offs to be made between the apparently competing objectives of industry - those of maximising the return of investment for the company while minimising environmental degradation. It is in this context that the tools of multi-criteria decision analysis (MCDA) are employed. They are used to structure the decision in such as manner as to make the decision making process transparent and robust. In using these tools, decisions are made which come closest to satisfying all parties involved. The application of these tools to Design for the Environment in minerals processing is explored in Section 5 of this thesis.

This thesis is presented in two parts. Volume 1 contains the main body of the thesis, whilst Volume 2 contains the Appendices. Volume 1 follows the development of the decision support framework. The first Section of work presented in Section 2 details an information structure that is based on flowsheet development and process analysis. This approach to information structuring was applied to the South African Minerals Industry to develop Life Cycle Inventories (LCIs) for the industry which are unique in their comprehensiveness and degree of verification. The applicability of this information structure and the inventory set to environmental decisions within the minerals processing industry in South Africa is demonstrated in this same Section. Accompanying Section 2 is Appendix 2 which contains comprehensive details of the models developed for the South African Minerals Industry.

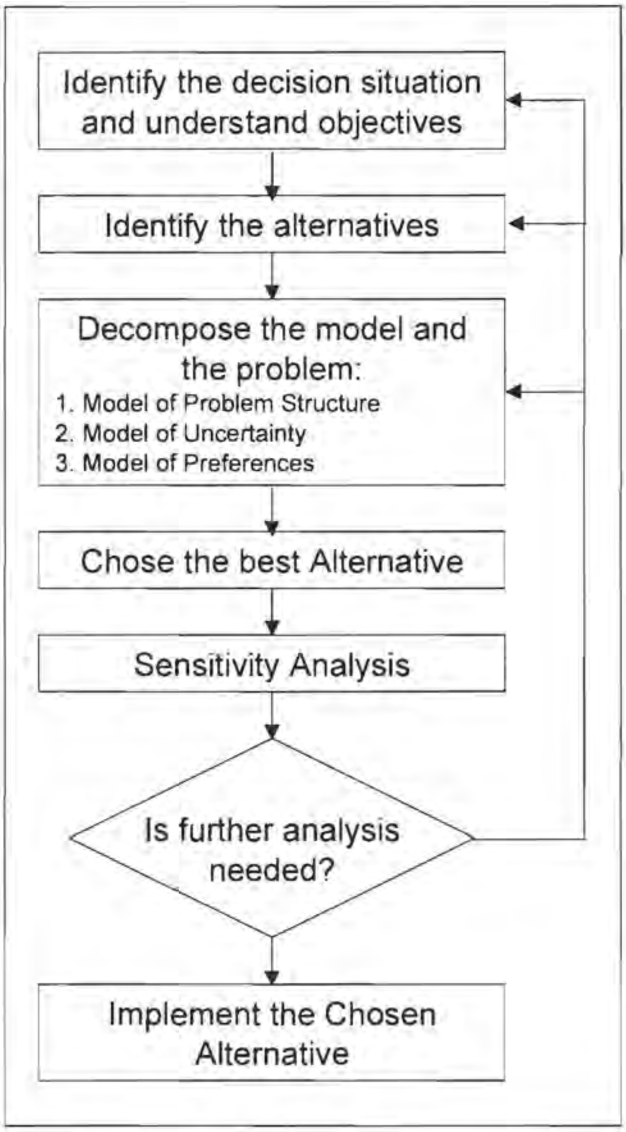


Figure 1-4 *Decision Analysis Process Flowchart (Clemen, 1996)*

Current applications of process design and synthesis for improved environmental performance are presented in Section 3. Deficiencies in these methodologies with respect to the formulation of environmental objectives are highlighted; as are deficiencies with respect to design in minerals processing. The main short coming in the formulation of environmental objectives is the degree to which environmental objectives are aggregated commonly. Section 4 of this thesis presents MCDA concepts and demonstrates how the structures inherent in LCA can be used in the formulation of environmental objectives that are not overly aggregated. The information structure presented in Section 2 is extended to inform the formulation of these environmental objectives.

An audit trail linking impacts to unit operations within the process is constructed. One of the main applications for this audit trail is to direct the improvement stage of LCA; the audit trail can be used to direct re-design and re-engineering for improved environmental performance.

In Section 5 a decision hierarchy for design of minerals processing plants is presented. The intention of this hierarchy is to guide the development of information sets (environmental, technical and social) during the design of a process. As such it is a decision support framework. The information sets are developed in accordance with the information structure presented in Sections 2 and 4. In Section 5 a case study of the design of a gold plant is used to demonstrate the applicability of the extended decision hierarchy to design for the environment in minerals processing. All details of the case study can be found in Appendix 5.

In Section 6, the hierarchy is extended further to a three stage design process which takes explicit account of stakeholder values in the selection of process and technology. It is at this point that the tools of MCDA are included in the decision support framework. This three-stage design process integrates process design, the project life cycle and EIA for the first time to ensure that information gathered in both of these decision processes is used to deliver the combination of technologies and site that minimise the trade-offs made between criteria, both economic and environmental. The three-stage design hierarchy is illustrated in the context of the design of a zinc refinery. Comprehensive results from the case study are included in Appendix 6. Conclusions and recommendations are included in Section 7.

Figure 1-5 overleaf has been included to illustrate the major linkages between Sections of this thesis.

There are four main themes that run through this thesis, they are:

- Minerals Processing
- Process Design
- Life Cycle Assessment
- Decision Making

Within these themes a number of considerations are included:

- Information structures
- Project Life Cycle

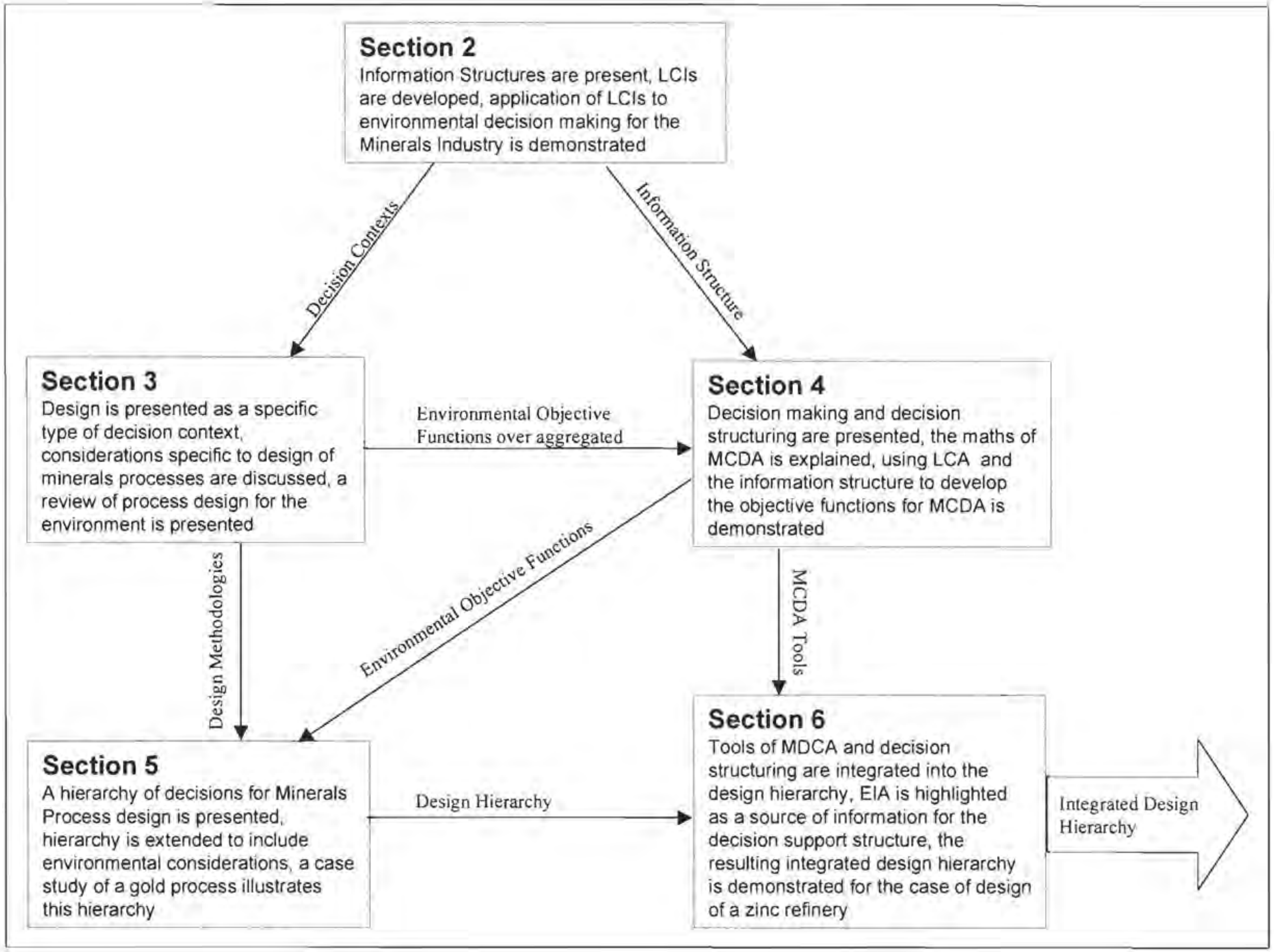
- Life Cycle Inventories
- Environmental Impact Assessment Process
- Impact Assessment
- Decision Contexts and Decision Structures
- Thermodynamics
- Uncertainty

Table 1-1 gives an indication of the Sections in this thesis that address these themes and considerations. Recommendations included in Section 7 are based on points in this table that have still to be addressed.

A CD accompanies this thesis. This CD contains all of the models developed for this thesis. There are three main directories on this disk, these directories relate to:

- Models of the South African Minerals Industry
- Case study on design of a gold plant
- Case study on design of a zinc refinery

Guidelines for installing and using these models are included after the Appendices in Volume 2.



Section 2
Information Structures are present, LCIs are developed, application of LCIs to environmental decision making for the Minerals Industry is demonstrated

Section 3
Design is presented as a specific type of decision context, considerations specific to design of minerals processes are discussed, a review of process design for the environment is presented

Section 4
Decision making and decision structuring are presented, the maths of MCDA is explained, using LCA and the information structure to develop the objective functions for MCDA is demonstrated

Section 5
A hierarchy of decisions for Minerals Process design is presented, hierarchy is extended to include environmental considerations, a case study of a gold process illustrates this hierarchy

Section 6
Tools of MDCA and decision structuring are integrated into the design hierarchy, EIA is highlighted as a source of information for the decision support structure, the resulting integrated design hierarchy is demonstrated for the case of design of a zinc refinery

Figure 1-5 *Thesis Structure*

]

Table 1-1 *Thesis Themes and Considerations*

		THEMES			
		Minerals Processing	Process Design	**Life Cycle Assessment and Life Cycle thinking**	**Decision Making**
CONSIDERATIONS	Information structures	~~Section :~~ Information sets and assumptions made to model the industry	~~Section~~ Assumptions governing Information and Information Structure required in Process design; Information Structure and Design Variables	~~Section 2:~~ Structuring LCIs; ~~Section 4:~~ Structuring Improvement Assessment Audit trail	~~Section 2:~~ Information structures for different decision contexts; ~~Section 4:~~ Information structures for formultation of Objective Functions
	Project Life Cycle	~~Section 3:~~ Placing minerals projects, and there effects in the context of the Project Life Cycle	Section 3: Places Process Design in the context of the Project Life Cycle		~~Section 3:~~ Effect of Decisions taken at different points in the Project Life Cycle
	Life Cycle Inventories	~~Section :~~ LCIs for the South African Minerals Industry	~~Section :~~ Developing LCIs for use in Process design	~~Section~~ Structuring LCIs	~~Section 2:~~ Using LCIs in decision making
	EIA process and outputs	~~Section :~~ Minerals processing EIA used to develop the case study	~~Section :~~ Integrating the EIA process and EIA outputs and Process Design	~~Section~~ Using EIA information in an LCA framework	~~Section 6:~~ Decision Making in EIAs, and integrating EIA information into Environmental Decision Making
	Impact Assessment	~~Section , 3, :~~ Temporal and Spatial effects of minerals wastes not well quantified	~~Section 3:~~ The potential impact associated with decisions taken in the design process	~~Section~~ LCA Impact Assessment	~~Section 4, 6:~~ Using Impact Assessment information in Decision Making
	Decision Contexts and Decision Structures	~~Section :~~ Different decision contexts in the Minerals Industry; ~~Section 3:~~ Effect of Environmental Decisions on process performance; ~~Section :~~ Environmental decision making in process design	~~Section :~~ Decision Contexts within Process Design	~~Section~~ LCIs in different decision contexts; ~~Section~~ Using LCA in a decision structure	~~Section 4:~~ Discussion of Decision contexts and Decision structuring
	Thermodynamics	~~Section 3, , :~~ Thermodynamic limits to process's environmental performance, relationship between thermodynamics and environmental impact	~~Section 3:~~ Considerations of Thermodynamic limits in Process Design		
	Uncertainty	~~Section :~~ Uncertainties associated with Minerals Processing flow sheet models		~~Section~~ Uncertainties introduced by using LCA equivalency factors	~~Section 5, 6:~~ Uncertainties associated with the tools of MCDA

2 Flowsheet and Information Structuring for Environmental Decision Making – Decision Making and Process Analysis

This section describes a generic approach to structuring information sets within the context of decision making as presented in the introduction to this thesis. Essentially there are three sets of information which inform the Design for Environment process:

- Technological
- Environmental
- Social

This section demonstrates that, even when limited information is available, it is possible to develop flowsheets (and from these mass balance models) which have value in supporting an environmental analysis of an industry or sub-sectors of an industry. These analyses then form the basis of decisions made within the industry.

A flowsheet for a process is essentially a diagram of the process within which unit operations are linked by process streams. The boundaries of each unit operation indicate a level of aggregation within the flowsheet – the wider the unit operation boundaries are drawn, the higher the likely level of aggregation of process-specific information. This section contains a description of how best to draw unit operation boundaries for environmental analysis, and thus support environmental decisions, i.e., to allow aggregation within the process while still ensuring that sufficient information detail is retained.

The information is structured using a systematic approach to flowsheet development. The flowsheets developed then form the basis for process models; the flowsheets are synthesised in order to determine a mass and energy balance for each. The collection of superfluous information, and the associated cost of information gathering, is avoided in this way. Essentially, the minimum amount of information on which to base a decision is collected. The minimum amount of information is that amount of information that is required to ensure mass balance closure for each unit operation. Thus there is a link between the boundaries of the unit operation and the minimum amount of information required. Thus, defining the decision to be taken by the decision maker will determine the unit operation boundaries, which in turn determine the level of aggregation of the techno-centric information set. This, in turn, determines the minimum amount of information to ensure mass balance closure.

This section contains a literature review of process synthesis tools as well as giving an indication of the current state of process synthesis for environmental analysis and decision making. It demonstrates that, in order for a process to be synthesised completely, significant information sets are required. However, these information sets are both costly and time-consuming to gather. Thus an abbreviated information set is desirable. A set of rules for establishing boundaries of unit operations and thus the minimum information set necessary to synthesise processes within the minerals industry is presented. Life Cycle Assessment is presented and discussed within the context of this information set. Together the tools of process synthesis and LCA are used to deliver a set structure for information.

This section details the development of the information required to support decisions on the environmental performance of minerals processing operations. The flowsheet structuring and parallel process synthesis exercises deliver mass and energy balance information for the industry. This information is augmented using the philosophies and structures of Life Cycle Assessment (LCA) to determine the potential environmental impact associated with the inputs to, and outputs from, the processes used in the industry. The result of this is an indication of the potential environmental impact associated with the industry being studied. This information structure is used to support environmental decisions. The South African Minerals Processing industry is used as an illustrative study of this approach. Examples of decisions are explored within the context of this industry.

2.1 *Information available and what it means*

This is essentially a literature review of the information that is available on the South African minerals industry – this is a review of its scope and meaning. This review is presented in order to establish a consistent scope for the structuring and analysis of information to support decision making. LCA has been introduced in the first section of this thesis as a consistent methodology for linking processes to their potential environmental impact. In order not to present biased or conflicting results, it is important for the information to be of consistent accuracy and of consistent scope. It is within this context that available information has been evaluated. A significant output of this research has been the mass and energy balances required by LCA. This is significant for South Africa as well as internationally for two reasons:

- As international markets move to a cradle-to-grave management of impacts it is necessary to make information available on the "cradle" of all processes, minerals processing. South Africa is a significant exporter of raw materials and thus information on the performance of the industry is a necessary first step in the down stream evaluation of processes, products and services.
- The mass and energy balances have been evaluated for the entire minerals processing industry using a consistent approach. This means that the information is comparable across the entire minerals industry. It is the first such inventory evaluated for an entire industry in South Africa, and, to the author's knowledge, unique for the minerals industry world-wide.

This inventory is significant because of it comprehensiveness. It has undergone peer review to ascertain its accuracy. It is an interactive inventory which can be easily changed to reflect changes in the industry.

There have been two attempts to quantify the waste stream generated by industries in South Africa, namely "The Situation of Waste Management and Pollution Control in South Africa" and "Hazardous Waste in South Africa", both of which were managed and edited by the Council for Scientific and Industrial Research (FRD, 1993; CSIR, 1991). These reports are discussed in some detail in Appendix 2-1 as they are the primary source of waste generation data for South Africa at present. However, the main aim of this section of this thesis is to evaluate the effects of different decision scenarios within the Minerals Industry – to analyse the different environmental impacts associated with different decisions. The information contained in both the FRD and the CSIR reports cannot be used in this context as is discussed below. Environmental decisions can relate to a number of different scenarios from different technology choices; to the exploitation of different reserves; to an evaluation of waste management practices within the industry.

Suffice it to say that, in this context, there are three major deficiencies in the FRD and CSIR information sets:

- The scope of the reports differs, making the information that they contain incomparable and inconsistent with the requirements of a Life Cycle Assessment.
- There is not uniformity in the aggregation of wastes into categories, again making comparison very difficult.

- The information is static; it is based on answers to questionnaires which are relative to a single year of operation for the industry. This makes interpreting the effect of changing technologies in place in the industry difficult if not impossible.

There is a wealth of information available on the technology in place in the minerals industry. This details both the nature of the technology and how it performs. A comprehensive listing of the types of information available as well as the relative value of this information is included in Appendix 2-2. Table 2-1 below contains a breakdown of the sources of information that were consulted in this current study. This table also includes an indication of the value of this information in structuring flow sheets for, and establishing models of, the mass and energy balances for the South African Minerals Industry.

Table 2-1 *Details of Sources of Information*

Source	Technical Information	Environmental Information
CSIR and DEA reports	None	Detailed within limits; not consistent; static
Journals	Excellent	Excellent
Books	Excellent	Excellent
Newspapers	Limited to new projects; current information	Interesting general information
Annual Reports	General	General; usually corporate environmental policy
Interviews and Plant Visits	Excellent	Excellent
Information Pamphlets	Varied; detailed within limits	Varied; usually simplified
EIAs	Detailed but fairly difficult to interpret	Detailed concerning impacts

2.2 Life Cycle Assessment

As was stated in the introduction of this section, the boundaries drawn around a unit operation will determine the level of aggregation of information required to evaluate a mass balance for that unit operation. It was recognised that, in order to use the models to support decisions it is necessary to ensure that there is sufficient (but not excessive) information detail within the process flowsheets and related models. In the Introduction to this thesis, Life Cycle Assessment is presented as a tool that is used to support environmental decision making. The flowsheets presented in this document have been developed to meet the specific requirements of LCA.

Life Cycle Assessment (LCA) has been selected as the metric whereby the environmental impact of a process will be determined. This has been discussed in the introduction to this document but is re-visited in this section in more detail. The main reasons for selecting LCA are listed here and discussed in detail in the text which follows:

- The extended boundary it uses, when compared with the boundary usually selected by the process engineer, ensures that the impacts associated with both process inputs and process outputs are included in the analysis (SETAC, 1993; Heijungs *et al*, 1992).
- It offers a structured approach to the aggregation of impacts (Jensen et al, 1997; SETAC, 1993; Heijungs *et al*, 1992).
- Extensive research into solving the allocation of impacts to products in multi-product systems has been carried out (Heijungs and Frischknecht, 1998; Huppes and Schneider, 1994)
- The mass and energy balances which represent the Life Cycle Inventories can be based on a model of the process under consideration. In other words the process is not regarded as a "black box" but as a dynamic system of inter-linked unit operations. This facilitates more transparent and directed interpretation of the impacts associated with the process or product under review.

2.2.1 LCA stage 1 – Boundary Definition

LCA expands the boundary of the system being analysed beyond that usually defined by process engineers. The boundary is expanded to give a comprehensive "cradle-to-grave" analysis of the process (SETAC, 1993; Heijungs *et al*, 1992). Thus the boundaries are drawn to include all upstream and downstream processes, and the environmental impacts associated with these. Figure 2-1 demonstrates the difference between the cradle-to-grave boundary of LCA and the boundary conventionally drawn by process engineers and designers.

Expanding the boundary to this extent allows a comparison of disparate systems because they are all being defined relative to a consistent basis – that of a cradle-to-grave analysis. This allows significantly different processes and products to be analysed with respect to the same basis.

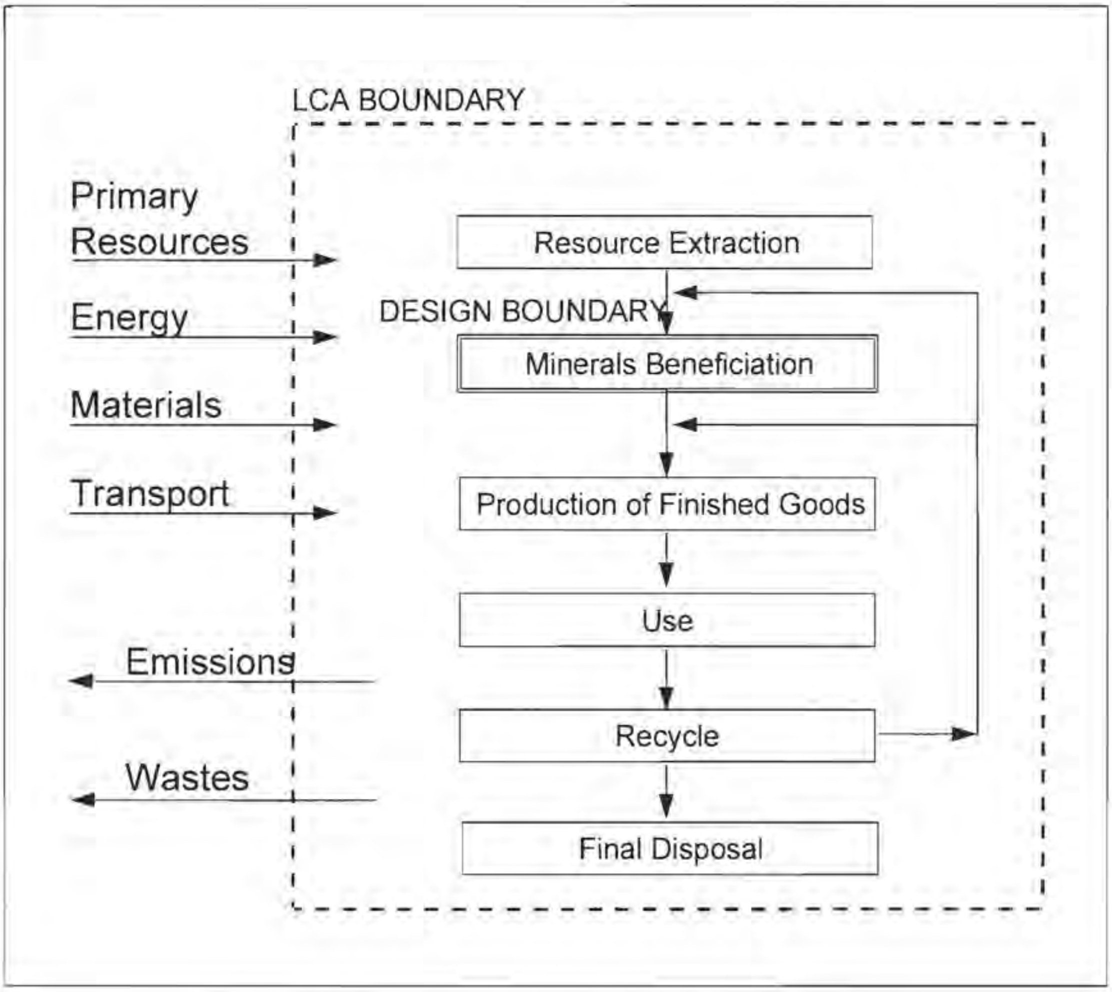


Figure 2-1 *Comparison of LCA and Process Design Boundaries*

2.2.2 LCA stage 2 – Inventory Analysis

The second stage of LCA is the evaluation of consistent mass and energy balances for the process (SETAC, 1993a; Heijungs *et al*, 1992b; Jonson, 1992). This is a mainstream activity of process engineers. The level of aggregation within these mass balances will, to a significant extent, determine the types of decisions that the information structure will be able to support. Thus, the unit operation boundaries within the mass balances must be defined carefully as already alluded to. The definition of unit operation boundaries is detailed in Section 2.3 below. While it is necessary to retain sufficient detail in the information set, aggregation at this point already starts to address the significant size of the techno-centric information set and reduce it to a more manageable size. The mass and energy balances are essentially the input-output inventory for the process, also called the Life Cycle Inventory (LCI).

2.2.3 LCA stage 3 – Impact Assessment

The third stage of LCA is that of impact assessment. In this stage the input and output inventories are linked quantitatively and qualitatively to the impacts which they embody. There are three stages in impact assessment:

- Classification
- Characterisation
- Valuation

Classification is a qualitative procedure in which the elements in the LCI are aggregated into a smaller number of impact categories. These impact categories are established before the LCI is calculated. Consensus has yet to be reached on a representative set of impact categories (Guinee *et al*, 1998; Jensen *et al*, 1997). Suffice it to say that care must be taken to ensure that the impact categories selected will support the required analysis as this aggregation, while again serving to decrease the size of the information set, also decreases the amount of information detail available to the decision maker. The linking of wastes to impacts is not necessarily on a one-to-one basis. One element in the LCI can contribute to more than one impact category. An example here is VOCs which contribute to both global warming and ozone depletion.

There are two common approached to classification; these are *problem-oriented* and *medium-oriented* approaches (Heijungs *et al*, 1992b). The problem-oriented approach aggregates impacts into their relative contributions to specific environmental problems. These are the categories which were included in Section 1 of this thesis and illustrated in Figure 1-2. The medium-oriented, or "critical volumes", approach aggregates the impacts according to the medium on which they have an effect, i.e., water, soil and air. This approach requires an indication of the total volume of the medium required to ensure no environmental damage is incurred.

In this thesis the problem-oriented approach has been adopted as this gives a better understanding of the impacts of the inventory. It represents impacts in a manner that society finds easier to interpret. In addition, the critical volumes approach required legal limits for potential emission quantities and concentrations. These are not readily available as yet.

In aggregating the impacts into categories there are a number of concepts which must be clarified. The elements in the LCI are also called stressors. These stressors have an impact on the environment, either direct or secondary, as is illustrated in Table 2-2 below.

Table 2-2 *Stressors and Impacts (SETAC, 1992)*

Inventory Item/ Stressor	Initial Impact	Secondary Impact
Acid Emission	Acid Rain	Acidified Lakes
Photochemical Oxidants	Smog	Health Impairment
Nutrients	Eutrophication	Bogs
Greenhouse gases	Global warming	Sea level rise
Ozone Depletors	Ozone depletion	Skin cancer
Toxic Chemicals	Toxic effect	Health Impairment
Solid Waste	Land Consumption	Habitat destruction
Chemicals to Groundwater	Groundwater impact	Health Impairment
Fossil Fuel use	Resource Depletion	

Characterisation is a quantitative process. It is based on current scientific understanding of the impact which different wastes have on the environment. In the case of the problem-oriented approach impacts are calculated relative to a reference substance. An example here is global warming. Carbon Dioxide is the reference substance for global warming. The real impact of CO_2 is used. All other global warming substances (such as CH_4 and VOCs) are evaluated on their global warming potential relative to that of CO_2. This relationship is called and equivalency factor, where the reference substance has an equivalency factor of 1 and all others are calculated relative to this. Comprehensive equations listings for all impact characterisation as well as the equivalency factors can be found in the work of SETAC (1992). Equivalency factors are continually being up-dated as better information becomes available (CML, 1998). As an illustration the equivalency factors for acidification are included in Table 2-3 below. In this case SO_2 is the reference substance.

Table 2-3 *Equivalency Factors for Acidification (SETAC, 1992)*

Substance	Description	Factor
SO_2	Sulphur Dioxide	1.00
NO	Nitrogen Monoxide	1.07
NO_2	Nitrogen Dioxide	0.70
NO_x	Nitrogen Oxides	0.70
NH_3	Ammonia	1.88
HCl	Hydrochloric Acid	0.88
HF	Hydrogen Fluoride	1.60

In this case the impact of the inventory elements is calculated as an acidification potential (AP) where AP is evaluated relative to the amount of SO_2 based on the potential amount of H^+ per mass unit relative to the potential amount of H^+ for SO_2. The effect score for acidification (expressed in mass per unit of time) is then AP times the emission to air (in mass per unit time).

Elements or stressors in the LCI can contribute to more than one impact category. This is illustrated in Figure 2-2 below.

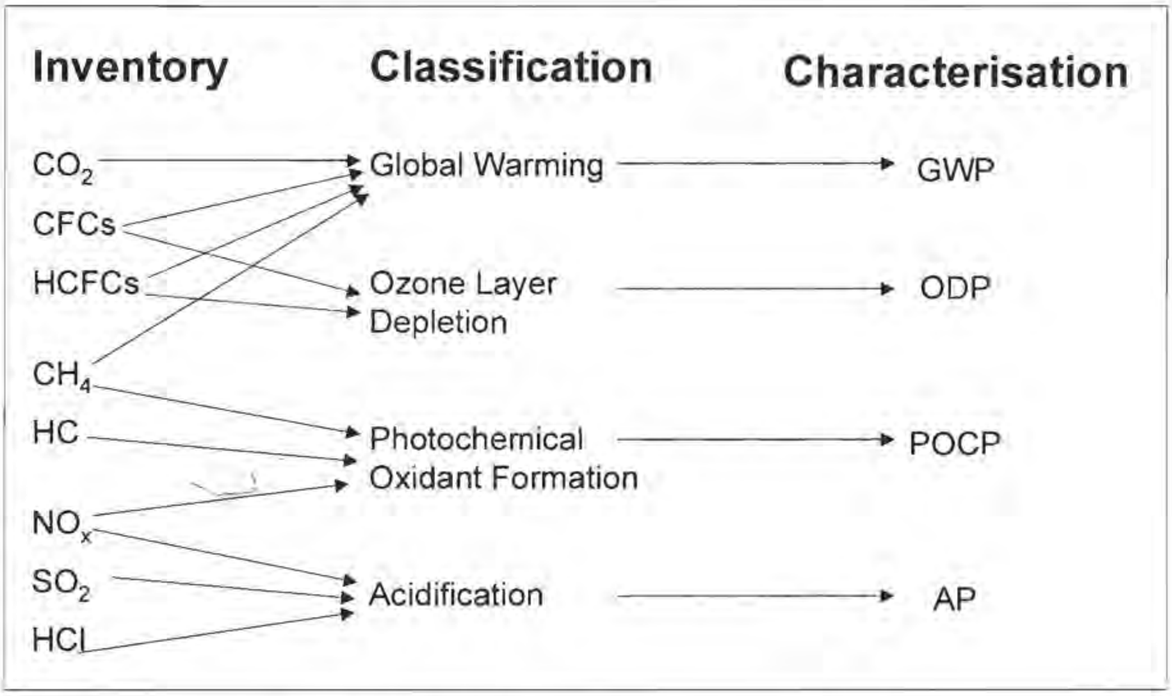


Figure 2-2 *Linking of Impacts to categories (PEMS, 1994)*

This figure illustrates both one-to-one and one-to-many relations between stressors and impacts.

The final result of characterisation is an indication of the total contribution of the process under analysis to each of the impact categories selected. This is also referred to as the environmental profile. While it is difficult to interpret these profiles in isolation, it is possible to compare the relative performance of two or more systems at this stage.

Valuation is the final step of Impact Assessment. This is the most subjective stage in LCA as it is here that relative weightings are assigned to the various impact categories. This allows the impacts to be compared relative to each other. Assigning weights to each of the impact categories makes it possible to calculate a single environmental number or index for the system under scrutiny. While this number may seem meaningless in isolation, when compared to the performance of other systems under the same set of weights. There are a number of techniques which can be used to interpret the weights or "preferences" placed on each impact category. These include Multi-attribute Utility Theory, Analytical Hierarchy and others. They are presented in Section 4 of this thesis and discussed in depth in the work of SETAC (1993) and Wrisberg and Triebswetter (1999). There is no consensus as yet on a possible set of globally or even regionally acceptable weighting values.

Figure 2-3 below has been included to illustrate the Impact Assessment Stage of LCA.

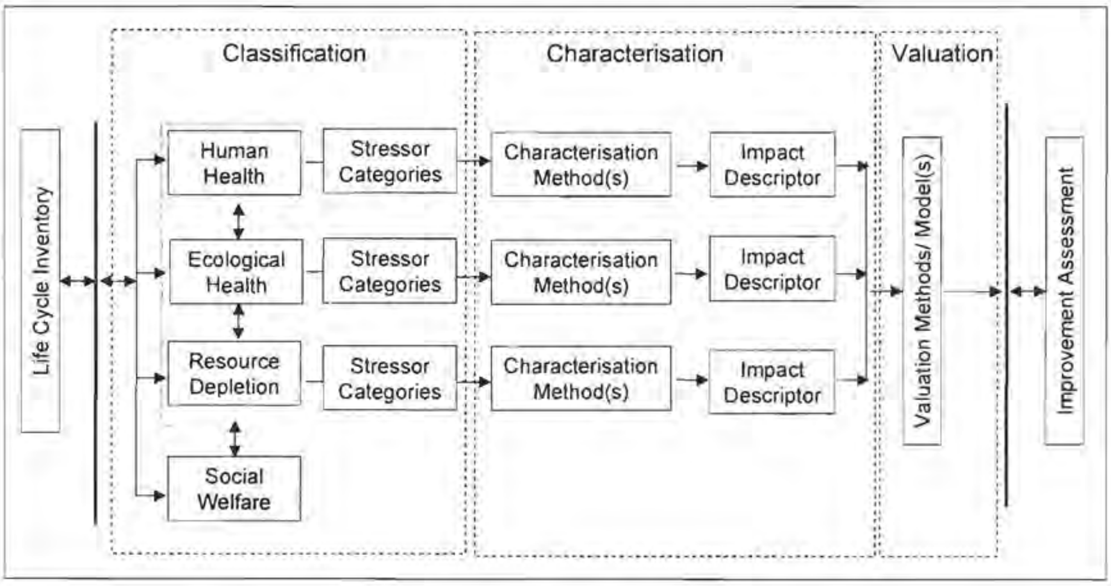


Figure 2-3 *Impact Assessment Stage of LCA (SETAC, 1992)*

2.2.4 LCA stage 4 – Improvement Analysis

The final stage in LCA is that of Improvement Analysis. It is at this point that options for improving the environmental performance of the system under consideration should be identified and evaluated. In order to evaluate the comparative environmental performance of technology options it is necessary to place a weighting or value on each of the impact categories. There is much contention in the debate about valuation within LCA as this is a normative exercise (Guinee *et al*, 1998; Heijungs, 1994). There is nothing inherently wrong about value judgements, indeed, all individuals have subjective values which they express either explicitly or implicitly (US EPA, 1995). A key objective of the valuation stage in LCA is to make these subjective value judgements transparent so that all stakeholders are aware of the value judgements made in reaching a decision.

There are a number of approaches to valuation, these include:

- Decision analysis using Multi-attribute Utility theory (SETAC, 1993)
- Analytical Hierarchy (US EPA, 1995)
- Modified Delphi Technique (developed by the Rand Corporation, based in Linstone and Turoff, 1974)
- Life Cycle Costing (White *et al*, 1996; Tellus Institute, 1992; OECD, 1989)

These are disparate tools and growth in their numbers is evidence of the fact that the debate on valuation in LCA is very much alive. The ISO 14000 (International Standards Organisation Environmental Management Code), which includes LCA within its framework, falls short of including the Valuation stage, preferring to aggregate Valuation and Improvement into a stage called Interpretation, included in draft codes 14 040 to 14 042 (ISO, 1997).

While the intended outcome of an LCA is to improve the environmental performance of the system, there is little or no guidance offered within the structure of LCA on how these options are supposed to be generated. One of the significant outcomes of the work presented in this thesis is an audit trail which links impacts to the unit operations responsible for generating them. In so doing the structure presented in Sections 2 and 3 of this document directs attention back into the process and highlights where the process should be re-engineered or re-designed in order to meet the requirements of the Improvement Analysis.

There are two components of the LCA process which deserve further mention. They are included in this discussion of Improvement Analysis as they can be used to inform decisions taken on how to improve the performance of the system under scrutiny.

2.2.4.1 Allocation

LCA was developed to compare the environmental performance of products (Keolian and Menerey, 1994; Jonson, 1992). In extending its use to the evaluation of processes a significant complication arose, that of the allocation of the impact of a process to products within a multi-product system. It is beyond the scope of this work to review in detail how impacts are allocated to products in a multi-product system. Significant work has been conducted on the topic and can be found in a number of references (Azapagic and Clift, 1999; Heijungs and Frischknecht, 1998; Azapagic, 1996; Huppes and Schneider, 1994; SETAC, 1993).

2.2.4.2 Normalisation

In the problem-oriented approach adopted in this work it is conventional to normalise the impact on the environment relative to the estimated global impact in that category. While this makes the interpretation of the environmental profile easier as it grounds it in reality, it must be recognised that this has the potential to bias the result being offered by the LCA. Different approaches to normalising the environmental profiles can be adopted and significant work has gone into identifying normalisation techniques which will have a significant result. An example in point here is the work of Clift (1998) who reports on an approach which extends a normalisation relative to the total contribution of the same category within a region within a certain period of time:

$$(\text{annual impact}) / (\text{total annual contribution})$$

to a form of double normalisation which includes a better understanding of the business giving rise to the impact:

$$\frac{[\text{impact / value of business}]}{[\text{total anthropogenic contribution / total global economic value}]}$$

Unilever Overall Business Impact Assessment (OBIA)

Figure 2-4 has been included to show the difference that normalising with respect to a social value (for example, job creation) has to normalising with respect to an economic value (value of sales). While this is a normalisation based on waste produced as opposed to impact, trends can be inferred from this information. This normalisation shows that, while some industries contribute significantly to the economy, their contribution with respect to a social value is not extraordinary. (The values used in drawing up this graph are included later in this section and detailed in full in Appendices 2-3 to 2-9. Figure 2-4 has been limited to available information, information was not available for the number of jobs in the ferro-alloys sub-sector.).

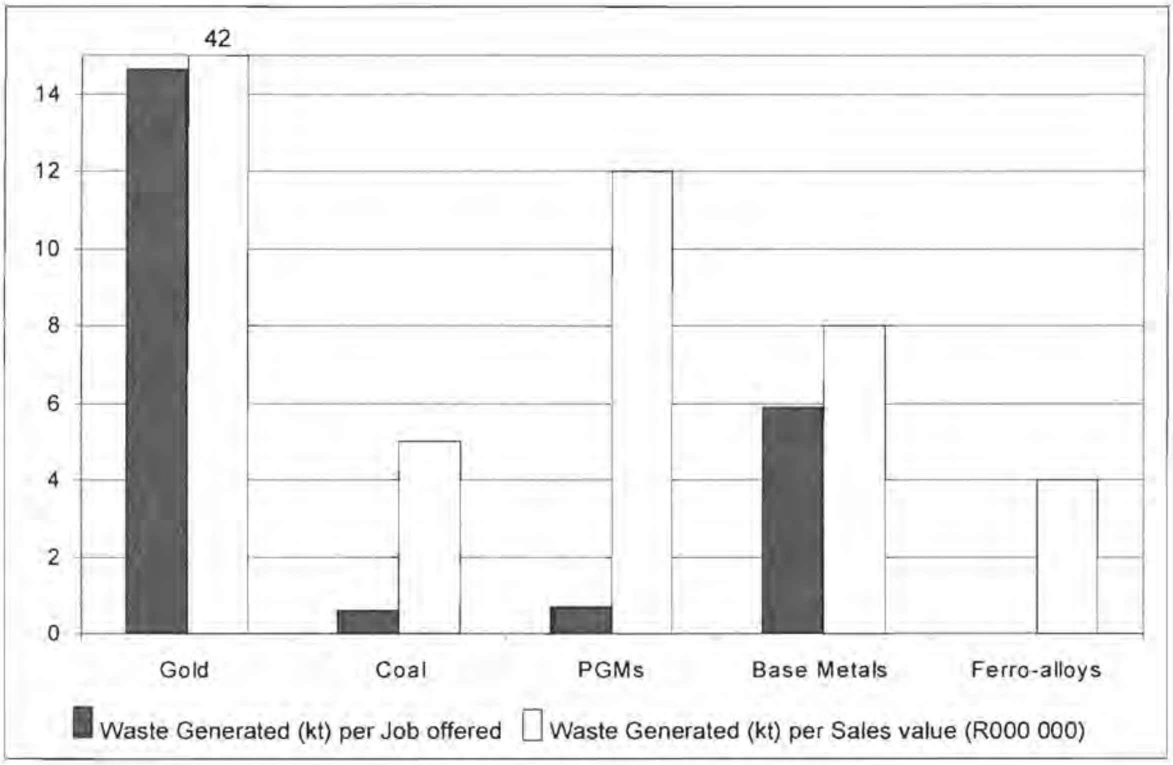


Figure 2-4 *Comparison of Normalisation techniques for selected sub-sectors in the South African Minerals Industry*

2.2.5 Existing LCA Tool-kits

LCA uses a cradle-to-grave boundary definition. It thus accounts for both inputs to and outputs from a system. In the context of process analysis there are three different elements here:

- Inputs to the process
- Products and Wastes from the process
- Downstream use, recycling and disposal of the Products

These can be defined to fall into the foreground or into the background of the system where the foreground includes the direct effects of the process and the background refers to impacts associated with resource provision, downstream use and disposal (Doig and Clift, 1995) There are two distinct groups here; namely, the inputs to the process and the downstream effects of the process; and the products and wastes from the process. The main difference between these two groups is that the former is essentially not manipulated by the system while the nature of the latter can change with changes in the process under analysis, i.e., production staff can exercise some degree of control over the products and wastes for a process and thus have some control over the environmental impact associated with these elements; while they have little, or no control over the environmental impact associated with the inputs to the process or the downstream use of the products. This is discussed in more depth later in this document.

However, when attempting to gather a complete information set to be used in calculating the environmental performance of a process, the inputs to the process as well as the downstream fate of products can pose a problem. For this reason a number of data bases have been developed which contain comprehensive information on the impacts associated with generic inputs to processes as well as generic downstream use and disposal. Examples of such databases are PEMS® (distributed by Pira International, 1996) and Simapro® (distributed by Pre', 1998). While these information sets make a significant contribution to decreasing the amount of information gathering which must be undertaken in completing an LCA, it must be recognised that they are generic and often reflect the environmental performance of the inputs/downstream processes in a specific region or country.

The information sets are usually sold in association with software which simplifies the evaluation of an LCA, i.e., once the mass and energy balances have been calculated they are entered into the software packages and the subsequent stages of LCA are handled by the software. The software packages all have very similar approaches, their merits being dependent on how comprehensive and accurate the databases they contain are.

A further information requirement needs to be discussed; that of the availability of equivalency factors. These have been evaluated for a significant variety of wastes and impacts. However, the information is not necessarily complete. There are significant deficiencies with respect to the analysis of minerals wastes. A system may require factors which are not available. Should this be the case a best estimate of the fate of the component in the environment must be made.

In summary, LCA can be used to develop a detailed environmental profile of a process, product or service. There are however, deficiencies in LCA, *viz:*

- There is no clear indication of how improvement should be directed back into the process in the improvement assessment stage. In other words the information structure within LCAs has been deficient in the past; there has been too much aggregation of plant specific information (the techno-centric information set).
- The impacts associated with solid wastes are generally quantified only in their contribution to land usage (see equivalency factors included in Appendix 5-1, PEMS, 1998). There is no attempt made to incorporate time or space dependant impacts, such as those associated with the generation of leachates from mine dumps. As such, this is a significant shortcoming and makes the use of LCA as an analysis tool within the minerals industry somewhat perfunctory.
- No indication of how an energy minimisation exercise can be carried out. The energy balance calculated is usually an inventory of energy required by the process.

The methodology presented in this section addresses the first of these short-comings. The second short-coming is extremely relevant to the minerals processing industry and is currently being researched (Petersen, 1998; Hansen, 1998). Research is also being conducted into how to apply LCA to energy requirements, using exergetic analyses of processes (Connelly and Koshland, 1997; Michaelis, 1995).

2.3 Information Management

The flowsheeting approach developed in this thesis is detailed in this section. A literature review describing the *status quo* of process synthesis and analysis for environmental decision support is included. Then the "rules" for determining the boundaries of unit operations are discussed with respect to their ability to retain the amount of information required when making an environmental decision; in other words will these boundaries obscure any important information?

The structure of an audit trail from unit operation to waste is described. The linearity/non-linearity of the flowsheets is evaluated. The flowsheet structure developed for information management to support the analysis of the environmental performance of processes and industries is then tested within the context of the case study (the South African Minerals Industry).

2.3.1 Literature review of process synthesis and analysis for environmental decision support

Although there has been a great deal of development in the field of process synthesis for improving the environmental performance of processes (see literature review in Section 3 of this thesis), this has concentrated on the design of new processes. There has been little development on process synthesis to facilitate the analysis of the environmental performance of technologies in place.

Two papers of note are those of Reuter *et al* (1995, 1996) which deal with the development of flowsheets for the clean production of zinc. This paper describes a methodology for the optimisation of zinc flowsheets based on technology that is currently in place in the zinc industry, i.e., there is no indication of how new or innovative technology applications would perform. Generalised flow diagrams are constructed for the technologies under consideration. These flowsheets are constructed using approximations of unit operations within the industry. Essentially a mass balance is calculated using only the input of reagents and raw materials into the processes. Values for reagent addition are industry averages. Stream splits are also used to control mass flow between unit operations.

The stream splits between the unit operations are then manipulated in order to obtain the flow sheet configuration which delivers the best economic performance. Thus stream splits (or split factors) are deemed by Reuter *et al* to be sufficient for modelling of minerals processes. Also, the complexity of the processes used in minerals processing is so great that split factors, as opposed to rigorous modelling, are often resorted to in industrial applications. Limitations on the memory available in the computer system used allowed synthesis of one element only – namely zinc. All other elements within the mass balance were aggregated into a single value.

Costs, both environmental and economic, were assigned to each unit operation. While this offers a different approach to other methods of optimisation where environmental limits are imposed on a system of equations – thereby constraining the potential solution space for the equation set – this approach is still not optimal because of the level of aggregation which it assigns to environmental impact. By allocating an environmental cost to a waste stream (essentially the cost of installing a further piece of equipment which will ensure that the process outflows meet legislated limits) a bias is placed on the out flow streams. To illustrate this consider two streams leaving a process; the first does not embody a significant environmental impact while the second one does. However, the cost of remediating the first is significant (for example a dilute aqueous stream), while the cost of remediating the second is low. Allocating a cost of remediation to a waste stream will bias the solution away from a technology that represents a lower environmental risk to one which has a higher risk. In this manner allocating environmental costs to out flow stream allows for aggregation of wastes into a single quantity which is, admittedly, readily comparable with economic information. However, the aggregation can often obscure potential environmental solutions by confining them to economic arguments.

Within the process presented by Reuter *et al* (1995) a mass balance is maintained over the entire system. The unit operations within the flow sheet are then combined to minimise cost. The optimal process flowsheet is the one which incurs the lowest total cost. The environmental cost for the flowsheet with the lowest economic cost is then presented. This environmental cost is essentially an add-on cost for the process. No indication of trade-offs between environmental impact and profit is offered. In addition there is no indication of which unit operations need to be re-designed to minimise the impact on the environment.

In their work of 1996, Reuter *et al* extend this approach to include a more comprehensive inventory of metals for the process under review (zinc refining). They also add complexity to the optimisation regime by incorporating the so-called "simulated annealing" algorithm into the model. These extensions of the model ensure that the solutions offered are more comprehensive with respect to materials includes, however, the observations regarding the inclusion of environmental impacts made above still hold.

A further review paper is that of Rossiter (1994) who evaluates process integration, or more intensive use of existing process plant, as opposed to end-of-pipe treatment, in developing flowsheets. This paper has a focus on particulate systems and thus is of value for the minerals industry. In this paper illustrations are drawn from the three main areas of process integration - pinch analysis, knowledge-based approaches and numerical optimisation. Inter-related methodologies for designing and revamping industrial processes are presented. A three-way trade-off is presented: capital cost / operating cost / environmental impact. Here environmental impact is aggregated into a single quantity by allocating weighting factors to impact categories and arriving at a single environmental index such as was described in the valuation stage of LCA.

Rossiter argues that an advantage of process integration is that it can be carried out using limited data sets, whereas process simulation requires complete data for the process. This is because process integration is conducted using assumptions governing specific unit operations while process simulations require large amounts of information (specifically thermodynamic information) so that they can model the processes in question accurately. Process synthesis and integration uses an abbreviated information set. This results in an answer which has a greater degree of inherent uncertainty. However, it is possible to calculate a solution without spending a great deal of time and money on gathering complex information. Further, Rossiter does not focus on the development of new technologies, rather on ensuring that existing process technologies are selected and interconnected in the most efficient order. In this respect an "efficient" process is defined with respect to capital and operating costs and environmental index.

The work of Cave and Edwards (1997) evaluates process selection by assessing the environmental hazard of the process. It does this by rating process routes according to two environment hazard indicators:

- Chronic toxicity - an indication of the operational environmental hazard associated with the process route selected.
- Plant hazard - an indication of the impact associated with a catastrophic failure at the plant.

These hazards relate to the wastes generated by the process only. All hazards are reduced to the effect of outputs of the process on a single species of fish, as it was argued that, ultimately, all impacts are manifested as a water impact. Should the indices selected be accepted as robust, this methodology can give a clear indication of the dominance of one suite of technologies over another and thus the approach can be used to develop flowsheets.

In their analysis of pollution reduction algorithms, Cabezas *et al* (1997) analyse environmental impact flows into and out of processes using the so-called WAR (Generalised Waste Reduction) algorithm. In this work they evaluate a rate of "flow" of impacts into, or out of a process. They state that these rates of flow are a function of the mass and energy flows into and out of the process, they are not, however, equivalent to mass and energy flows. No indication of how mass and energy flows are to be linked to impacts is given. Impact flows into the process are said to give an indication of the internal environmental efficiency of the process, i.e., how efficiently the processes uses the raw materials and reagents entering it. Impact flows out of the process give an indication of its external environmental efficiency or how significant the potential environmental impacts associated with streams leaving the process are.

These flows are normalised in three ways that can be used to aid environmental decision making:

- Total impact associated with non-products - units of potential environmental impact (as this is a flux it already has units of impact per time); this index is used when comparing different technologies on an absolute basis.
- Potential impact associated with the product - units of potential environmental impact per mass of product; this facilitates comparing technologies independent of the size of the process.
- Mass of non-products per mass of product - this gives an indication of the mass inefficiency of the process and again is useful in comparing technologies independent of the size of the process.

Although useful on a plant-wide basis, there is little indication of how the performance of single unit operations can be compared, as the impact categories are aggregated for the process as a whole before normalisation takes place. Increasing information detail will give a better indication of those unit operations which represent the greatest environmental impact.

A number of approaches to synthesising and comparing flowsheets for the support of environmental decisions have been reviewed in this section. These methodologies, while rigorous and quantitative, require further development in:

- Quantification of environmental impact, including an indication of whether these impacts are associated with inputs to or outputs from the process.
- A structured approach to aggregation of impacts.
- An analysis structure to facilitate the interpretation of the impact profiles/values calculated, i.e., there is often too much aggregation around environmental impact to the detriment of decision support with regards to process re-engineering and design.

2.3.2 Boundaries for flow sheet development

In order to address the perceived deficiencies within process synthesis and analysis for environmental decision support presented above, an approach to information structuring within flowsheet development has been developed. This structure has as its main aim retaining sufficient information detail to support environmental decisions, while keeping the information set required as small as possible. In the introduction to this thesis LCA was presented as an attractive basis for environmental decision making. LCA has specific information requirements. In addition, the deficiency within the fourth stage of LCA is addressed – that of improvement analysis – as sufficient information detail is retained to direct attention back into the process in order to guide re-engineering and re-design. The information structure is explored within the context of the South African Minerals Industry.

In this thesis it has been decided to limit the boundary of the LCA to a "cradle-to-gate" view. Figure 2-5 shows where LCA defines the boundaries of a process to lie, as well as the section of this which has been attributed to the South African minerals beneficiation industry. (For the purpose of comparison this figure also includes the classic chemical engineering process or design boundary). It can be seen as a "cradle-to-gate" view, as the processes have been modelled only to the point where products are available to the secondary manufacturing sector. It is argued that the inter-dependence between resource extraction/beneficiation and resource consumption industries as part of an integrated material chain management structure requires such a "cradle-to-gate" analysis as a necessary first step. Figure 2-6 details this boundary.

A generalised, as opposed to specific, approach to the modelling of the minerals beneficiation sector has been adopted, not only because it allows some simplification of the vast numbers of processes found within the South African minerals sector, but also in order to preserve company-specific confidentialities. The generalised approach to flowsheet development presented in this section retains detail to the level of plant specific information without highlighting any specific plant or company. This is important as, in order to build up an LCI a great deal of company-specific information is required. However, there is great sensitivity within the South African Minerals Industry to the potential environmental liabilities associated with their processes. Thus it was necessary to ensure that all the companies that supplied information were comfortable with the way in which the information was used and disseminated.

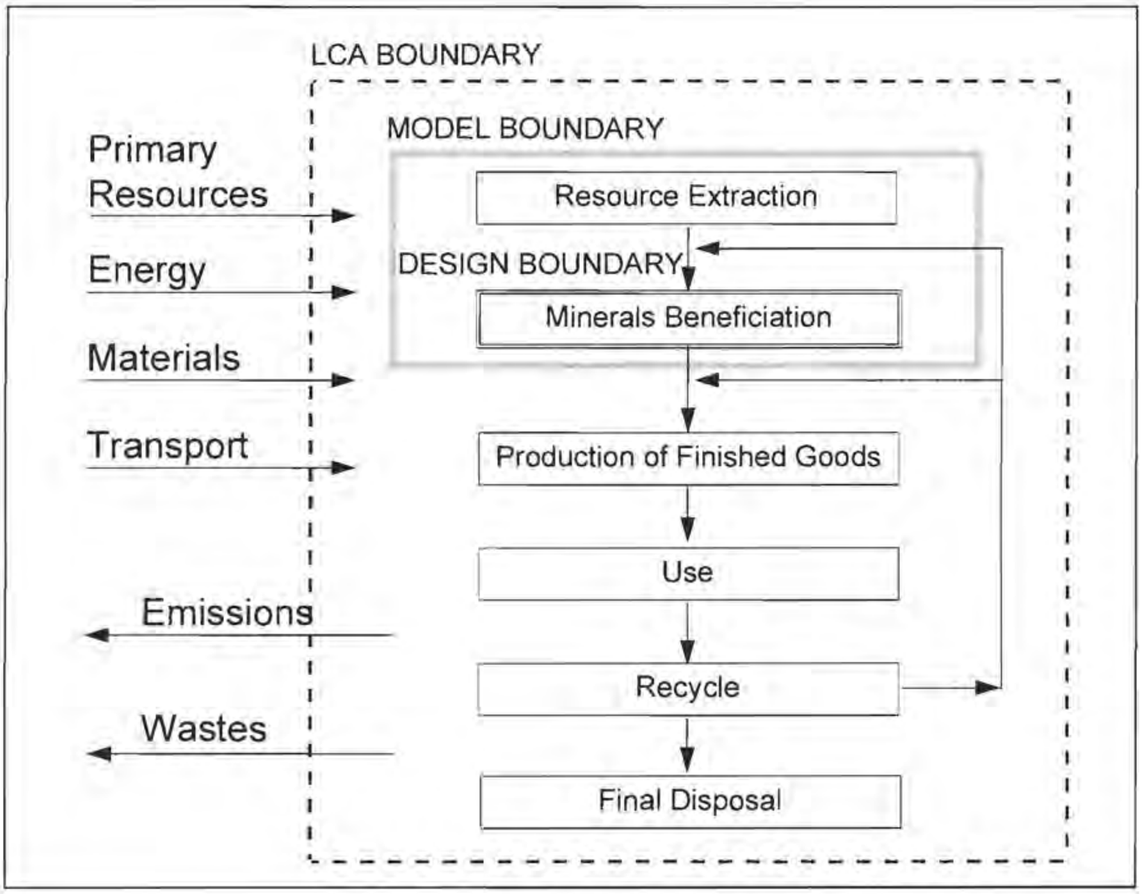


Figure 2-5 *Classic LCA Boundary Definition*

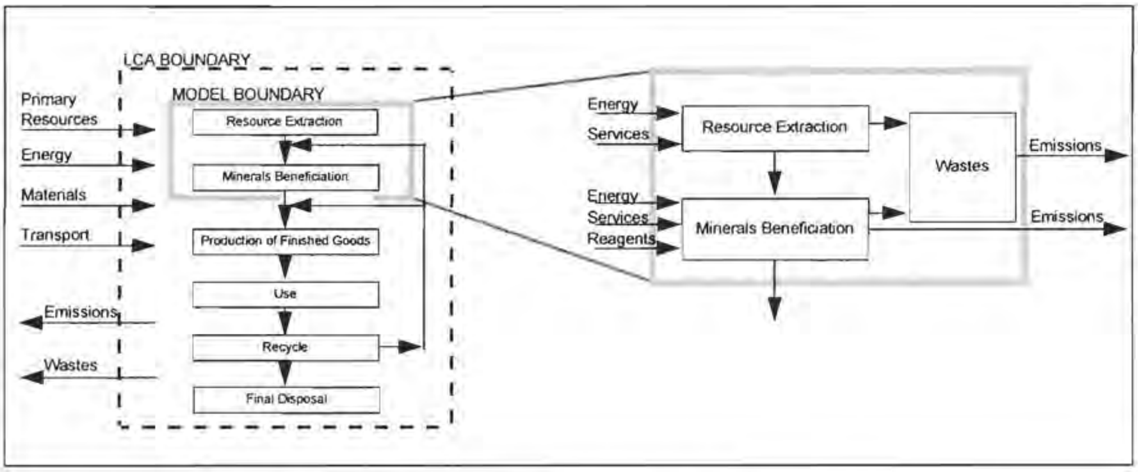


Figure 2-6 *Boundary Definition for LCA of the South African Minerals Industry*

The industry was divided into six sub-sectors: gold, coal, base metals, platinum group metals, ferro-alloys and the washing of minerals sands to produce titanium rich products. (Ferro-alloys includes the production of iron and steel as well as products which are a combination of iron and other elements such as ferro-manganese and ferro-silico- manganese. Further details are included in Figure 2-7). The main reason for selecting these groupings is because they divide the minerals beneficiation sector along lines of common process routes. They are also similar divisions to those used in the various sources of information such as:

- The South African environmental position reports (FRD, 1993; CSIR, 1991)
- The Johannesburg Stock Exchange, South Africa
- The Department of Mineral and Energy Affairs of South Africa
- The Chamber of Mines of South Africa
- Existing divisions within the corporate structures that control the industry.

A further note on the boundary drawn for the South African minerals industry - the mining of ores has not been included in the boundary. As such this is not a true cradle-to-gate analysis. However, the impacts of mining are generic (though their effects are site-specific) and some are independent of the product being mined. The majority of impacts are visual, some loss of land use, and the generation of acid rock drainage within the mines (resource consumption is included as an impact category in the LCAs included in the report). Including mining in the boundary would increase complexity of the models significantly and is deemed to be beyond the scope of this study. However, it is necessary to highlight the potential for mining and minerals processing to become integrated processes, as there is the potential to include minerals processing units within the mining process and thus decrease the amount of material brought to the surface of the earth. These technologies are not sufficiently developed to include in this study (see the definition of the complete set of unit operations later in this section).

2.3.3 Strategy for flow sheet development

Whilst the aim of this section is to demonstrate the role of flowsheet development in the practice of LCA for the specific case of minerals processing, it is proposed that the approach has general validity for other decision scenarios. Each flowsheet has been constructed to a level consistent with the quality of information required by a process-based LCA study. In other words there is a defined focus on waste type, origin and hazard value within each flowsheet. Flowsheet structure is driven also by information availability.

Figure 2-7 contains details of the generalised flowsheets derived for each of the six sub-sectors, these are included here in order to facilitate the discussion which follows. This discussion defines how unit operation boundaries within the flow sheets are drawn.

The flowsheets included in Figure 2-7 show all the sub-processes that are required to establish mass and energy balances for these sub-sectors. One section of this diagram, the flowsheet for the base metals industry, is expanded below in Figure 2-8.

The following are strategic considerations used in defining unit operations within each flowsheet.

- Common Function: if the function of process units is the same within different flowsheets, they are integrated into one unit; for example, since the crushing stage of a gold plant is the same no matter what process route is followed thereafter, crushing will be defined as a unit. An example here is the communition unit on the gold flowsheet, Figure 2-7A. The assumption set governing the operation of this unit is an average of all the information for the industry in South Africa (assumption sets are discussed later in this section). In this manner company-specific information can be used while still protecting confidentialities.
- Mass Flow Rate: units which have a high through-put, high reagent addition or high waste generation will have an obvious effect on the input-output model of the process as required by LCA. They must be kept separate in order that their effect on the total waste stream is not obscured. This is the reasoning behind keeping the two different elution routes separate in the gold flowsheet, Figure 2-7A.
- Hazardous Waste: if a unit gives rise to a hazardous or toxic emission or requires a hazardous or toxic reagent in its operation, it must be kept separate in order that the point at which that component enters and leaves the process can be pinpointed. Cyanide dissolution in the gold process (Figure 2-7A) is such an example.
- Energy Intensity: energy generation has significant impacts on the environment; thus it is special concern. Within minerals processing significant amounts of energy are invested in order to overcome the entropy inherent in the very dilute raw materials entering the processes. There is always a balance to be reached between the purity of the product leaving a minerals processing plant and the amount of energy which it requires. This is explored in more depth in Section 3 of this thesis. Suffice it to say that units with a high energy

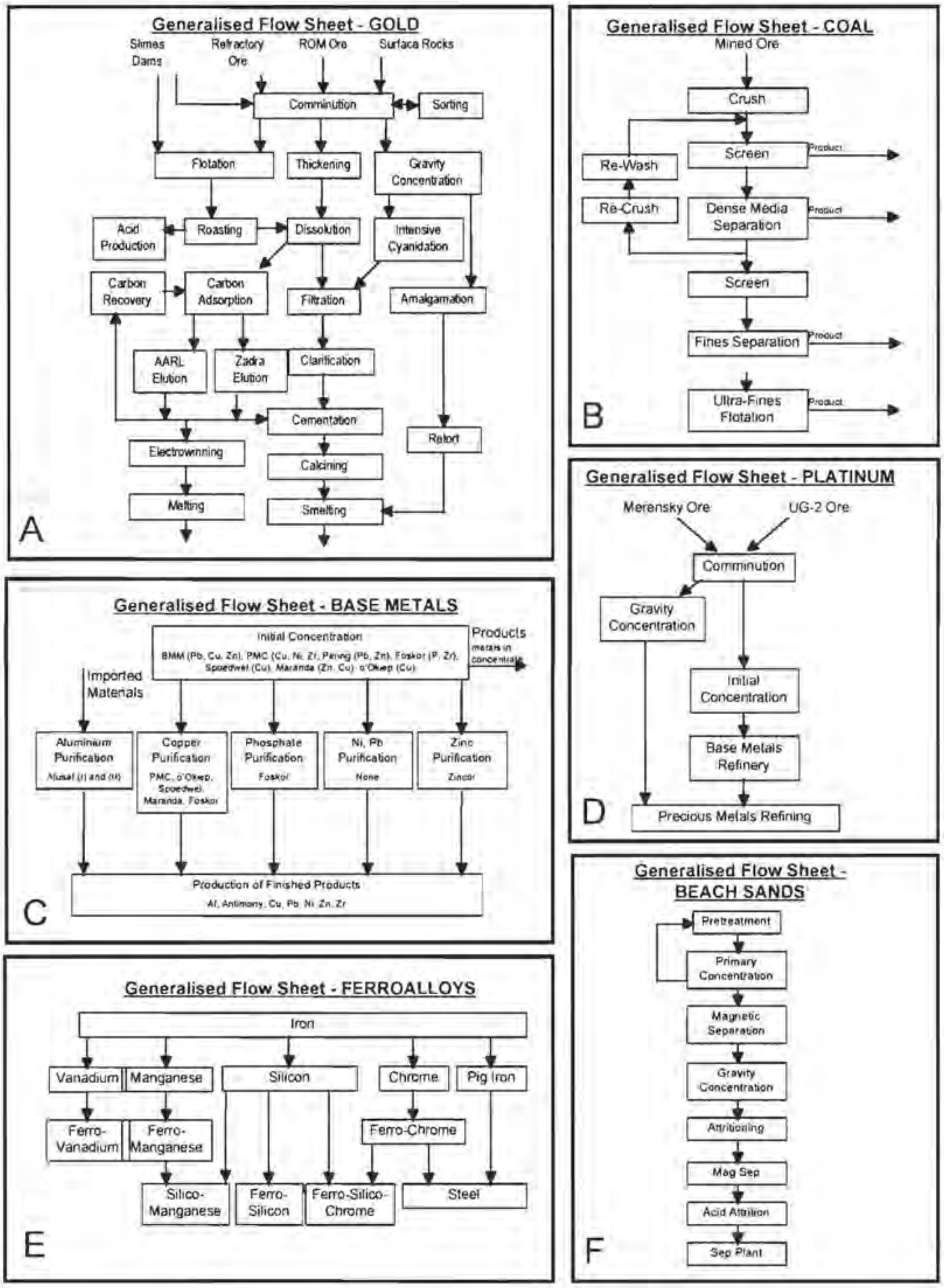


Figure 2-7 *Generalised Flowsheets for South African Minerals Industry*

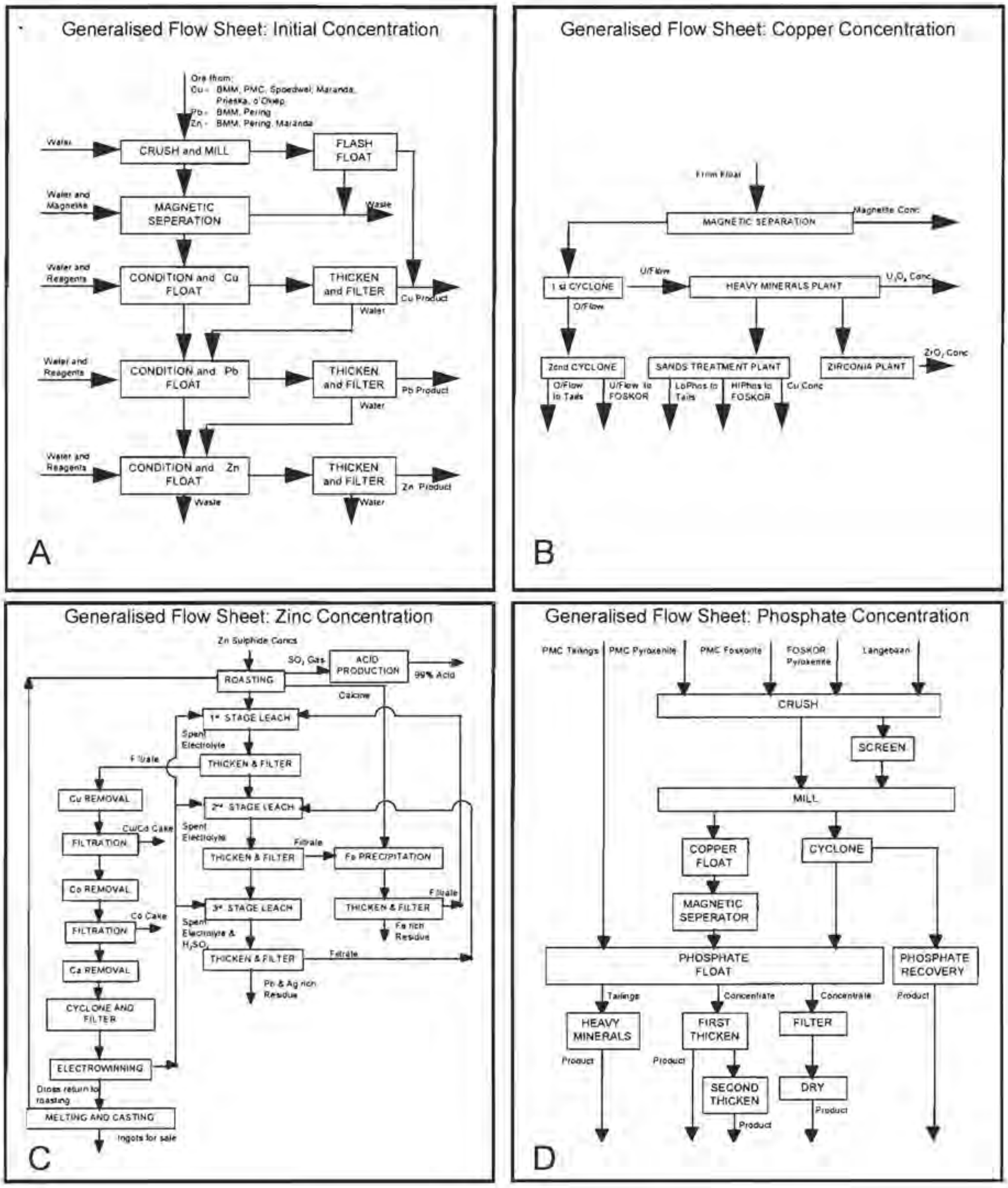


Figure 2-8 *Detail of Generalised Flow Sheets for the Base Metals Industry*

Note: this figure is available in more detail in Appendix 2-6.

consumption must be identified. This is the reason for keeping crushing and milling as separate units in the phosphate processing flowsheet (Figure 2-8D)

- Common Waste Generation: it is often the case that a unit that generates a specific waste is not always the point of exit for that waste from the process. It is necessary to ensure that the unit operation responsible for the nature of the waste is easily traceable in order to assist in process re-design and re-engineering. Thus it is important to couple waste generation with point of exit, for example linking leaching with filtration and thickening in the zinc circuit, Figure 2-8C. In this case the nature of the waste is determined to a greater extent by the operation of the leaching unit, than by the operation of the thickening and filtration units.

2.3.4 Development of Generalised flowsheets

Figure 2-9 shows the generalised flowsheet for the zinc purification industry. This flowsheet was finalised after all the process information available for the industry in South Africa had been analysed. This figure illustrates where the zinc industry links into the Base Metals flowsheet presented on Figure 2-8C. The figure is detailed to the point of main process streams only i.e., the input of reagents and services as well as the output of emissions and waste are not shown though these are known and can be identified in the inventories which accompany this flowsheet. A specific approach to mass balance modelling was adopted for the calculation of the mass and energy balances that accompany the flowsheets. This approach is based on the use of computer spreadsheets. It is described later in this section.

The creation of a generalised flowsheet is a necessary first step to the determination of mass and energy balances around individual unit operations within the overall process. Figure 2-10 shows the unit operations defined for the zinc process in South Africa and how they are related to the generalised flowsheet presented. These have been chosen according to the flowsheet development strategy presented already. Sufficient information detail is retained to construct an audit-trail from unit operation, through wastes to impact thereby assisting in the improvement analysis phase of LCA. This audit trail is described in full in Section 4 of this thesis.

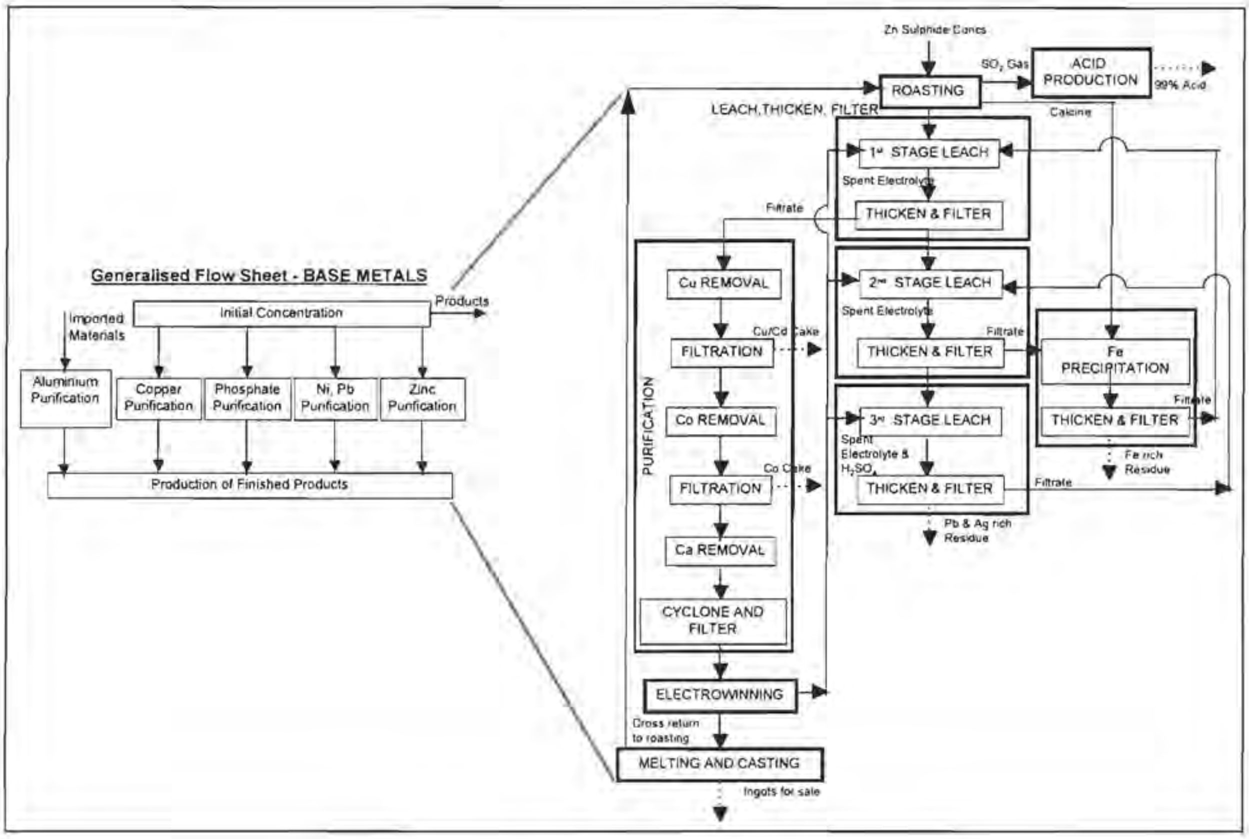


Figure 2-9 *Details of Zinc Flowsheet*

Figure 2-9 shows how a complete process diagram fits into the general flow diagram for the base metals industry. Figure 2-10 below shows where the unit operation boundaries have been drawn within the flow diagram to aggregate process units according to the strategy for flowsheet development included above. This final, simplified flowsheet is then modelled using a structured approach to mass and energy balance modelling as described below. The mass and energy balances for the process form the basis of LCIs for the zinc industry. Internal recycle streams, such as the use of part of the zinc product within the process, are not included in this diagram. This is discussed below.

Within the generalised approach to mass balance modelling there are two distinct types of information; the information which is used to establish mass balance closure for each unit operation, and the information which controls the stream flows between the unit operations within the flowsheet. These are described below. Once stream splits and assumption sets have been defined they are discussed in the context of degrees of freedom and design variables.

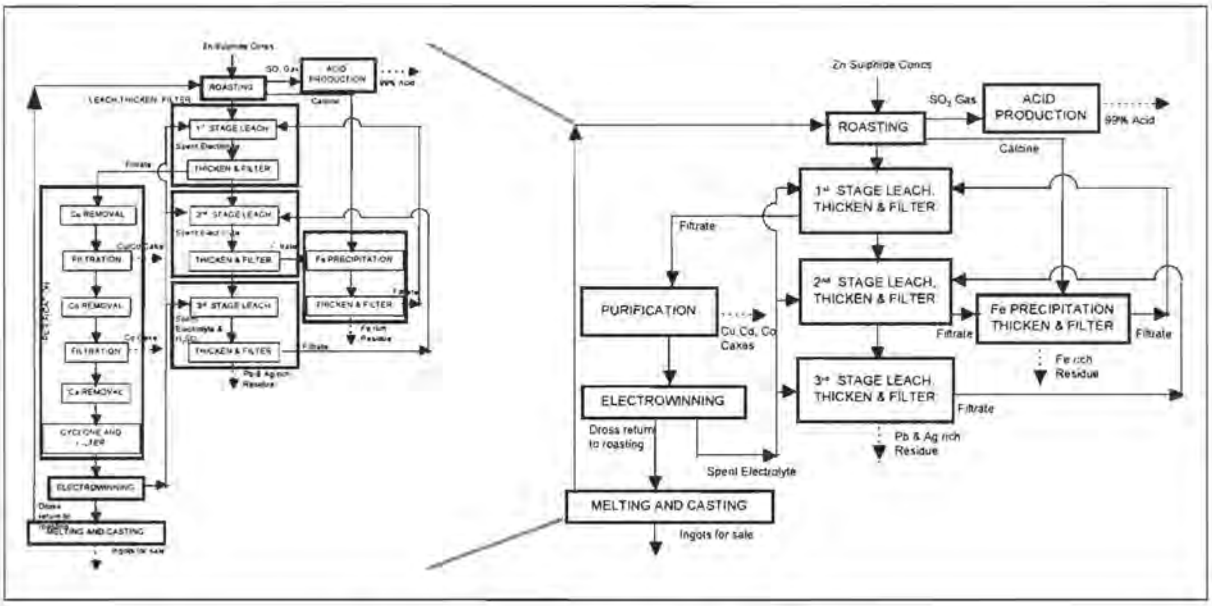


Figure 2-10 *Unit operations in Zinc Model*

Note, an important simplification that is made is that the flowsheets do not include information on recycle streams where these do not cross unit operation boundaries. These stream can be excluded from the flowsheet only when recycles operate in closed circuit. By definition material operating in closed circuit does not cross the process boundary and therefore there are no impacts associated with these streams. If recycle operate between unit operations or had a bleed stream they need to be included in the flowsheet as these structures can affect the nature of the stream and thus the impact of the process as a whole.

2.3.5 Degrees of freedom and Design Variables

In the discussion which follows these two concepts are defined and discussed within the context of the assumptions sets (or information sets) used to define the process models. Once these assumptions sets have been, defined mass and energy balances for the processes can be calculated.

2.3.5.1 Degrees of freedom and the Assumption sets

Within a system of equations there are two types of variable, independent and dependant. An independent variable is one that does not rely on others in its evaluation. A dependent variable is a variable that is fixed by a combination of independent and/or dependent variables. In this context "degrees of freedom" relates to the amount of information that is still required before a unique solution to the set of mass and energy balance equations can be established. Once there are no degrees of freedom remaining in the assumption set for each unit operation then the information set can be deemed to be "necessary and sufficient".

A complete description of the assumption set for a unit operation is given in Section 2.3.6. All assumption sets are defined relative to the process input stream to the unit operation.

The discussion which follows gives an indication of the degrees of freedom for the mass balances and demonstrates the total number of independent pieces of information required in order to ensure mass balance closure for the processes. The degrees of freedom available are limited by the requirement to ensure mass balance closure for each unit operation. The following example is included to illustrate this point, for a single unit operation, illustrated in Figure 2-11, there is a feed stream which is a vector of stream components:

$$\underline{F_j} = m_j.(x_1, x_2, \ldots\ldots x_i, \ldots. x_w) \qquad \textbf{Equation 2-1}$$

where: $\underline{F_j}$ is the feed vector to unit operation j

x_i are the mass ratios of the components in the stream

m_j is the mass flow rate of the stream to unit operation j

w is the total number of components in the inventory

or

$$\underline{F_j} = (f_{j,1}, f_{j,2}, \ldots\ldots f_{j,i}, \ldots. f_{i,w})$$

where: $f_{j,I} = m_j . x_I$

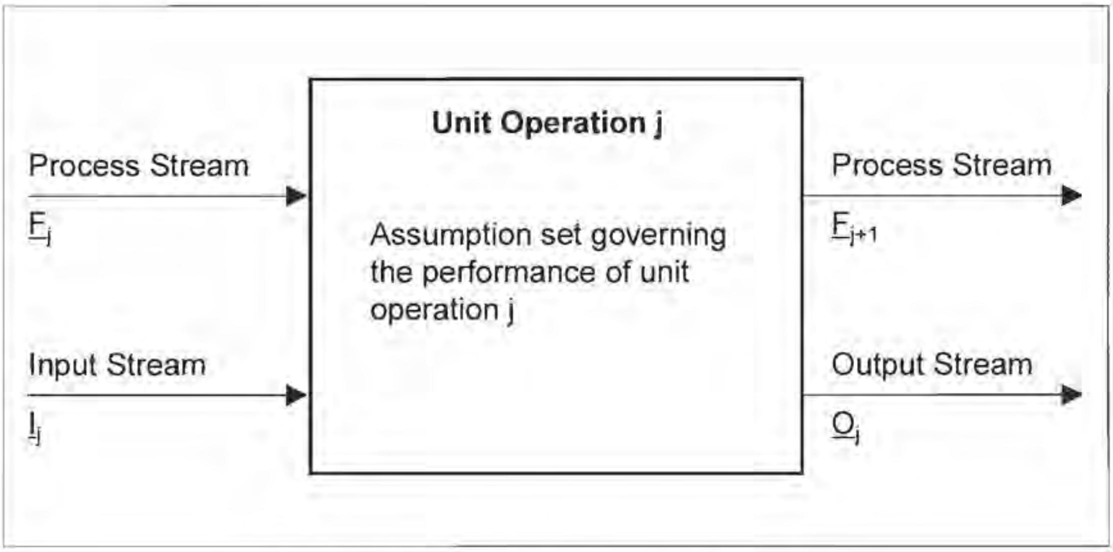


Figure 2-11 *Generic Unit Operation within Flowsheets*

Here the input stream includes the input of all services and reagents required by the unit operation. The output stream includes both saleable and non-saleable outputs from the unit, other than the process stream. For a steady state mass balance over unit operation *j* as illustrated in Figure 2-11 the equation will be:

$$\underline{F}_{j+1} = \underline{F}_j + \underline{I}_j - \underline{O}_j \qquad \textbf{Equation 2-2}$$

where: $\underline{I}_j$ is the vector of reagents input to the unit operation j

$\underline{O}_j$ is the vector of outputs from the unit operation j; these outputs could be in the form of saleable or non-saleable products

These two vectors have the form:

$$\underline{I}_j = (i_{j,1}, i_{j,2}, \ldots\ldots i_{j,i}, \ldots\ldots i_{j,w})$$

$$\underline{O}_j = (o_{j,1}, o_{j,2}, \ldots\ldots o_{j,i}, \ldots\ldots o_{j,w})$$

Thus for a single component, *i*, the mass balance equation for unit operation *j* would read:

$$f_{j+1,i} = f_{j,i} + i_{j,i} - o_{j,i} \qquad \textbf{Equation 2-3}$$

The feed to the unit operation is known so there are two additional pieces of information required before it is possible to evaluate this equation:

- The amount of the component added to the unit j
- The amount of the component which leaves this unit in the output stream

There are thus two degrees of freedom per component per unit operation. Thus, for a system which has w number of components and p number of unit operations there are 2.w.p degrees of freedom. This would imply that, in order for the assumption set to contain sufficient information to ensure mass balance closure on each unit operation, (2.w.p - 1) pieces of information are required (requiring mass balance closure for the process as a whole removes one degree of freedom). As discussed at the beginning of this section it will be necessary to reduce this number of degrees of freedom to zero before mass balance closure can be ensured.

It must be recognised that this is a significant amount of information. Aggregating the unit operations as much as possible within the flowsheets is vital to ensure that the amount of information to ensure mass balance closure is as small as possible. However, as has already been stated, it is necessary to ensure that there is sufficient detail in the information set to support environmental as well as economic decisions. This links back to Section 2.3.3 which details the "rules" for drawing boundaries around unit operations.

2.3.5.2 Design Variables

Essentially, design variables are those variables chosen by the design engineer to form the basis of a mapping of process performance. Design variables are necessarily independent variables. Design variable are discussed here as they relate to the assumption set used to calculate unit operation mass and energy balances. However, their main application is in design of processes and thus this concept is only applicable when flowsheets are being developed within the design process.

There is a difference in the design variables chosen for design in the chemical processing industries (CPI) and those chosen in the minerals processing industries. In the CPI extent of reaction and reaction rate can usually be described as a function of temperature, pressure and composition. Thus design variables are usually made drawn from temperature, pressure and composition. However, predictive modelling of processes in the minerals processing industry is not as advanced (and far more complex with respect to thermodynamic information requirements) as modelling in the CPI. It is not possible to describe unit operation or process performance as a function of the three variables identified above. For this reason the design variables in minerals processing are often heuristic and tied to mass and energy flows. The assumption sets as discussed in Section 2.3.6 below can be made up of design variables as they are also formulated relative to mass and energy flows.

2.3.6 Unit operation Assumptions

The operation of each process unit is dictated by a specific set of conditions relating to technological performance. A "necessary and sufficient" set of information to ensure mass balance closure for the unit operations must be put in place. Where information is not directly available from plant data, it is necessary to infer the requisite assumptions from other recorded process information. As an over-riding constraint, mass and energy balance closure around each unit operation must be maintained. Such a set of assumptions is illustrated in Figure 2-12. Essentially an input-output model for each unit operation is established.

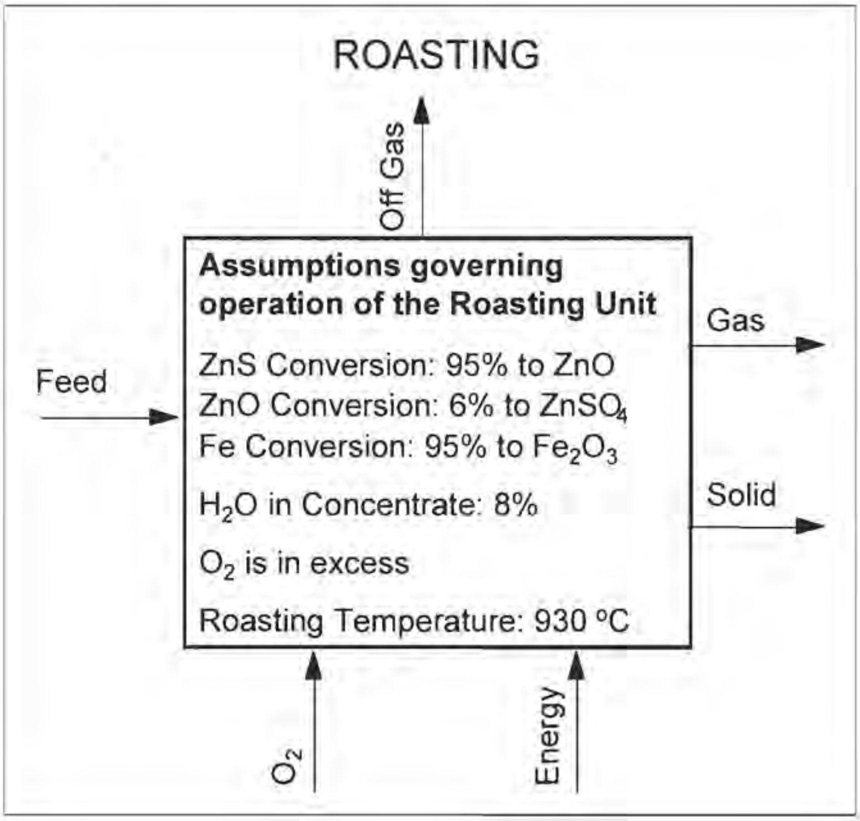


Figure 2-12 *Assumption set for a single unit operation*

In the context of the flowsheets developed, two distinct types of unit operations can be identified - reactors and separators. **Reactors** are unit operations in which the physical and/or chemical nature of the feed stream is changed. An example of a physical reactor is a mill, whereas a chemical reactor might be a leach unit or a smelter. The action of a **separator** is to separate a feed stream into its different phases be these solid, liquid or gases. Separators include filters and dust removal systems such as electro-static precipitators.

As an observation, it is possible to identify unit operations which perform both reactor and separator functions. An example here is a roaster in which, for example, zinc sulphide is roasted to produce zinc oxide thus it is a reactor. There are two main outputs from the roaster, an off-gas and the zinc oxide, thus the roaster can also be seen as a separator. However, the primary function of the roaster is the conversion of sulphide to oxide. The roaster is usually followed by a number of units (dust collection systems as well as gas scrubber) the main functions of which are to separate out materials more effectively, these are then referred to as separators.

It is possible to detail the information required to establish mass balance closure for each of these unit operation types. Input - output balances are calculated for each unit operation relative to the feed material entering the unit operation, thus the composition and amount of feed to each unit process must be known. The assumption set must be sufficient to define mass balance closure relative to this feed stream. Table 2-4 contains details of the information required by each unit operation type.

Table 2-4 *Information required for different unit operation types*

Unit Type	Mass Balance Requirements	Energy Calculation Requirements
Reactor - Physical	Utilities and reagents required	Energy required to bring about physical change
Reactor - Chemical	Extent of reaction, reagents and utilities	Energy required to bring about chemical change; potential for an energy output
Separator	Degree of seperation of phases, utilities and reagents	Energy required to seperate the phases

The inventories calculated for the South African minerals industry have been evaluated using an assumption set made up of mass-weighted averages for the industry. These averages are calculated relative to mass throughput and assumption value for each unit operation. In doing this, the mass balances, although generalised, are representative of the sum of processes in the country. Thus company-specific confidentialities are protected while still using plant-specific information. This is significant as it encouraged the South African Minerals Industry to supply plant-specific information for the development of the LCIs and to come on-board in the verification of these inventories.

2.3.7 Stream Splits

These can be quantified from macroscopic information on industry performance or a specific understanding of the industry. An example of the former approach can be seen with reference to the flowsheet for gold on Figure 2-13. The highlighted route shows what happens to refractory ore that reports to the conventional leaching process. The amount of refractory ore mined is known, as is the number of plants processing refractory ore which use conventional filtration. These two pieces of information combine to determine what percentage of the stream reporting to dissolution is refractory in nature and what percentage of the stream leaving dissolution and reporting to conventional filtration is refractory.

The latter case is again demonstrated with respect to zinc. Referring to Figure 2-10 one can see that there must be a calculated split of the spent electrolyte between the three leaching units. The amount of acid required for the first leach is calculated and removed from the stream. This approach is repeated for the second and third leaches.

This approach is consistent with the stream splitters defined by Reuter *et al* (1995).

As has been stated, the stream split assumptions control the movement of materials between unit operations. The assumptions governing the reactor unit operations determine the nature of the materials leaving that unit - be this chemical or physical. Stream splits determine the amount of material flow into a unit operation, thus stream splits, together with assumptions governing separator unit performance, determine the amount of material entering and leaving the unit operation. Thus the nature of material quantified in the LCI is determined by the assumption sets governing reactor performance, while the amount is dictated both by the separator assumption sets and by the stream splits.

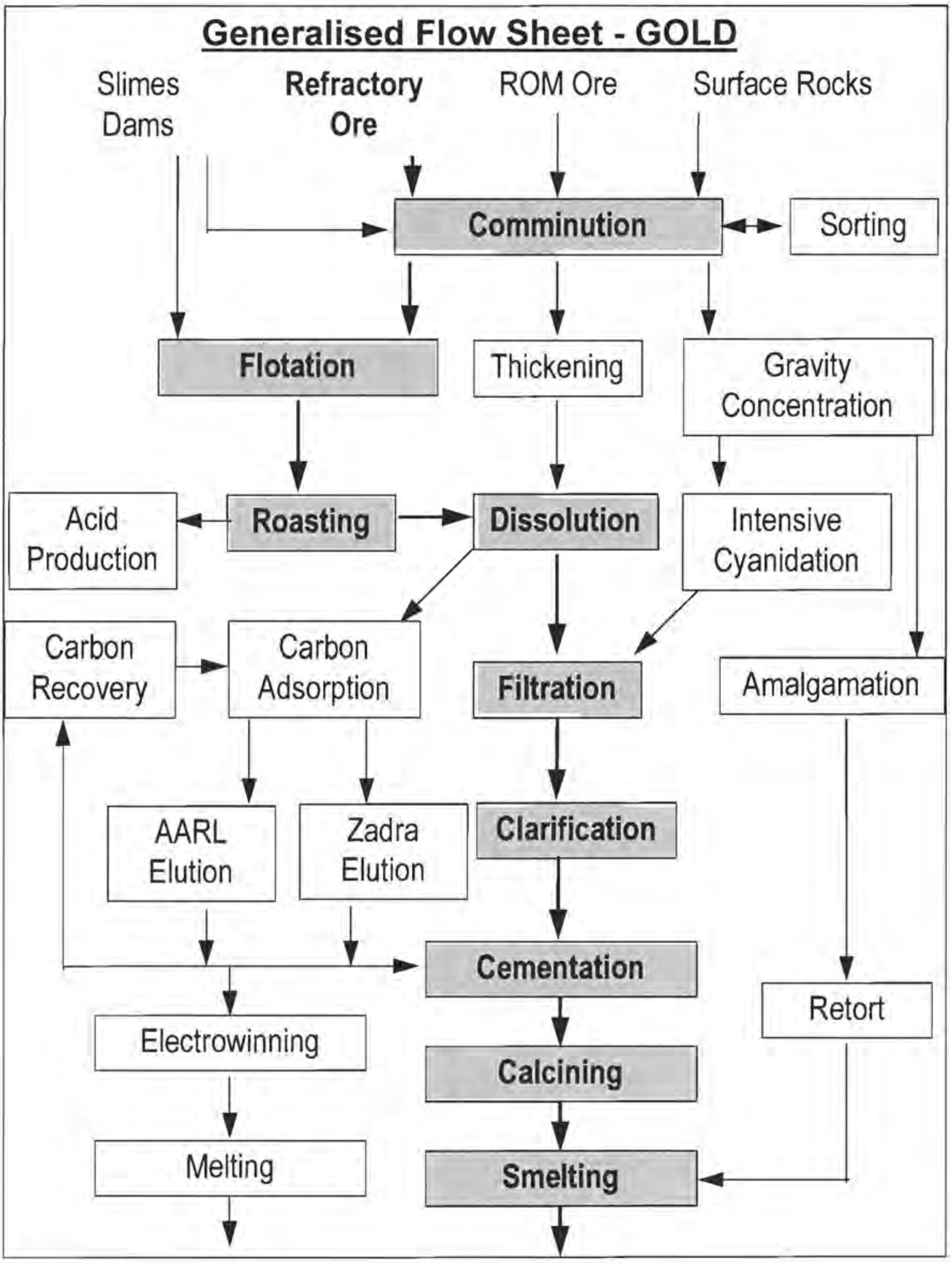


Figure 2-13 *Generalised Flowsheet for Gold*

2.3.8 Information Sets and LCA

Elements in the LCI are then linked to impacts during the impact assessment stage of LCA. Impacts are dependent on both the nature and the amount of material in the input and output streams. Thus impact is governed by both the assumption sets and the stream splits within a consistent flowsheet.

Allocation of impacts to products within a multi-product system is also facilitated by this information structure. It is possible to select any one of a number of approaches to allocation (SETAC, 1993b; Huppes and Schneider, 1994; Lindfors *et al*, 1995; Azapagic, 1996; Azapagic and Clift, 1999; Heijungs and Frischknecht, 1998) all of which are based on input-output models for a process as a whole. However, as opposed to applying these approaches to the entire process it is possible to apply them to each unit operation within the flowsheet as each unit operation is an input-output model in its own right. This is illustrated in Figure 2-14. However, as allocation methodologies are not the topic of this thesis this point will not be pursued further. Suffice it to say that any preferred approach can be pursued within the generalised approach to flowsheet structures developed here.

Note: in Figure 2-14, process stream 2 is defined in terms of Equation 2-2 included in Section 2.3.5.

Table 2-5 below is a summary of the above discussion of information sets and their interpretation within LCA.

2.3.9 Using *MS Excel®* to model the flowsheets

The programming philosophy used in developing the spreadsheets used to model the flowsheets in this thesis was that of keeping global process variables in one place, i.e., only recording these variables once in the spreadsheet. This was done both to aid data verification and to ensure greatest flexibility to model different scenarios.

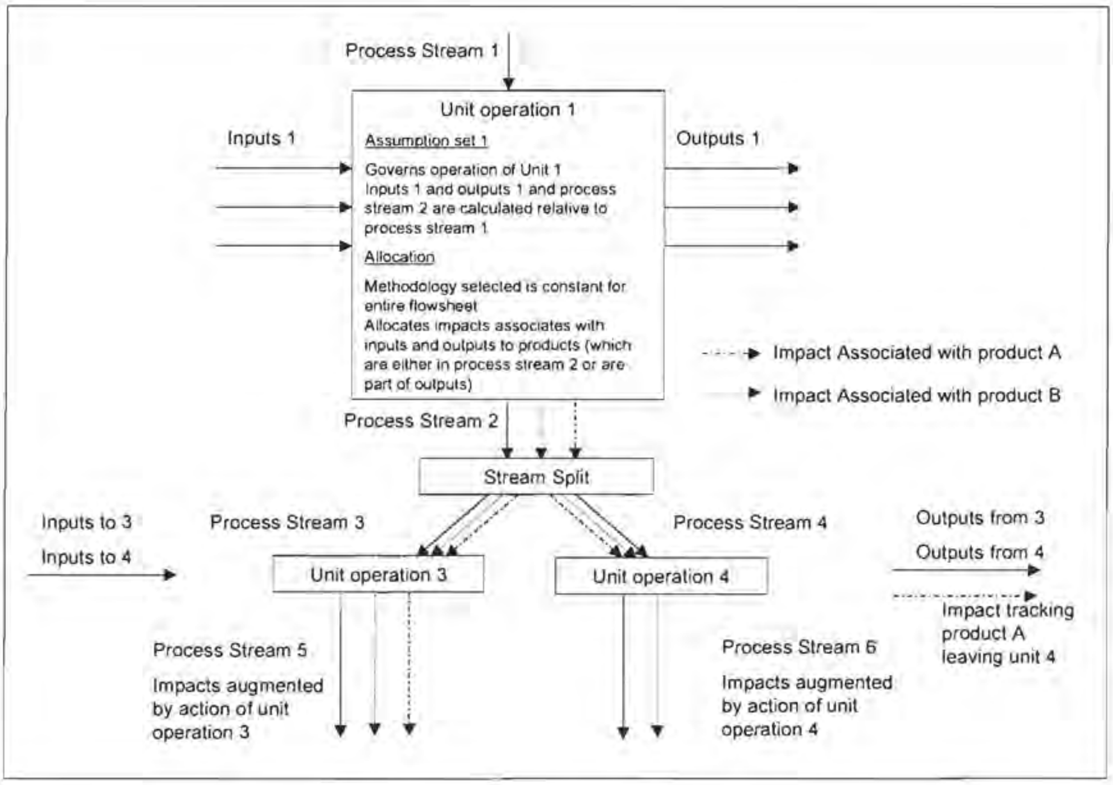


Figure 2-14 *Allocation and the information sets*

Table 2-5 *Information sets and LCA*

	Unit Operation Assumptions	**Stream Splits**
Elements in LCI	Define nature, together with stream splits define quantity	Together with technology assumptions define quantity, linear relationship between stream split and quantity
Impacts associated with the unit operations	Define nature of impacts associated with the unit; contribute to amount of impact associated with the unit	Together with technology assumptions define quantity or amount of impact
Allocation	Input-output amounts for each unit operation are based on the assumptions, thus impacts can be allocated to different outputs from the unit as required	Once the input-output amounts are defined by the unit operation assumptions, and an allocation regime chosen, the stream splits are used to control the allocation of impacts to products

The spreadsheets were developed on four levels.

Assumptions governing both the operation of the unit operations and the stream splits between unit operations within the flowsheet are hard-coded into a single spreadsheet. This is the only point in the model where these variables are stored. Hierarchically, the data contained in this sheet can be viewed as the "highest" or most important information as it is this information which dictates the performance of the process.

Below this Assumptions spreadsheets lies a control spreadsheet which manages the flow of information through the model. This spreadsheet refers to the stream splits stored in the Assumptions spreadsheet; it then sends these streams to the correct unit operation. The mass balance over the unit operation then evaluates the operation of that unit and returns a process stream which the control sheet then feeds on to the next unit in the flowsheet.

The bottom level comprises the mass and energy balances over each of the unit operations defined within the respective flow sheet. Essentially these balances are templates which model the operation of the unit operation. By ensuring mass balance closure over each unit operation, a consistent mass balance for the process will always be calculated.

There is a final level of spreadsheets involved in the evaluation of the inventory for the process. There are two main inventories:

- Inputs: these include the feed to the process as well as any reagents required.
- Outputs: these constitute both the products and the wastes from the process.

These spreadsheets comprise a matrix of information. Figure 2-15 shows an example of the matrix generated for a process. The stream components are then linked to potential environmental impacts during the impact assessment stage of LCA. This results in a matrix of environmental impacts. The audit-trail requirement of the model developed is facilitated using this approach.

Spreadsheets were developed in two or more inter-linked *MS Excel* files to increase speed of access and to minimise problems associated with lack of computer memory. Assumptions governing these spreadsheets can be found together with the analysis of each industry sub-sector in the appendices listed below.

Unit Operations

Stream Components	Feed	Crushing	Milling	Flotation
Ore				
Water				
Frother				
Energy				

Figure 2-15 *Example of Input Matrix*

- Gold – Appendix 2-3
- Coal – Appendix 2-4
- Base Metals – Appendix 2-5
- Platinum Group Metals – Appendix 2-6
- Mineral Sands – Appendix 2-7
- Ferro-Alloys Industry – Appendix 2-8

Complete models are included on the CD included with this thesis. Please see the Guidelines included at the end of the Appendices in Volume 2 for instructions on how to access these models.

2.4 Mathematical programming

Translating the approach detailed above into Linear Programming terms – both the mass and the composition of the feed stream to the process are known. It is the vector quantity detailed above but of different dimension:

$$\underline{F_j}' = m_j.(x_1, x_2, \ldots\ldots x_i, \ldots\ldots x_n) \qquad \textbf{Equation 2-1a}$$

where: $n = w + 2$

The reason for "n" being given this dimension is that there are two additional "components" in the streams (other than chemical components), these are:

- Energy required by the unit operation as a function of mass flowrate through the unit operation. It is necessary to include energy required by the process as the impacts associated with the provision of energy to the process are significant.
- Capital Cost + Operating Cost for the unit operation expressed as a function of mass flowrate through the unit operation. Economic arguments are included in the information structure as these are required to formulate economic objectives. A discussion on the formulation of objectives using the information structure is included in Section 4 of this thesis.

The main reason for including these two elements in the calculation of the system is to ensure that a complete input-output analysis is available for the process. Arguments in the literature review of this section explained why it is necessary to include environment as a specific objective or set of objectives within process synthesis and process analysis. In the same way, it is necessary to ensure that all information is included in supporting environmental decisions. These should not focus only on environmental issues but should include a specific understanding of the economic effect of a decision. Thus it is necessary to ensure that economic information is available at the same level of detail as the mass flow and its associated environmental impact information. Thus, in order to establish the complete input-output model referred to at the beginning of this paragraph all input and all outputs must be included, not only mass flows.

For the case of a sub-sectorwide mass balance, for example a mass balance of the entire gold industry in South Africa, the mass ratios of the feed stream are calculated as the mass weighted average of the compositions of all feed streams for the industry. The mass flow rate is the sum of all the feed rates for the industry.

The steady state mass balance for each unit operation (with reference to Equation 2-2):

$$\underline{F}'_{j+1} = \underline{F}'_j + \underline{I}'_j - \underline{O}'_j \qquad \textbf{Equation 2-2a}$$

Where all the vectors have been augmented to include the two additional quantities of energy and capital flows.

The outputs from a process can be divided into two categories, saleable and unsaleable. The reason for choosing the terms "saleable product" and "unsaleable product" are that there has been a widespread debate about the perceptions conveyed when calling a stream a "waste stream". Social perception is extremely important when dealing with environmental issues. For this reason concise and positive terms are required when naming streams. In the context of "Clean Technology" it is important to view all waste streams as potential raw materials even if a process in which they can be utilised has yet to be defined. "Waste" and "Unsaleable Product" are interchangeable terms in this thesis). The term co-product has specifically been avoided as it is possible to confuse co-products with unsaleable products in a multi-product system (for example the base metals refinery in the Platinum industry which has a multitude of products). Taking this discussion into account Equation 2-2a can be rewritten as:

$$\underline{F}'_{j+1} = \underline{F}'_j + \underline{I}'_j - \underline{P}'_j - \underline{U}'_j \qquad \textbf{Equation 2-4}$$

where $\underline{F}'_j$ is the process stream to unit j

$\underline{I}'_j$ are the inputs to unit j

$\underline{F}'_{j+1}$ is the exit process stream from unit j (thus the feed to unit j+1)

$\underline{P}'_j$ are the saleable products from unit j

$\underline{U}'_j$ are the unsaleable products from unit j

Once mass balance closure for the process has been achieved and all recycles accounted for (recycle streams are seen as process streams) it is thus possible to construct three matrices:

- A matrix of inputs to the process – $\underline{I}'$. Care should be taken to ensure that feed streams to the process, as opposed to process streams between unit operations, are recorded as inputs to the process and not merely process streams.
- A matrix of saleable products – $\underline{P}'$

2.5 Examples of Decision Making Situations

This then is the methodology used to develop flowsheets systematically:

- All flowsheets in place in the industry are researched. These are then analysed according to the five steps or "rules" as presented in Section 2.3.3 in order to determine the boundaries for each unit operation.
- Unit operations are combined to ensure that all process flows are described.
- An assumption set is established for each unit operation; this assumption set ensures mass and energy balance closure around each unit operation.
- Stream flows between each of the unit operations are then calculated to reflect total mass flow in the industry as a whole.

The processes are modelled in a spreadsheeting package (*MS Excel* in this case). The mass balances calculated using this approach meet the requirements of the second stage of LCA, that of establishing the Life Cycle Inventory (LCI). They also contain sufficient information to support the audit-trail structure detailed in Section 4 of this thesis.

Generalised flowsheets using this structure were developed for six minerals processing sub-sectors within the South African minerals processing industry. These are included in the Appendices as indicated:

- Gold – Appendix 2-3
- Coal – Appendix 2-4
- Platinum Group Metals – Appendix 2-5
- Base Metals – Appendix 2-6
- Ferro-Alloys Industry – Appendix 2-7
- Mineral Sands – Appendix 2-8
- Cross-sectoral Considerations – Appendix 2-9

These appendices are self-contained discussions on the specific sub-sector. They contain details of the profile of the industry as well as a description of the technologies in place in the industries. All of these inventories have been evaluated for the 1996 production year as this is the most recent year for which a complete assumption set could be determined. Mass balance models using the information structure presented in this section are also included. The mass balance model for the gold industry is printed out in its entirety and included in Appendix 2-3. The other models have been included on the CD available with this thesis. The information presented in the appendices is an aggregation of information from all of these sources. The information was then moderated by industry. It is thus not possible to reference a single source for the majority of the values presented in the appendices. Each appendix has an accompanying bibliography. The documents listed in these bibliographies are the source documents for the initial flowsheets developed for the relevant industries.

The mass balances reflect the technology in place in the South African minerals industry as for the year January to December, 1996. This year was chosen as the "baseline" year as it is the most recent year for which complete economic information was available. The waste stream calculated for each industry is presented and discussed. The reader is urged to survey these appendices as they contain a comprehensive detailing of the waste generation potential of the South African minerals industry and represent a significant volume of work in their own right. The case studies presented in the main text which follows do not represent all scenarios that were developed. However, all of the scenarios are included in the appendices.

While it is recognised that the information contained in these mass balances is highly aggregated, the information does have an inherent value. This section illustrates the types of decisions that this information structure can support. These decision types are illustrated using case studies based on the models included in Appendices 2-3 to 2-9. A complete discussion of each case study can be found in the relevant appendix.

2.5.1 Technology Trends

Technology trends can be analysed in two ways. The first is an interpretation of past practices and the second is a prediction of what the potential for changing the environmental impact of an industry is in the future. These are the two case studies which are presented here. Historical changes in technology are investigated for the gold industry, while the potential for innovative smelting technologies is investigated for the production of ferro-alloys products.

2.5.1.1 Historical technology advances – Gold

Gold mining is one of the oldest industries in the South African economy and the development of technology within the industry can be traced back over more than 100 years. Initially mercury amalgamation was used for gold recovery. Ore was crushed and then passed over a bed of mercury which concentrated the gold. This mixture or amalgam was retorted (boiled) to recover the gold.

The next process to be used was cyanide dissolution of the gold from finely milled ore. The liquor was then clarified and the gold recovered from solution by cementation. The solid product from cementation was smelted to produce a gold product for refining to final purity at Rand Refineries. In 1996 a small gold refinery was commissioned by one of the mines in the Free State, one of the country's nine provinces. Previously governmental controls limited companies in their ability to refine their own gold. There is potential for this smaller scale refining of gold to play a larger role in the technology suite of the industry.

The third most notable technology shift was to Carbon-in-Pulp (CIP) gold recovery. The gold-cyanide solution is brought into contact with activated carbon onto which the gold adsorbs. The gold is then eluted or washed from the carbon, usually in a semi-batch process, which renders a cleaner solution for the downstream hydrometallurgy refining steps. The carbon has to be reactivated before entering the process again. In general, higher recoveries are achieved than in the normal clarification / cementation route.

This case study highlights the three technology-specific process routes. The base case presented is that of the status quo for 1996 where all the stream splits and unit assumptions are pertinent to what actually occurred in the South African industry in that year. The general flow diagram can be found on Figure 2-13, the three flow routes described above can be found within this flowsheet.

In order to study the effect of *Amalgamation*, the same quantity of ore at the same average grade as was mined in 1996 was passed through the amalgamation process only. For *Filtration* alone, all the ore was passed through the dissolution/filtration route only. The stream splits "up-stream" of the dissolution unit were assumed to correspond to those of 1996. Finally the *CIP* process route was followed. Here again the upstream stream splits from 1996 were used.

Figure 2-16 and Figure 2-17 graphically compare the three process routes described above. With respect to inputs to the process, there is the expected move from amalgamation reagents to CIP reagents.

Figure 2-17 shows how the waste generation profile alters with changing technology. The CIP process as a whole generates a greater quantity of waste than do the other process routes adopted. The nature of the waste also changes from a mercury-rich stream to one containing dissolved salts and cyanide.

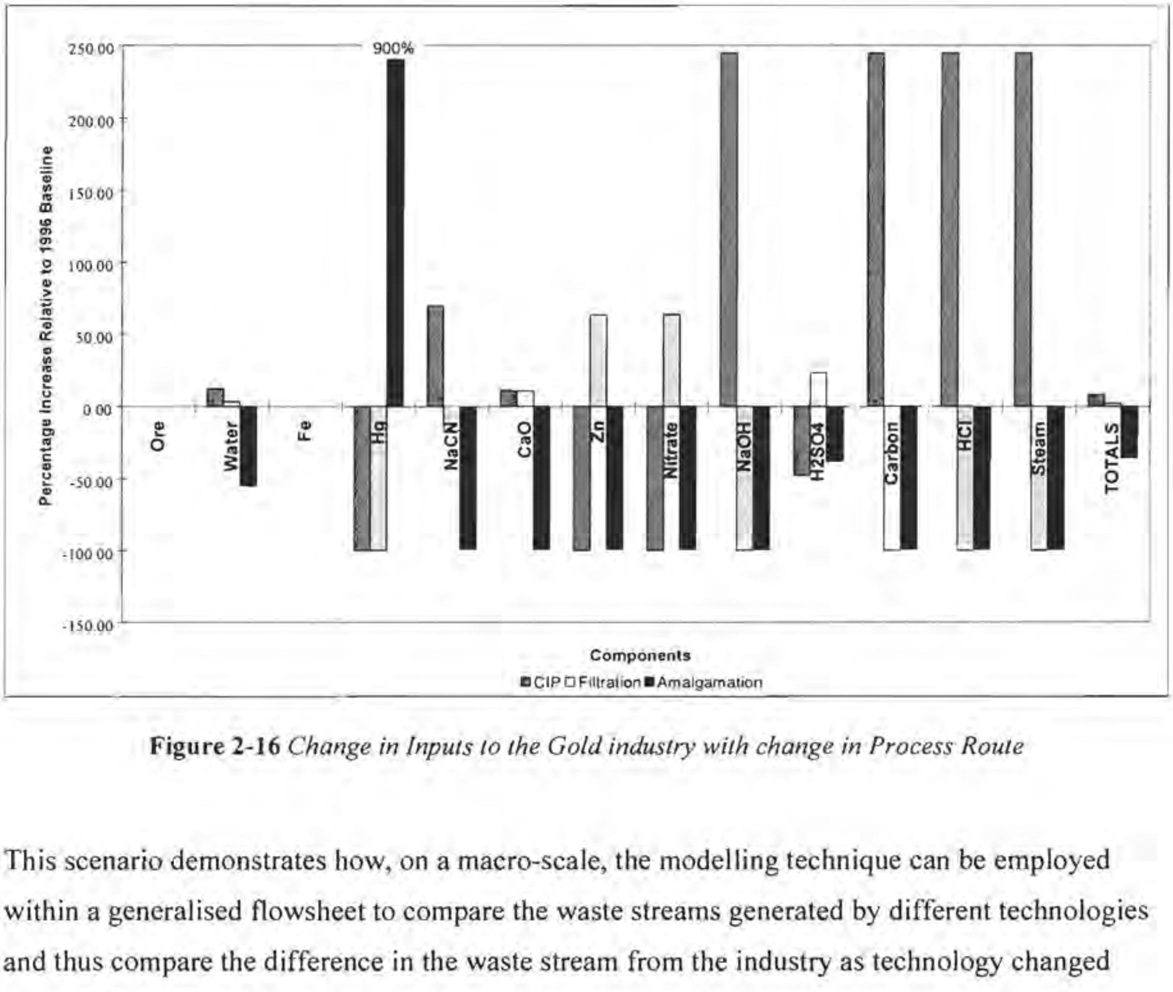


Figure 2-16 *Change in Inputs to the Gold industry with change in Process Route*

This scenario demonstrates how, on a macro-scale, the modelling technique can be employed within a generalised flowsheet to compare the waste streams generated by different technologies and thus compare the difference in the waste stream from the industry as technology changed through the years.

The results gained from this example can also be used to demonstrate what could happen new gold mining rights be ceded to small mining ventures. This is a distinct possibility with the

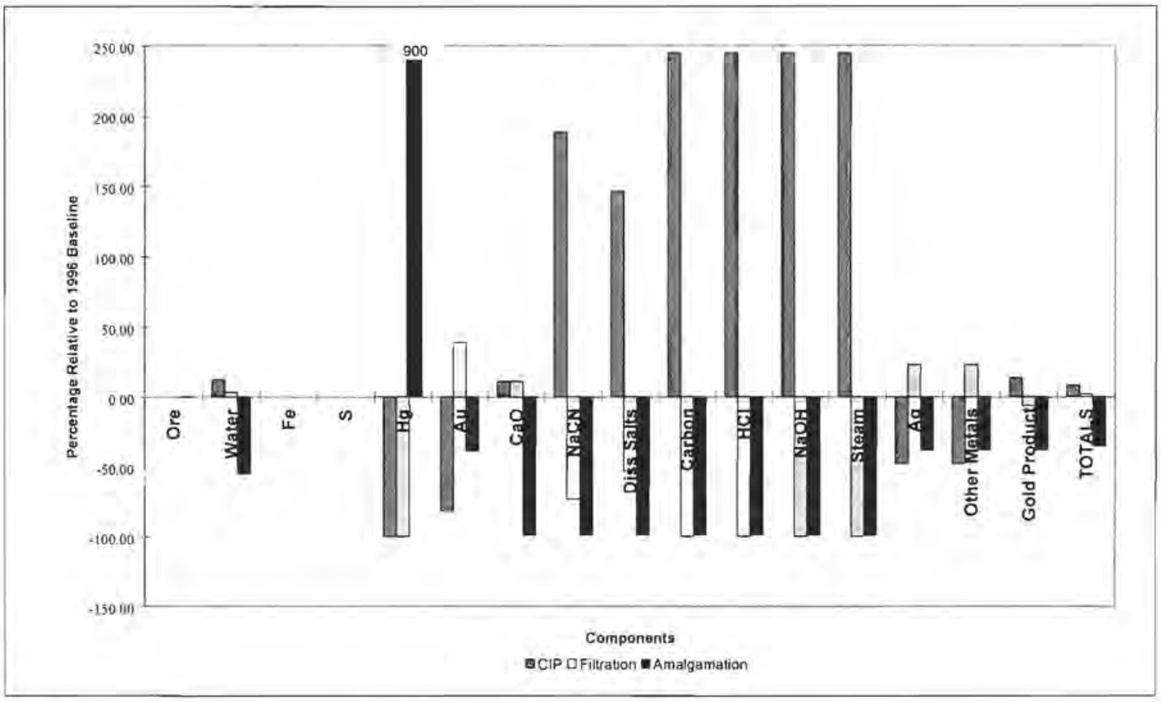


Figure 2-17 *Change in Outputs from the Gold industry with change in Process Route*

release of the Government White Paper on Minerals (the new policy document for the Minerals Industry, DMEA, 1998) which proposes that mineral rights no longer rest in the private sector. Should this be the case it is postulated that these rights will be re-issued to formally disadvantaged sectors of the economy operating as collectives of small scale mines. Unless they could afford to invest in the capital intensive routes of filtration or CIP, these new operatives might settle on mercury amalgamation to recover gold from ore. This would result in the mercury-rich waste stream illustrated.

The alternative to small separate processing plants is the establishment of a centralised processing plant where small operators could bring their material for beneficiation. This has the advantage of higher recoveries. The disadvantage would be dependence on the sampling techniques used to determine the amount of gold contributed by each operator as well as problems associated with transport.

A complete impact assessment (the third stage of LCA) would be required to highlight the trade-offs to be made between the higher water usage of the cyanide dissolution routes and the hazardous mercury waste associated with the amalgamation route. This is explored further in the case study included in Section 5 of this thesis.

2.5.1.2 Improvement in Technology – Ferro-Alloys

This case study explores the effects of changing technologies within a specific sector of the ferro-alloys industry. The generalised flow diagram for the ferro-alloys industry can be found on Figure 18 below. The section of the industry under examination is the flow of iron ore through pig iron to carbon steel. There are a number of existing technologies with the trend in the industry being a move to the Corex™ (™ owned by Voest Alpina) process and then the linking of the Corex™ process to a direct reduction of iron. Complete descriptions as well as the flow sheets for the specific processes referred to in this case study can be found in Appendix 2-7.

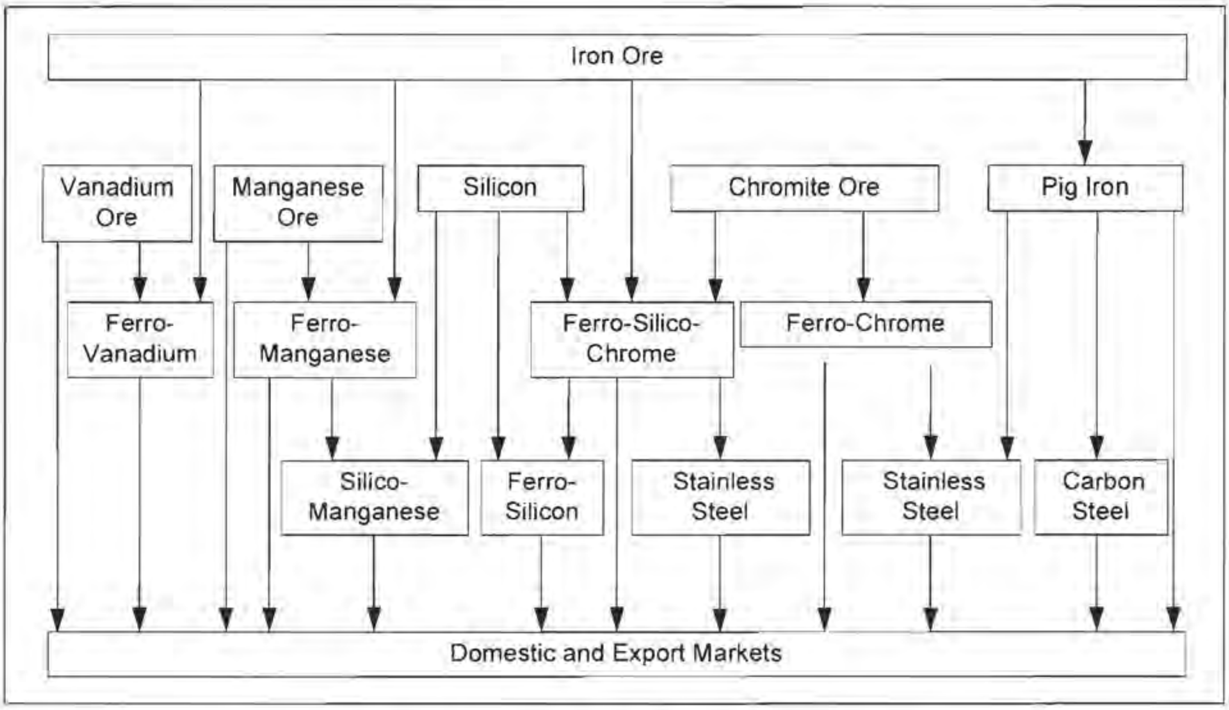


Figure 18 *Overall flow diagram for the Ferro-Alloys industry*

Note: this is a generalised flow diagram, more detailed diagrams for each process identified above can be found in Appendix 2-7.

The steel manufacturing sector has gone through many stages of development. The waste generation potential of these technologies is compared here. The Corex ™ process is used to demonstrate the waste generation potential of modern technologies. Figure 2-19 shows how the waste stream differs for four different technologies. First is a blast furnace, the oldest technology currently employed. This is followed by the next step in technological development, the basic oxygen furnace (BOF), then by the Corex™ process and, finally, by the coupling of a Corex™ reactor with a downstream direct reduction process (DRI) using the CO- and CO_2-rich off-gas from the Corex™ process in the reduction of iron.

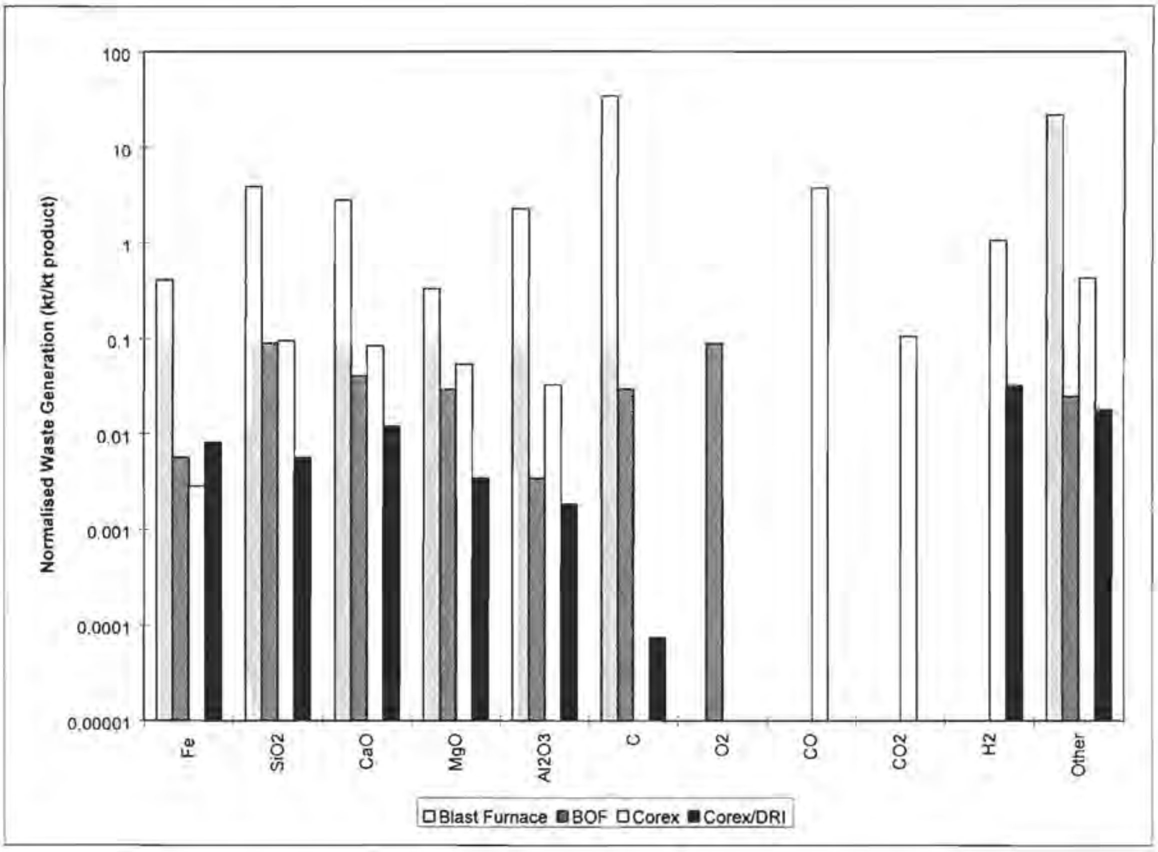


Figure 2-19 *Change in Waste Generation with Development of Technology*

The waste generation potential of the blast furnace is the worst, generating the most waste per tonne of product. When the Corex process is run without a downstream DRI section, the waste generation is also significant. Of the four technologies compared here, coupling a DRI and a Corex process gives lowest waste generation.

The total waste generated per ton of product by the four processes is included in Table 2-6. These figures bear out the observations made about Figure 2-19 and indicate the magnitude of the difference between the waste streams.

Table 2-6 *Waste generation potential of Steel production technologies (normalised with respect to ton of product)*

Technology	Waste Generation (kt/kt product)
Blast Furnace	66
Basic Oxygen Furnace	0.31
Corex	5.6
Corex/DRI	0.08

2.5.2 Process Performance

There are a number of approaches to viewing the performance of a process. The two case studies presented here show just how diverse such evaluations can be. In the first case the gold industry is used to demonstrate how the waste stream changes when the operating conditions of a single unit operation within the flowsheet are changed. The second case study demonstrates how different processes within the base metals industry perform relative to one another. The comparison of technologies within the base metals industry is only possible because of the uniform boundary drawn around them (that of the LCA study) and because equivalent information sets are available for each process. "Equivalent" infers that the scope, detail and accuracy of the information sets are similar for all processes under consideration.

2.5.2.1 Effect of changing operating variables – Gold

As has been pointed out, the flowsheets are structured so that it is easy to change a single process assumption and to observe the effect of this on the waste inventory of the process as a whole. It is also possible to see how such a change affects the waste generation of units down-stream from that unit. Effects of changing unit efficiency on the waste stream as a whole are made transparent.

Two main classes of variables exist within the system: continuous variables such as the grade of gold in the ore entering the process, and discrete variables such as an operating condition specific to a single unit. Changing a continuous variable makes determination of the waste inventory's sensitivity to that particular value possible. Changing a discrete variable reveals the sensitivity of the process to the efficiency of a specific unit operation.

To ascertain the system's sensitivity to these variables, assumptions within the flowsheets were changed by an arbitrarily determined set amount (a ten percent decrease in the values assumed for the process in 1996). Only those results in which the waste inventory changes markedly have been detailed here.

Two sets of results are included. These are presented in Figure 2-20 and Figure 2-21, which show the percentage increases in waste generation as a result of various changes in assumptions governing these unit operations.

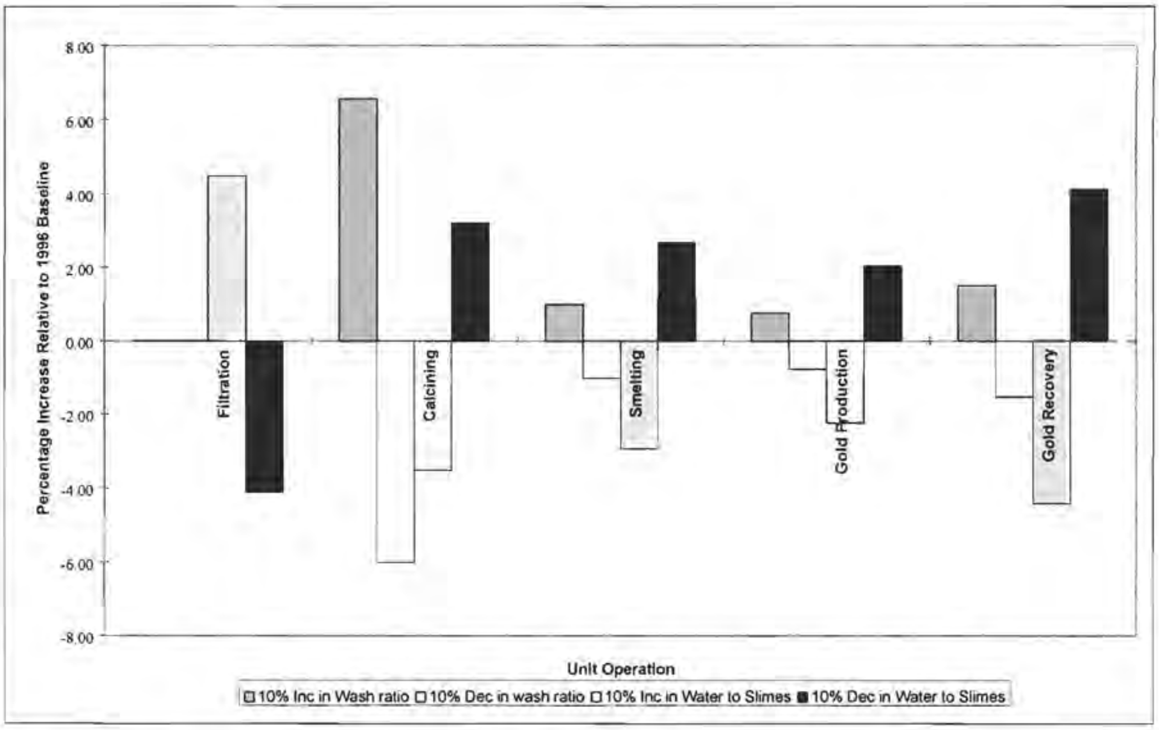


Figure 2-20 *Percentage change in waste generated with change in operating conditions - Filtration Process*

Wash water is the water used in the washing of the filter cake. Increasing the wash water will increase the recovery of gold for the process as a whole. Increasing the water reporting to the slimes dam is essentially decreasing the operating efficiency of the unit. This demonstrates that decreasing the efficiency of a single unit (the filtration unit) may lead to a increase in efficiency in downstream units. However, the streams leaving the downstream units have far higher environmental impact and thus the trade-off between the two competing efficiencies may be worthwhile. The balance here is the economic viability of the change.

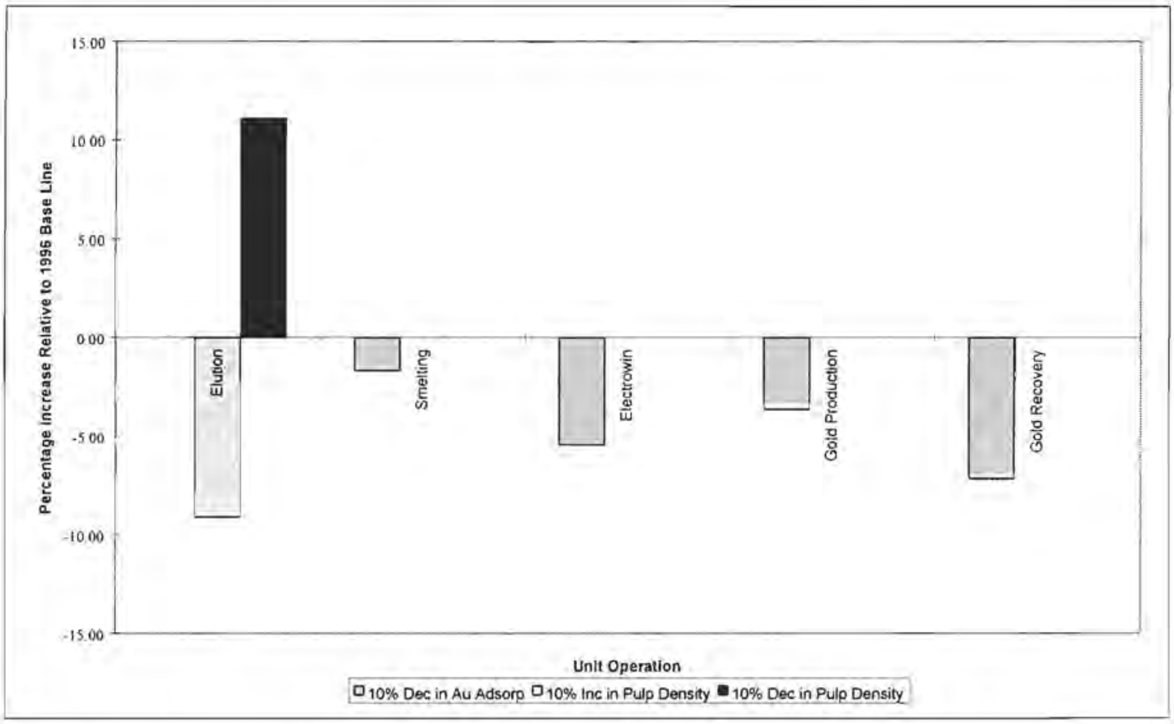


Figure 2-21 *Percentage change in waste generated with change in operating conditions - CIP Process*

These operating conditions reflect the changes in process performance which could result as the process matures. Again there is a trade-off to be made between increasing the efficiency of a single unit and decreasing the efficiency of another.

These results demonstrate the interlinking of the unit operations within a process. Such scenarios have some major implications:

- It is possible to infer what will happen during the life-time of a plant where unit operation efficiency is not constant; being low during commissioning, working up to a peak and then tailing off as a process matures.

- The models could also be used as a training tool to show operators how profoundly they can affect the waste generation potential of a process. Each decision could be related to a base case and it would be possible to quantify the effect on the waste inventory, of decisions made in the day-to-day running of the process.
- Also possible is linking of decisions, as they would occur within an hierarchical management structure, to their postulated environmental impact. This discussion is detailed further at the end of this section.

2.5.2.2 Relative environmental performance of Technologies – Base Metals

The overall flow diagram for the base metals industry is included in Figure 2-22 below. The process routes to be compared are the hydrometallurgical purification of zinc (roast-leach-electrowin process) and the pyrometallurgical purification of copper (smelting). As such the systems analysed included the upstream initial concentration of the ores to metals in concentrate. This study is significant as there are many claims at present that hydrometallurgical process routes have better environmental performance than pyrometallurgical process routes (Monhemius, 1996).

A factor which needs to be taken into account is that of the hazardous nature of the waste being generated by the processes. Hazard is a subjective concept and different definitions are applied in different countries. In this case study the hazard rating applied to wastes has been consistent with the South African Water Act (DWAF, 1998). Within this act there are five groups of hazard ranging from highly toxic (Group 1) to non-hazardous (Group 5). All wastes which fall in groups 1-4 according to this rating have been included as hazardous. Table 2-7 contains ratios of

- Product to total waste produced
- Income to the process to total waste produced by the process
- Income to the process to hazardous waste produced

Including income in these ratios is important as this gives an indication of the ability of the process to pay for its environmental liability (where environmental liability is seen as an indication of the environmental risk associated with a waste; this liability will be greater for wastes which are more hazardous).

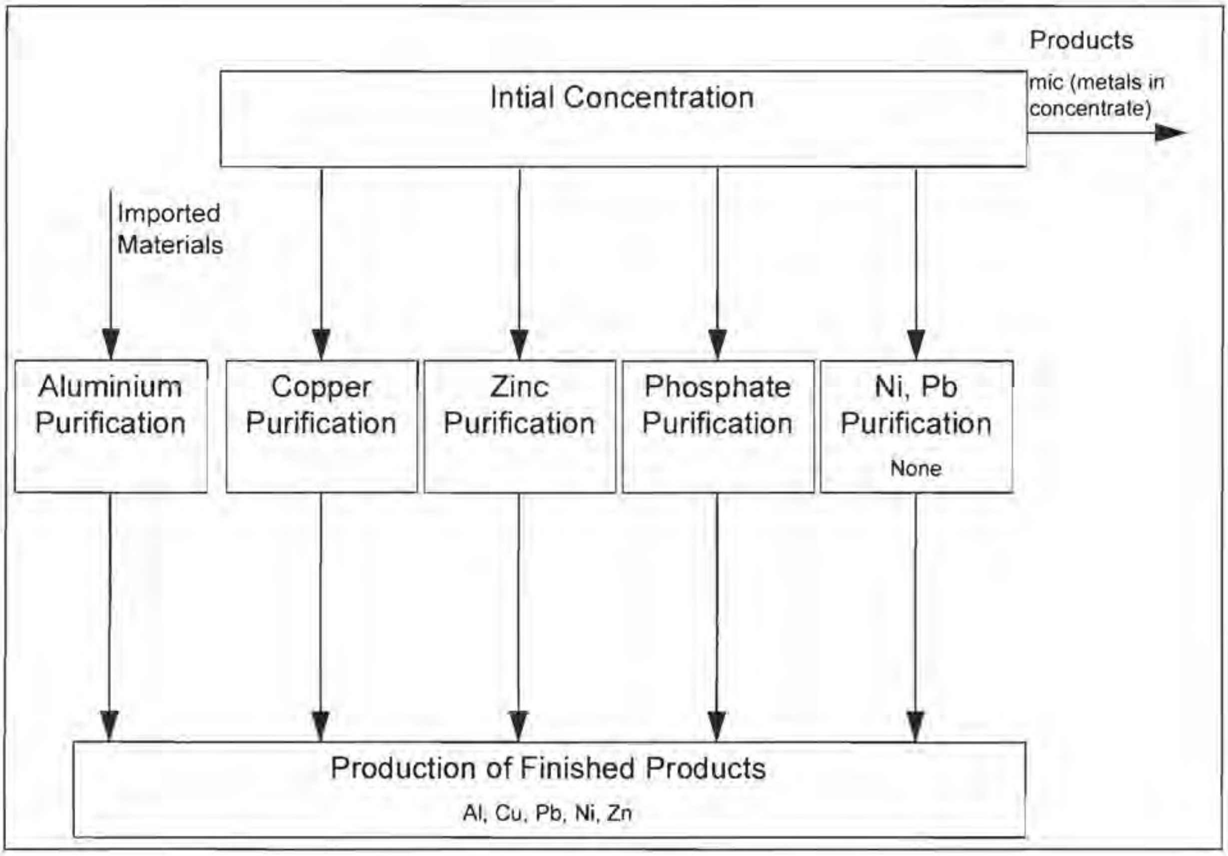


Figure 2-22 *Overall Flow diagram for the Base Metals Industry*

Table 2-7 *Comparison of Total Waste and Hazardous Waste generated in the Production of Copper and Zinc*

	Product:Total Waste (kt/kt)	Income:Total Waste (R '000/kt)	Income:Hazardous Waste (R '000/kt)
Initial Concentration			
Cu	0.002	30	
Zn	0.03	130	
Zn:Cu	14	4	
Purification			
Cu	0.02	820	900
Zn	0.3	3 800	10 000
Zn:Cu	16	5	11
Overall			
Cu	0.003	90	1 300
Zn	0.15	1 800	10 500
Zn:Cu	47	21	8

Studying the first column in this table shows that, in producing the same amount of waste, 47 time more Zinc than Copper is produced. However, Copper has a higher sales value than Zinc. When this is greater value is factored in to the analysis it can be seen that, in producing the same amount of waste, Zinc generates 21 times the income than the Copper process. The Zinc process produces far more hazardous waste however, and the amount of income from Zinc is only eight times that of copper for the same amount of hazardous waste.

This would imply that, overall, the zinc process would be in a better position to pay for remediation of its environmental impact than would copper. There is an initiative in South Africa at present to promote "value-added" processes, i.e., the purification of metals in concentrate (mic). Should this be the case, the income generated by the Zinc industry is eleven times greater than that of the copper industry in producing the same quantity of hazardous waste and thus more attention should be paid to the Zinc industry than the Copper industry in this respect.

Although somewhat cursory, this case study illustrates the concept of comparing disparate technologies and products. This is made possible by the consistent boundary drawn when establishing the various flow sheets.

2.5.3 Strategy Decisions

Again there are different types of decisions to be made. The two presented here do not refer to the same type of strategy. In the first example the strategic decision to be made is which ore body to exploit in the platinum industry. The second strategy referred to is the adoption of one or other approach to allocating wastes to products. This demonstrates the allocation mechanism described in Section 2.4.

2.5.3.1 Comparison of Feed Material – PGMs

The generalised flow diagram for the platinum industry is presented in Figure 2-23 below. The technologies being compared are detailed on Figure 2-24 which is the flowsheet describing the initial beneficiation stage within the industry. Also included is Table 2-8 which details the waste stream from the industry on a component basis. Further detail is added to this waste inventory by presenting it according to unit operation, this is included in Table 2-9. Some of the units in this table are found in the base metals refinery. For further details of the industry see Appendix 2-5.

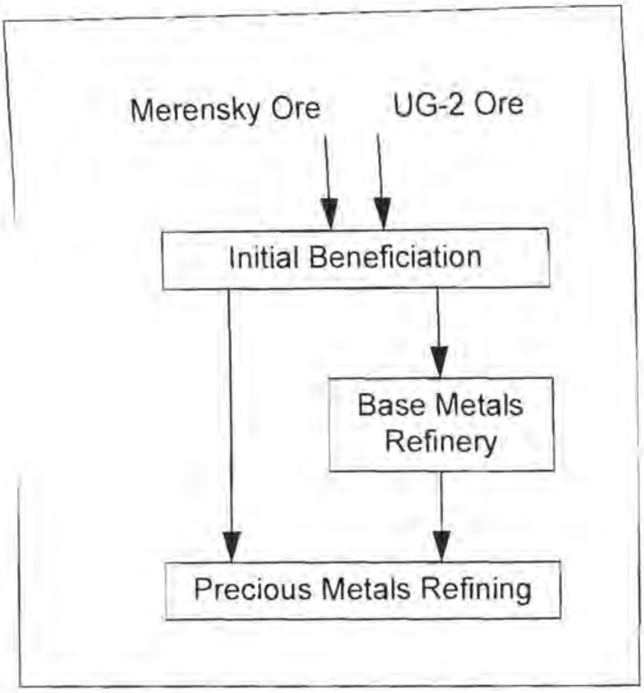


Figure 2-23 *Generalised flow diagram for the Platinum Industry*

Table 2-9 contains details of the waste streams leaving different unit operations within the process. Separating the waste generated by the two flotation and two smelter processes from a waste minimisation point of view may be misleading. The total waste generated by the units is a function of their efficiency and of the amount of material entering the process. The differing nature of the ores also affects the nature of the waste stream. Figure 2-25 and Figure 2-26 are included to clarify the position. These figures reveal which parts of the waste stream can be attributed to the various units on a normalised basis. Values have been normalised with respect to PGMs leaving the unit. This is an elementary calculation as all streams leaving the unit operation are known.

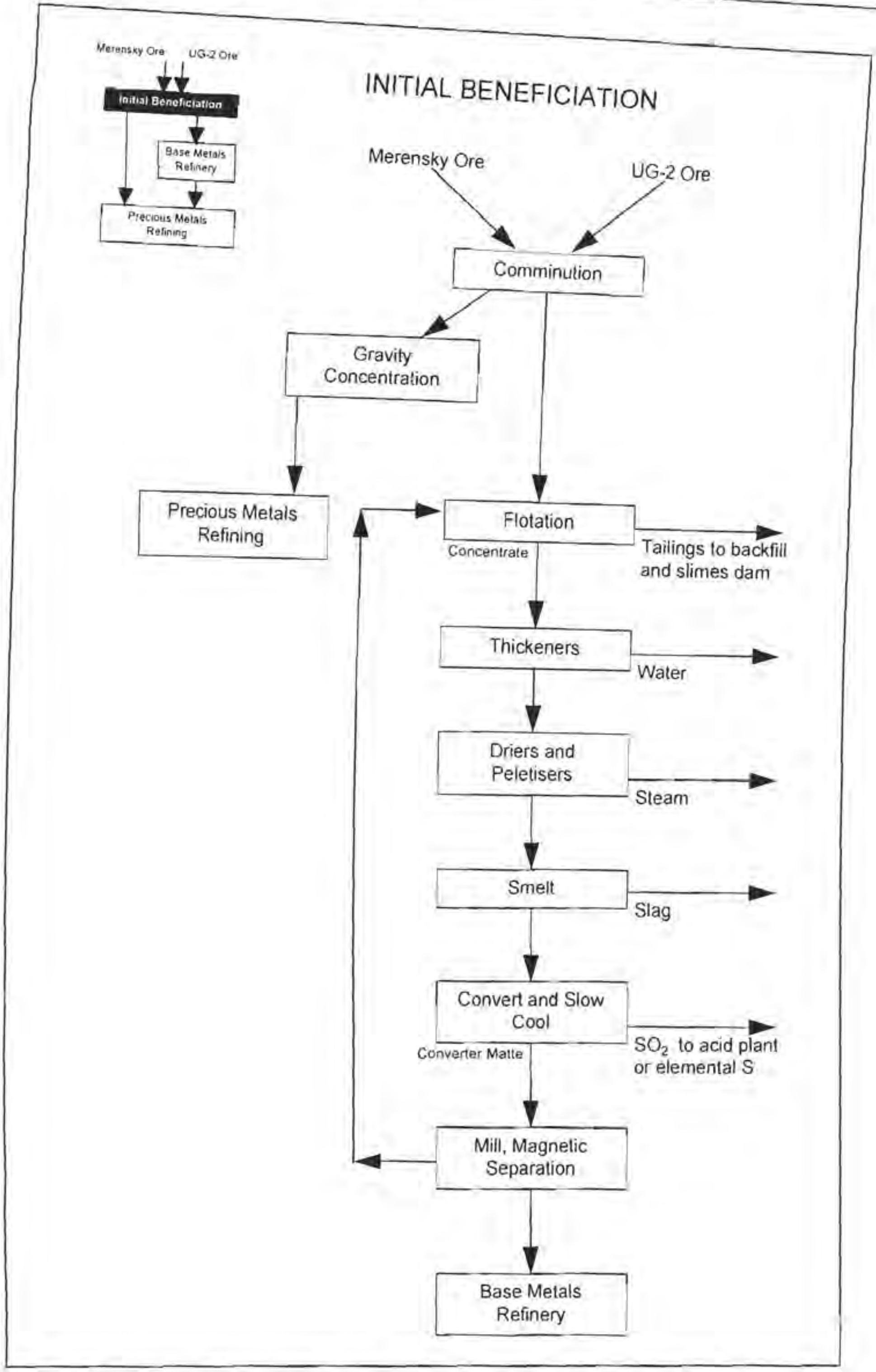


Figure 2-24 *Initial Concentration in the Platinum Industry*

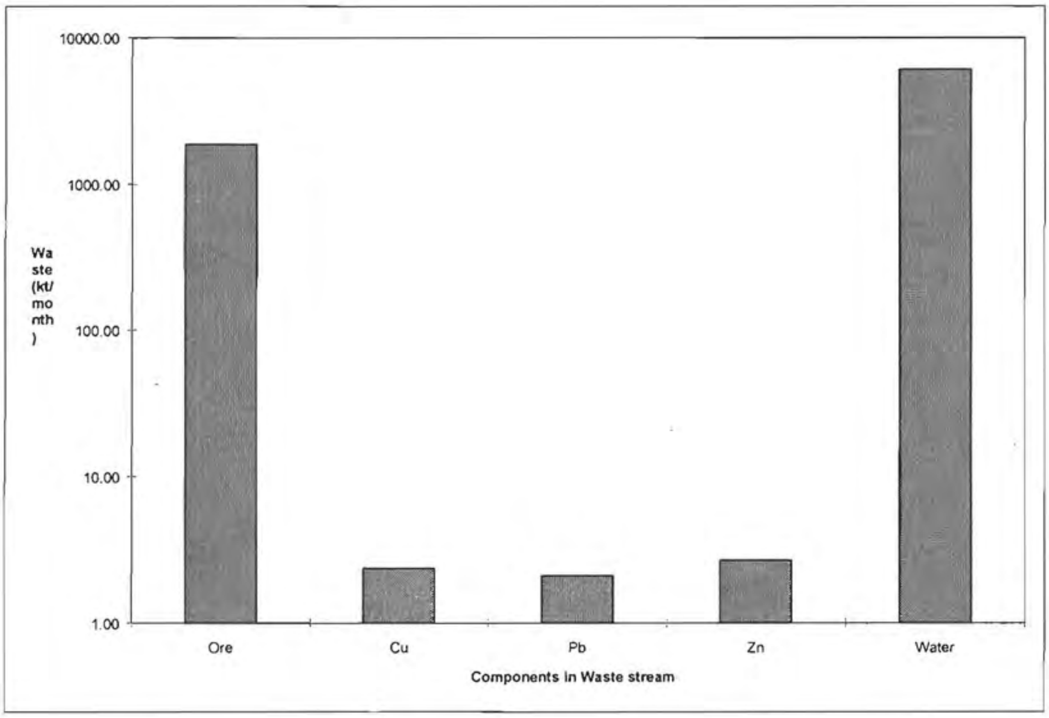


Figure 2-27 *Total waste stream from Initial Concentration in the base metals industry*

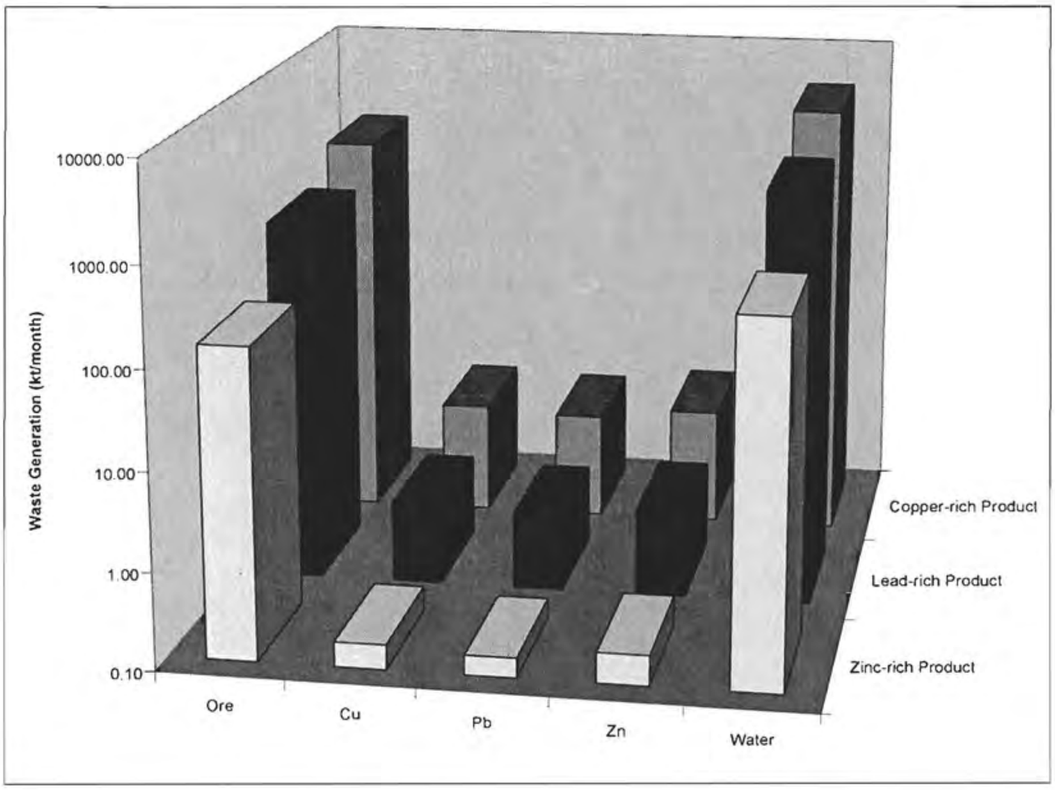


Figure 2-28 *Breakdown of Waste Stream by Product*

in the normalised amount of PGMs leaving the units is directly related to the efficiency of the units in recovery. There is obviously a disparity in the recoveries experienced with the two types of ores. Reagent addition differs between these two processes as do the types of metals occurring in each of the two ores. That there is less ore in the waste for the UG-2 smelter would suggest that the processes upstream of these smelters operate more efficiently.

2.5.3.2 Allocation of waste stream to product – Base Metals

This case study explores the allocation of the waste stream to products within the generalised flow diagram for the base metals industry to be found on Figure 2-22. While the individual processes within the industry may produce a single product (though this is seldom the case), the generalised flow diagram produces a range of products. Allocation is explored in this context. If a process gives rise to more than one product and has more than one point of output from the process then the waste stream can be allocated to each product in accordance with its point of exit from the process. The approach developed makes it possible to allocate the waste stream to that metal according to all the processes involved in its purification.
In this case study the initial beneficiation stage of the base metals industry and its linking to the downstream processes of copper purification and zinc purification are investigated. The initial beneficiation stage yields three products - a lead concentrate, a copper concentrate and a zinc concentrate. These products leave the operation from three distinct stages of the process. The waste stream from each stage can thus be apportioned to the product leaving it according to a set of determined ratios. Waste streams can also be allocated to the products from the two purification stages generating them.

For simplicity the waste stream generated by the initial concentration stage on its own is considered. This is depicted in Figure 2-27.

The waste stream leaves the process at three distinct points which coincide with points at which the products leave the process. It is thus possible to allocate a waste stream to its point of exit from the process and link it to a product stream. These waste streams are illustrated in Figure 2-28. This is a simple example as the unit operation boundaries have been chosen so that waste and product exits coincide, if this is not the case then a more complex allocation algorithm as mentioned in Section 2.2.4 can be applied.

However, the product streams each contain three saleable components - copper, lead and zinc in differing proportions. It is possible to assign the waste stream to a specific component. This allocation can be carried out in two ways. An illustration of allocation on a mass weighted basis is included in Figure 2-29.

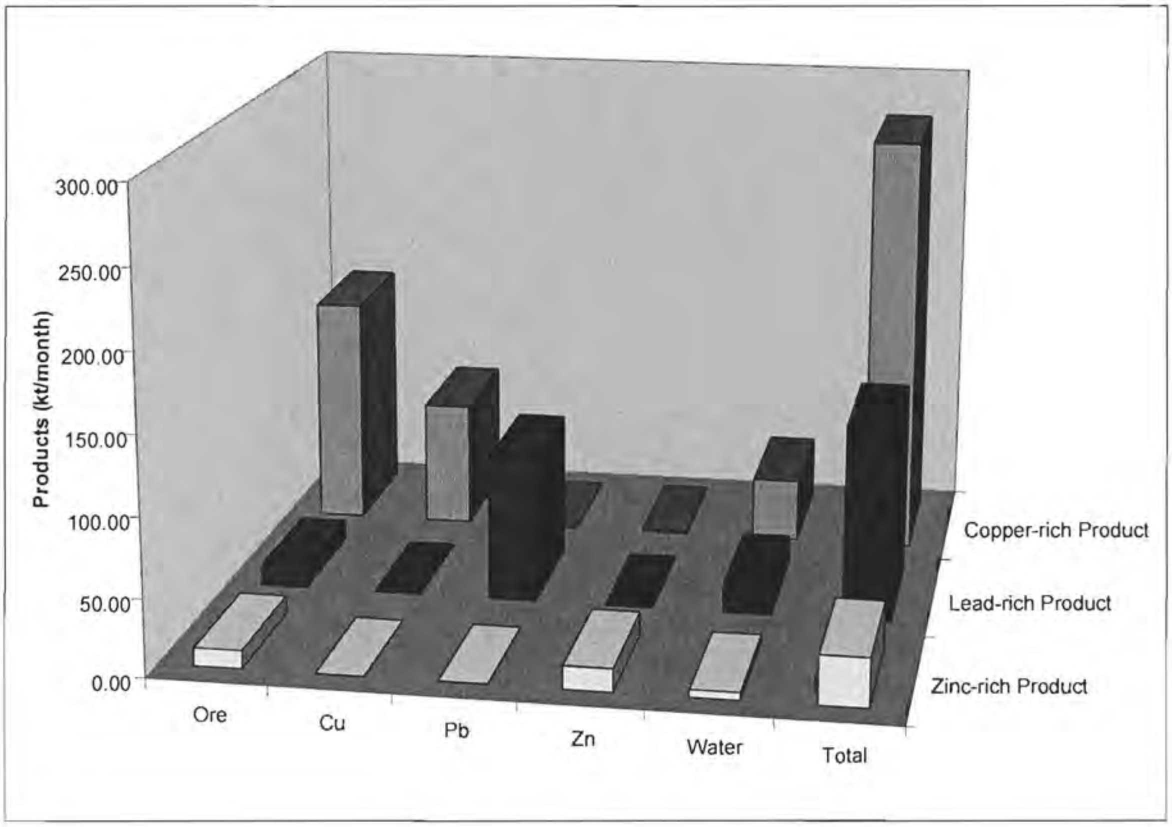


Figure 2-29 *Break down of Products*

Alternatively, wastes can be allocated on a value weighted basis. This is included because the ability of a process to pay for the remediation/re-processing of impacts associated with the wastes which it generates is determined by the income which it earns. In calculating the values in Figure 2-30 the following constants were used (DMEA, 1997):

Copper mic	R 3730/tonne
Lead mic	R 1100/tonne
Zinc mic	R 1110/tonne

("mic" = metal in concentrate)

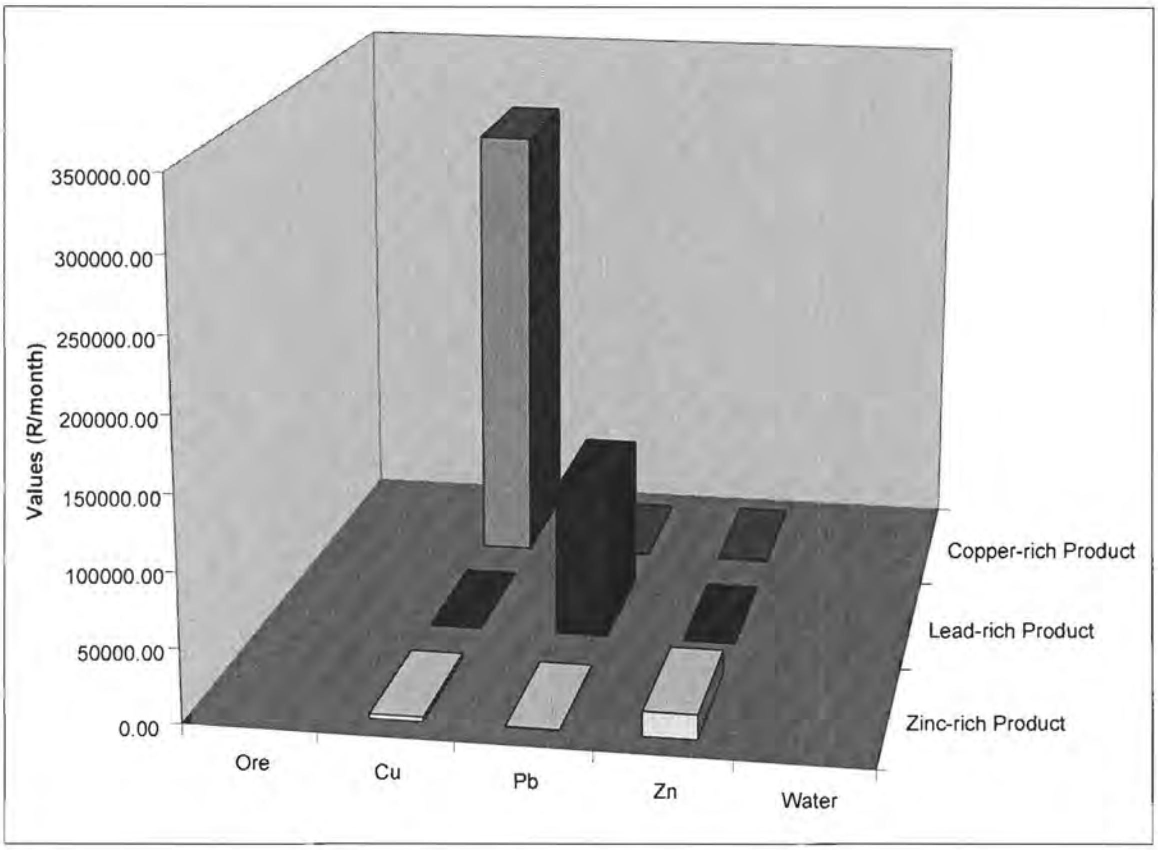


Figure 2-30 *Value of products*

The weightings represented by Figure 2-29 and Figure 2-30 were then used to allocate the waste stream to the specific products using either a mass-, or a value-based approach. The result of this allocation can be found on Figure 2-31. This figure demonstrates that allocating waste relative to mass throughput, or relative to value of product can affect the result of the allocation exercise. This case study demonstrates that the information detail retained in the information structure can be used in a number of ways to support environmental decision making. In the case of a mass weighted allocation it can guide decisions around waste minimisation, while the value weighted allocation can guide decisions on technology choice.

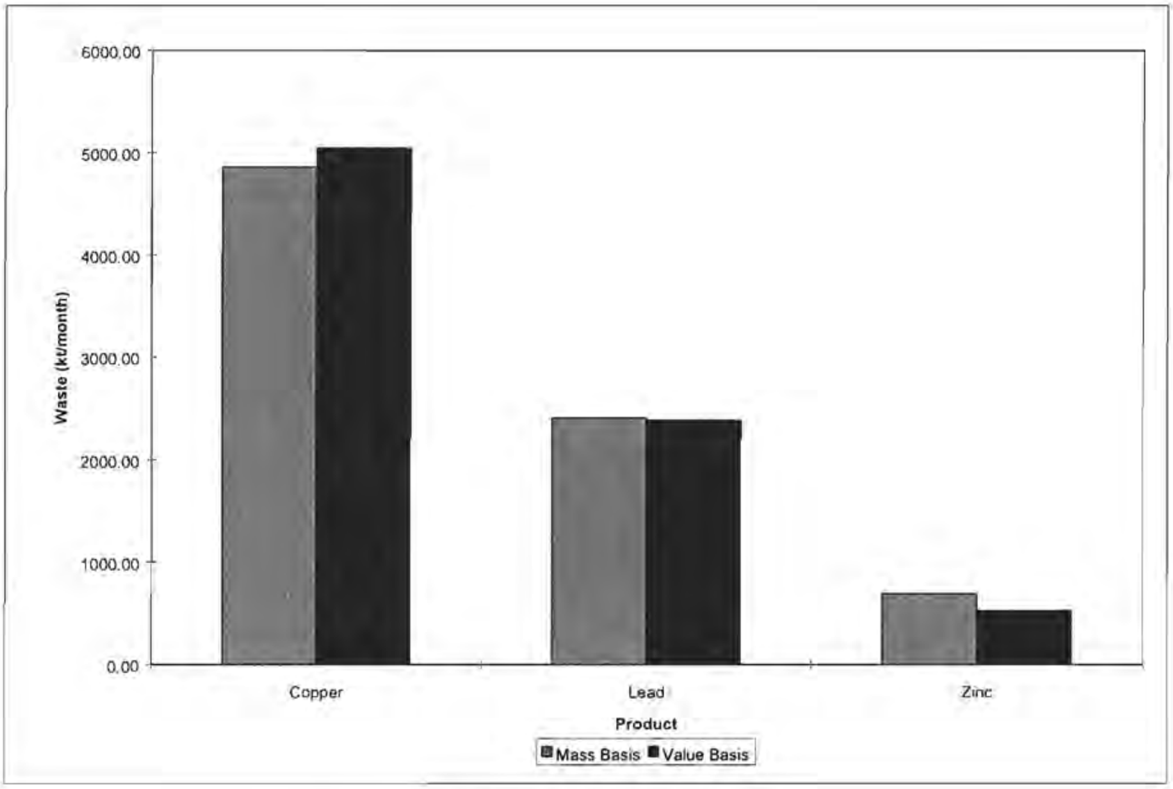


Figure 2-31 *Waste Stream Allocation*

A further decision that can be support using this type of analysis relates to the current South African Department of Trade and Industry initiative to increase the value added to South Africa's primary products - to increase the level to which metals are beneficiated. Reviewing the selling prices for copper where the value of metal in concentrate averaged R3 700 per ton for the year 1996 (DMEA, 1997), while that of metallic copper was R10 200 (DMEA, 1997) a shift in focus for the industry from extraction to purification seems sensible. Analysing the change in the waste stream that this shift in focus would produce can be used to support these decisions.

Figure 2-32 and Figure 2-33 show the differences in the waste generation potential of the various metals once waste has been normalised with respect to the income generated by the product. Referring to Figure 2-32 one can see that for each unit of income for the copper process, less waste is generated in the production of concentrates, than in the production of the refined metal. The cost, when the overall amount of waste generated is normalised with respect to income, is R26/tonne of copper product. The picture for Zinc is different (Figure 2-33). The refining process of this product produces far less waste per unit of income than does the initial concentration phase. The overall waste generation cost for Zinc is R1/tonne.

Thus, when value-added processes are contemplated, if the only factor to be considered is their waste generation potential in relation to income derived, then zinc processing should be chosen in preference to copper processing. This analysis needs to be placed within the context of resource available and supply and demand in the international market. This is included to illustrate the types of decision it is possible to support using the information structure developed.

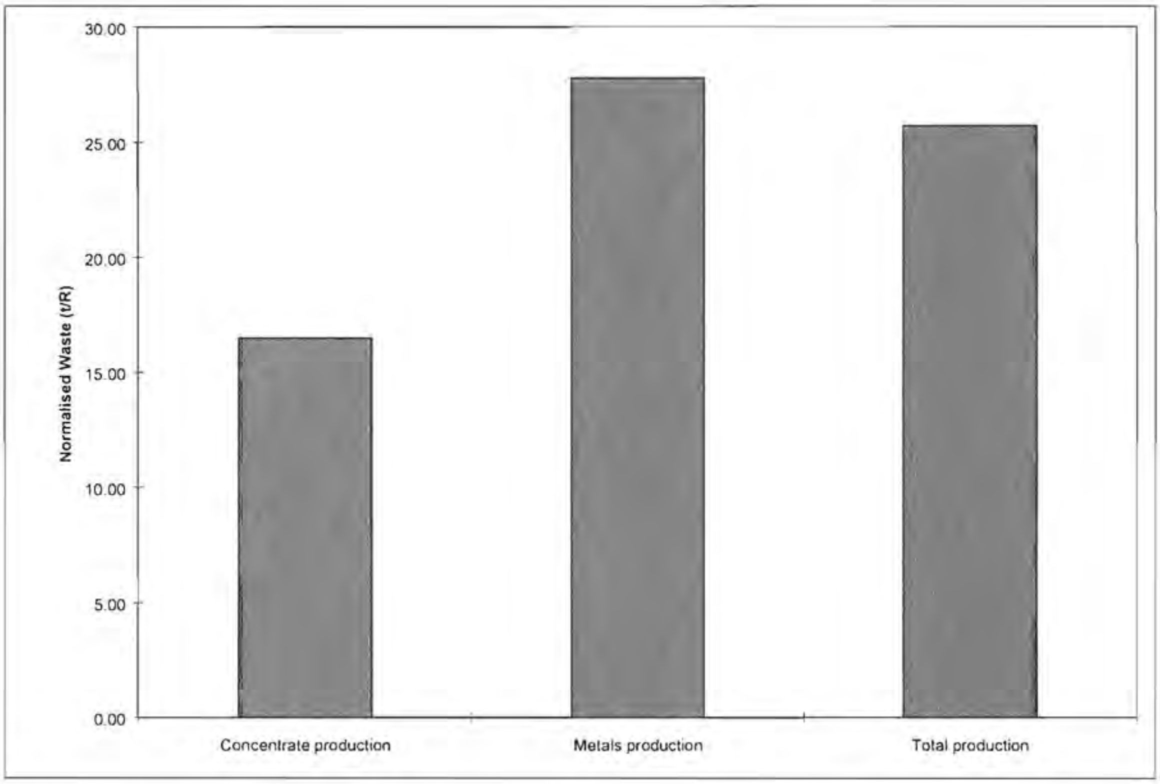


Figure 2-32 *Waste Generation of the Copper Industry Normalised with respect to value of Copper produced*

This methodology is at odds with the allocation methodology as described in ISO 14 001 (ISO, 1999) where allocation is never made on the basis of economic performance. However, this approach does facilitate an analysis of an industry that has value when decisions on resource extraction and beneficiation are to be made.

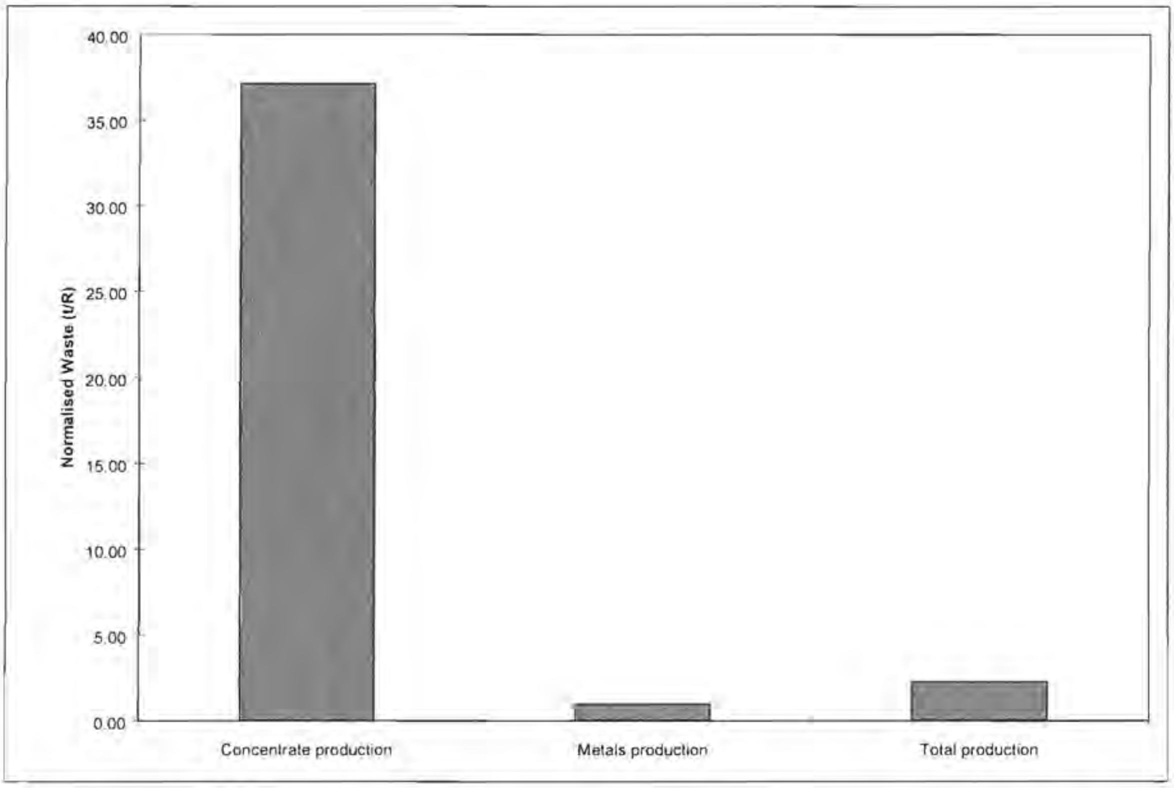


Figure 2-33 *Waste Generation of the Zinc Industry Normalised with respect to value of Zinc produced*

2.5.4 Strategic Considerations

The case studies presented here take a strategic view of the industry within which minerals processing can be viewed as a series of interlinking processes. The case studies presented in this section have been included to demonstrate the fact that minerals processes do not exist in isolation but rather form part of more complex industrial systems. This is due to the complex nature of mineral ore bodies. While it is possible to identify the major mineral present in the ore body as the primary product, a significant number of by-products can be produced. However, it is not always cost effective to develop purification systems at each plant. Thus there is significant potential for separate processes to be integrated in order to maximise the utilisation of a single mineral resource.

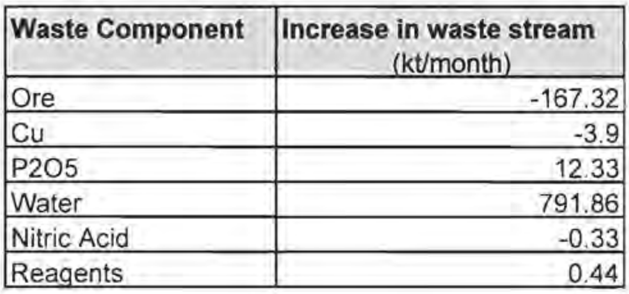
The case study included in this section investigates the linking of a phosphate producer with a copper smelter. The reason for this is that the ore-bodies being exploited by these two companies are adjacent. Thus there is some phosphate in the copper ore, and some copper in the phosphate ore. Instead of each company developing a small plant to recover the by-product material in their feed-stream, they route their waste to the process belonging to the other company. This maximises the recovery of the by-product.

2.5.4.1 Interlinking of Processes – Base Metals

There is an interesting interlinking of processes between the major copper producer and downstream production of phosphate rock. What could be considered a waste stream from the copper process is sold on to the producer of phosphate where the phosphate contained in the waste stream is removed. Thus the waste ore becomes a "product". The phosphate producer also sells a stream on to a fertiliser manufacturer.

A comparison of the plants working on an interlinked basis was made with the processes working independently. It was assumed that the phosphate producer would not increase production to make up for lost capacity should the waste stream from the copper producer not be available. Table 2-10 is included to show the change in the waste stream when the processes are decoupled. The values in this table show the percentage change in the waste stream as a ratio of the base-line (or coupled) waste stream; i.e., a negative value denotes a decrease in the waste stream on uncoupling of the process.

Table 2-10 *Increase in waste stream when the copper stream is sold on to the phosphate producer*



Waste Component	Increase in waste stream (kt/month)
Ore	-167.32
Cu	-3.9
P2O5	12.33
Water	791.86
Nitric Acid	-0.33
Reagents	0.44

As expected, the amount of solid waste decreases as does the quantity of copper being lost. However quite a large increase in the water waste stream occurs because a significant amount of water is used in the phosphate process. Figure 2-34 has been included to give an indication of the masses of material involved. Note: This figure is plotted on a log scale.

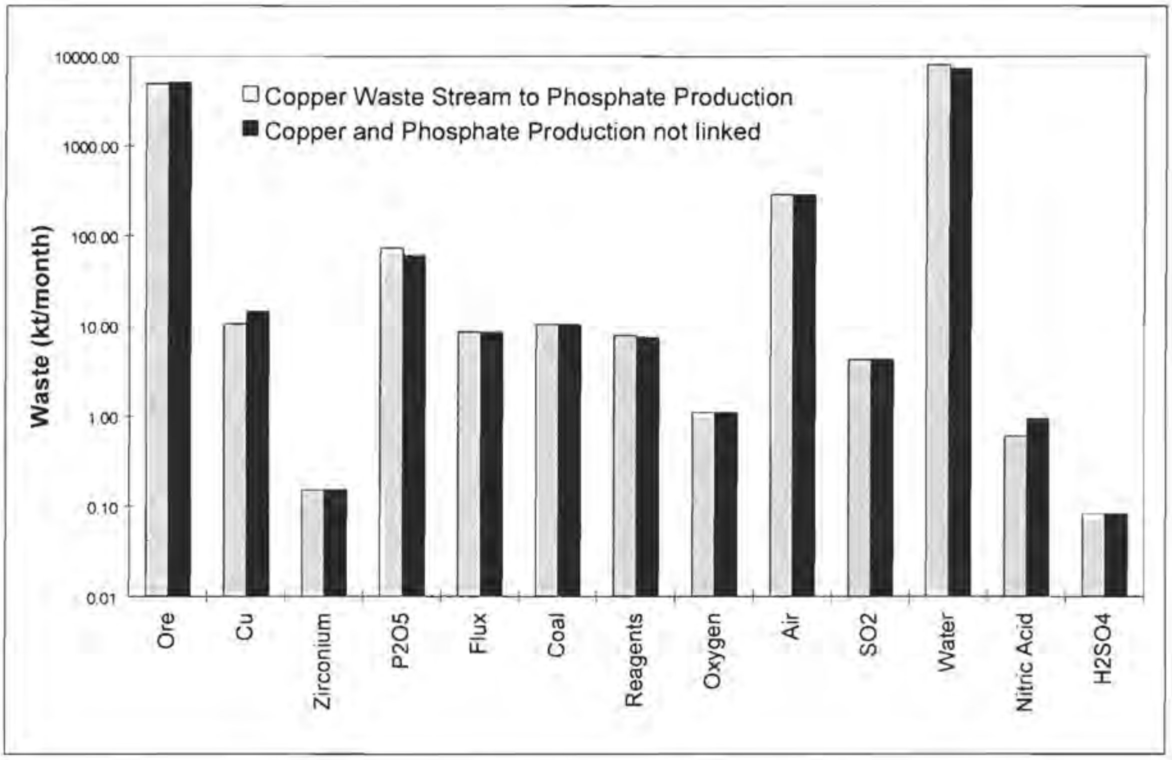


Figure 2-34 *Change in Waste stream with decoupling of Processes*

What this figure shows is the relatively low mass increase that the values in Table 2-10 represent. In studying the waste stream components it becomes obvious that the nature of the waste will not change radically. The coupling of the two processes does not introduce a new component into the waste stream.

Table 2-10 demonstrates that the magnitude of the waste stream increases with the coupling of the processes. The magnitude of this change is 600 kt/month. In conjunction with this increase in waste there is an increase in product. This increase in the product stream is reflected in Figure 2-35 which shows an increase in the phosphate stream and in the stream available to the fertiliser producer.

If a phosphate product value of R86.00 per ton is assumed (DMEA, 1993), and a phosphate value of R40.00 per ton in the stream sold to the fertiliser producer is estimated, the resulting increase in income for the phosphate producer would be R4 500 000 per month. The increase in income

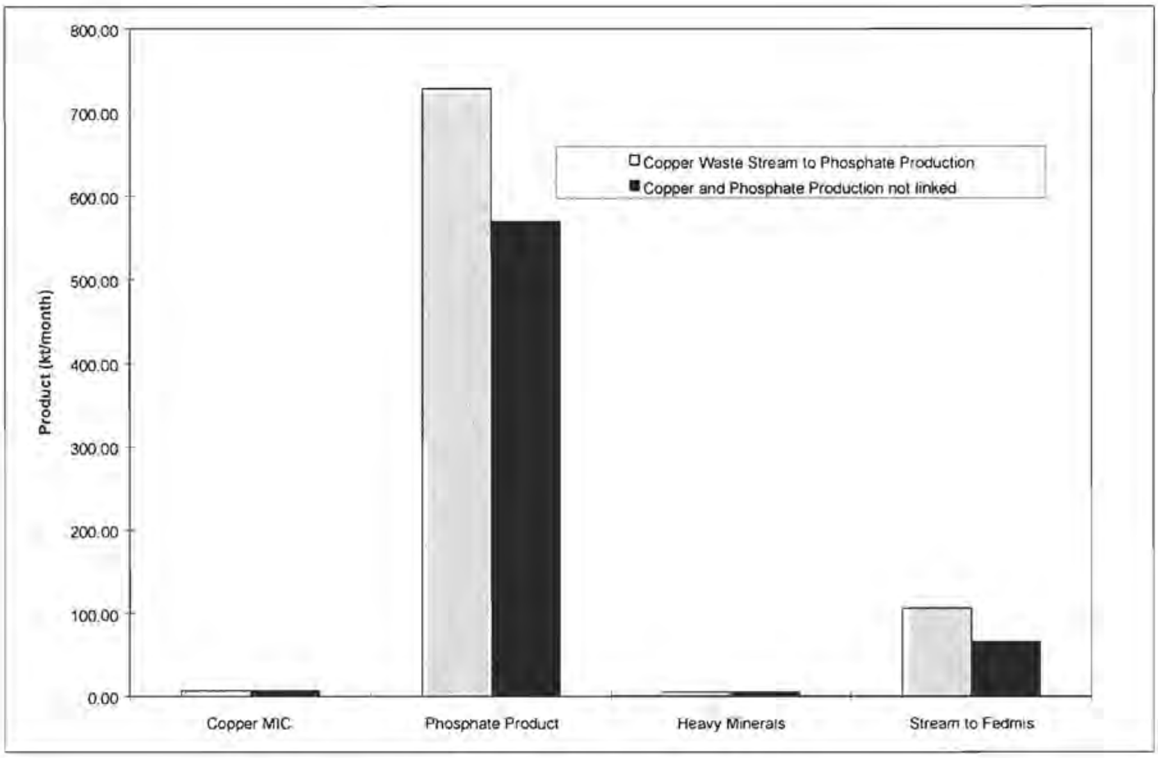


Figure 2-35 *Change in Products with decoupling of Processes*

per increased kiloton of waste is R7200. This result is counter-intuitive in that the total waste increases when a waste stream is processed.

It must be recognised that this case study is an investigation of the decoupling of technologies in plants in existence in the South African industry. Further information would be required if another source of phosphate ore (to make up the volume of ore from the copper process on decoupling the processes) were to be sought. The intention of this case study is to explore an existing interlinking of minerals beneficiation plants, not to propose development scenarios for the industry.

The case study demonstrates two aspects of the information structure developed:

- The information structure can be used to support decisions that are strategic in nature
- It is possible to link models together to support decisions on the integration of the minerals industry

2.5.5 Cross-sectoral Considerations

There are a number of cross-sectoral analyses which can also be made more easily by this approach. The first to be offered here is one which highlights the importance of the minerals industry, and particularly the gold industry, within the South African economy. However, when the industry is viewed with respect to a number of indicators other than economic indicators (such as the provision of jobs) a different view of the industry is presented. This case study links to the discussion of normalisation presented in 2.2.4.2.

The second case study views the energy requirements of the industry in the context of the industry's waste generation potential.

2.5.5.1 Economic Considerations

An analysis of the waste stream normalised with respect to economic and labour indicators is presented here. This demonstrates the performance of different minerals processing sub-sectors with respect to indicators other than the purely economic one which are usually used to analyse the industry.

Information on the economic performance of the industry, as well as the number of jobs offered by the industry as a whole is not freely available. For this reason values from the 1993 production year have been used. The mining industry as a whole made the following contributions to the national economy in 1993:

Table 2-11 *Economic contribution of the Minerals Industry*

Indicator	R 000 000	%
Contribution to GDP	30 150	8.4
Contribution to State Revenue	1 102	1.5
State Aid to the Mining industry	25	
Contribution to Exports	38 118	48.7
Gold's contribution		29.7
Employment*	617 147	4.1

* Number of employees

The following values can be calculated if one considers the employment offered by an industry and normalises the number of jobs with respect to the waste generated by it (The ferro-alloys industry is not included as figures are not available.):

Table 2-12 *Employment offered by the Minerals Industry normalised with respect to the waste generated by the industry*

Sub-sector	**Waste Generated** (t) per Job offered
Gold	14644
Coal	624
Platinum Group Metals	703
Base Metals (excl Phosphate)	5885

It becomes apparent that, from a waste generation point of view, jobs in the gold mining industry are very costly. - More than 14 kilotons of waste are generated for every job offered. Employment opportunities per ton of waste in the base metals industry are also fairly expensive. This reflects on the advisability of the present government initiative concerning value-added stages in the base metals industry.

The coal mining industry generates the least waste per job. It is closely followed by the platinum industry. However, should some sort of rating system which accounts for the type of waste generated be used, then the picture would be very different. It would reveal that wastes produced by the coal industry are fairly benign compared to those generated by the platinum industry.

Closer scrutiny of the value of sales from the industry and normalising of these values with respect to the amount of waste generated, results in the values quoted in Table 2-13 below :

Table 2-13 *Waste generation normalised with respect to sales value for the industry*

Sub-Sector	**Waste Generated (kt) per Sales value (R000 000)**
Gold	41
Coal	5
Base Metals	8
PGMS	12
Ferro-alloys	4
Sands (Titanium est)	14

Again, gold mining waste generation is pinpointed as being very high relative to the income earned from sales. The coal and base metals sub-sectors far out-perform the platinum sub-sector and are more on a par with each other. Ferro-alloys generate surprisingly little waste in relation to their sales value. As previously indicated, the value used for the sales of titanium is an estimate. However, it does reflect poorly on the industry.

2.5.5.2 Energy Usage

The Mintek reports "Review and Analysis of Energy Use in the Metal Industries" (Granville *et al*, 1993) were used in estimating the energy consumption for the sector. These give consumption figures for the various processes. The coal requirements for the pyrometallurgical processes were included in the mass balances (and thus the waste inventories) for the various sub-sectors. In this analysis, therefore, only the electricity consumption is given for each stage. Information on energy provision from other sources is not available and thus has not been included in this study.

Table 2-14 contains a breakdown of the energy usage for the minerals industry. Energy use has been normalised with respect to both mass and value of product.

Table 2-14 *Details of Energy use in the South African minerals beneficiation sector for the 1996 production year*

Sub-sector	**Production for 1995**		**Electricity Used**		**Electricity Consumption**	
	Mass (kt)	Value (R000 000)	Concentration (GWh)	Purification (GWh)	Mass (GWh/kt)	Value (GWh/R000)
Gold	0.52	24 000	4 700		8 900	190
Base Metals						
Initial Conc	400	820	850		2.1	1 000
Aluminium	170	800		2 900	17	3 600
Copper	130	1 400		220	1.7	160
Zinc	94	290		420	4.5	1 400
PGMs	0.17	6 300	1 700		10 000	280
Ferro-Alloys						
Initial Conc	35 000	3 400	450		0.01	130
Ferrochrome	830	880		3 300	4.0	3 800
Mn-Alloys	1 700	1 200		6 300	3.6	5 300
Silicon	100	160		1 000	11	6 600
Steel	7 600	4 100		27 000	3.6	6 600
Mineral Sands	100	1 500	2.1		0.02	1.0

Table 2-14 compares total energy use in the various sub-sectors. This figure clearly demonstrates the dominance of the steel-making sub-sector in energy consumption within the industry. The gold sub-sector also draws a large amount of energy. This can be ascribed to the size of the industry, i.e., the amount of ore which it processes.

Two other comparisons can be made from this table. Energy utilisation at different points between the concentration and purification processes can be compared. Normalisation with respect to mass, and to value, of product can also be compared. Interpretation may be easier if one uses Figure 2-36 and Figure 2-37, which follow.

Figure 2-36 contains details of energy use normalised with respect to mass of product. The fact that a great deal of energy is required by the comminution stage included in the initial benefication stages of all sub-sectors may explain this. Furthermore, low grades of ore are processed in the initial benefication of gold and platinum, to obtain the same amount of product far more ore has to be crushed than in, for example, the copper industry. That the platinum process uses less energy than the gold process, can be ascribed to the fact that platinum ores are far softer than gold ores and so require less milling.

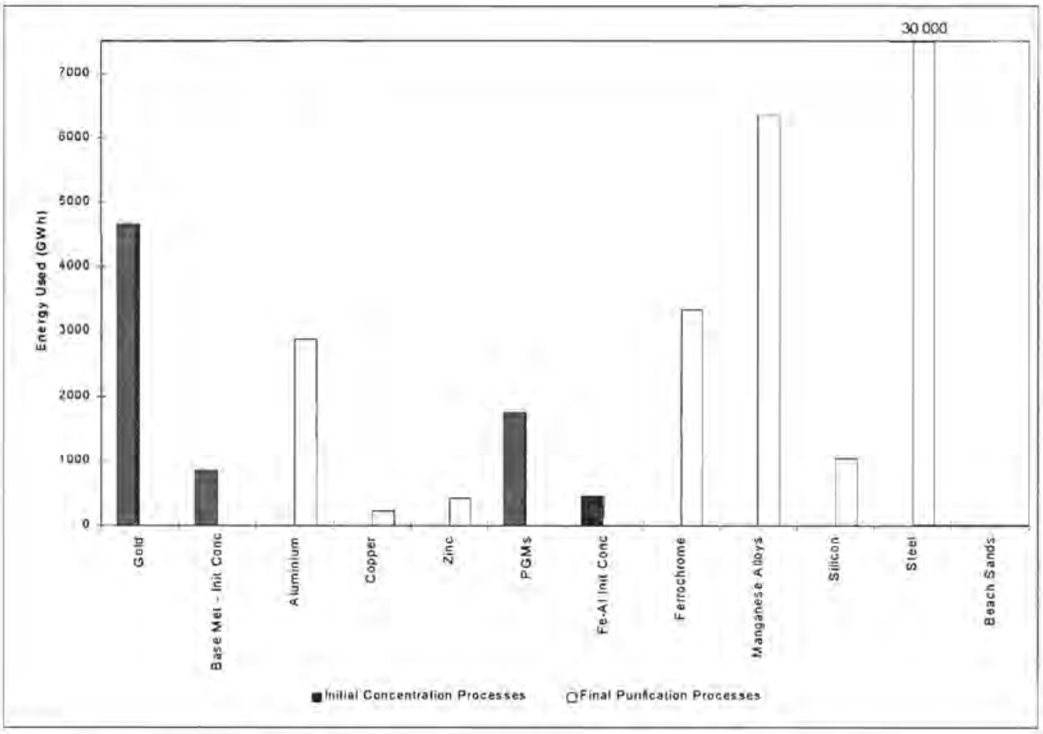


Figure 2-36 *Comparison of Total Energy Used in the Production of Different Metals*

All the purification processes, except zinc electrowinning, are smelting processes. As would be expected, the amounts of energy drawn by the smelting processes, which are similar, correspond closely. The quantity of energy used in zinc electrowinning is fairly high.

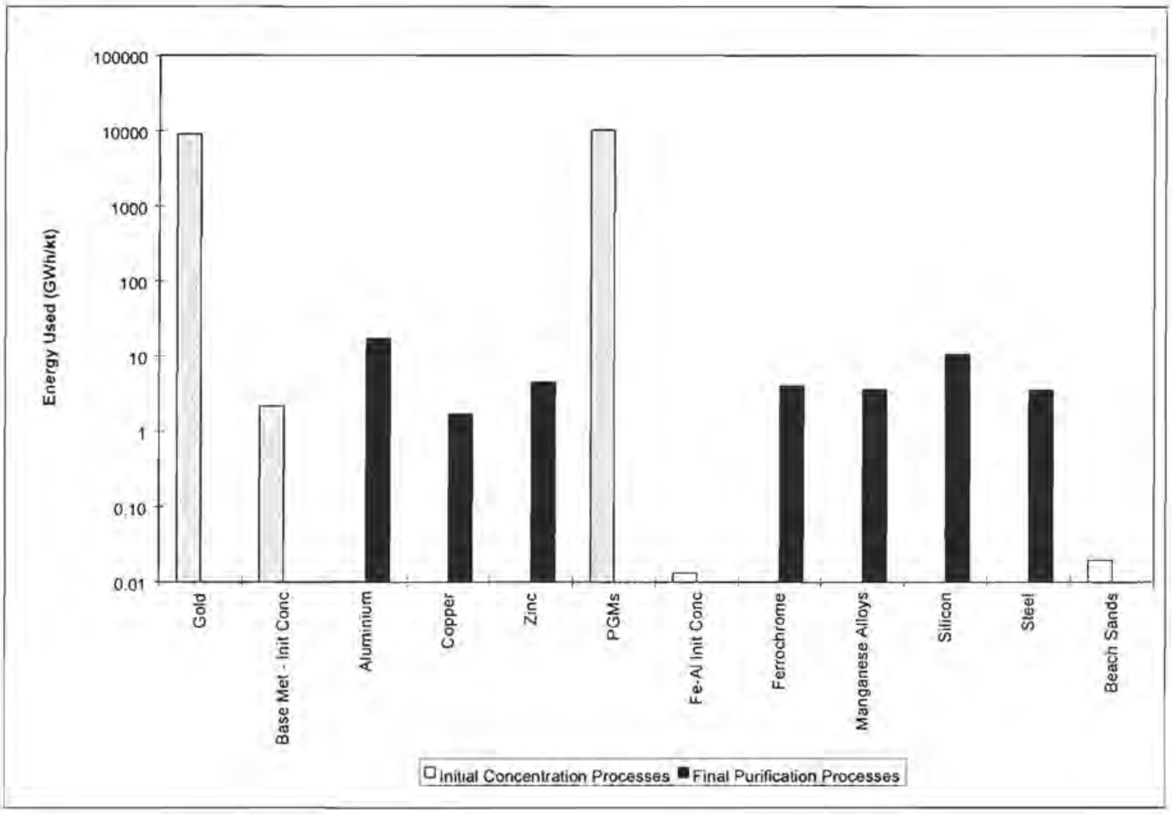


Figure 2-37 *Energy used normalised with respect to mass of product*

Figure 2-37 is included to show a "return on investment" with regard to energy use. This compares the two methods of normalisation, i.e., with respect to mass and with respect to value of product, and makes the energy intensity of the ferro-alloys industry very obvious. Far more energy is used relative to product value generated than in, for example, the gold industry.

Because the ferro-alloys and copper industries are far less able to pay for electricity consumption, they have reduced their use of this service. However, the industries with a higher value product (gold and platinum) have had less need to attend to this - so their energy usage is very high in comparison to product output. This shows the affect of economic drivers on process efficiency.

2.6 *Summary of Information Structuring*

The case studies presented above are based on the approach to information structuring within the context of flowsheet development as presented in this section. The information structure is consistent with the requirements of LCIs. The case studies included in this section demonstrate that it is possible to use LCIs to support environmental decisions. However, as these case studies demonstrate, the types of decisions that the information structure can support are many and varied. It is thus necessary to place them in a more generic framework.

Table 2-15 describes such a generic framework. In this table, different decisions are grouped into generic categories according to their nature. In many ways this grouping also depends on the position of the decision maker within the company structure. The table also shows how the decisions are interlinked and where information from one decision cycle is transferred to another. Decision cycles have been mentioned in Section 1 and will be described in more detail in Section 4 of this thesis.

The gold case study demonstrated the different decisions which can be taken at different points in the management hierarchy of a company. For example, a change in process route or technology choice may be made by the higher echelons of management, and a change in operating unit efficiency by senior plant personnel, while a change in a single process variable for one unit operation may be decided by a plant operator. Figure 2-38 details the effect of three such changes, the first in a process route, the second in the efficiency of the CIP unit and the third in an increased wash ratio in the Filtration unit. This figure shows how the waste stream generated would change according to the decisions detailed.

All of the case studies can be located within the matrix of decisions as proposed by the UNEP (1999). This has been done in Table 2-16 below.

Table 2-15 *Examples of decision situations requiring environmental information (after UNEP, 1999)*

Level of Decision	Interactions	Decision Process/ Cycle	Examples of situations requiring environmental information
Operational Level		1. Operational management (including operational purchasing and procurement)	- Compliance with regulation - Environmental management - Product stewardship and chain responsibility - Supplier choice - Benchmarking
		2. Communication and marketing	- Marketing decisions - Ecolabelling - Environmental reporting
Tactical Level		3. Design and development (products, services and processes)	- Product development at different levels - Process development - Technology development
Strategic Level		4. Capital investments and acquisition	- Investments in new technologies or product lines - Permit decisions -Acquiring another company
		5. Strategic planning	- Policy development - Development of new technologies - Strategies for research and development

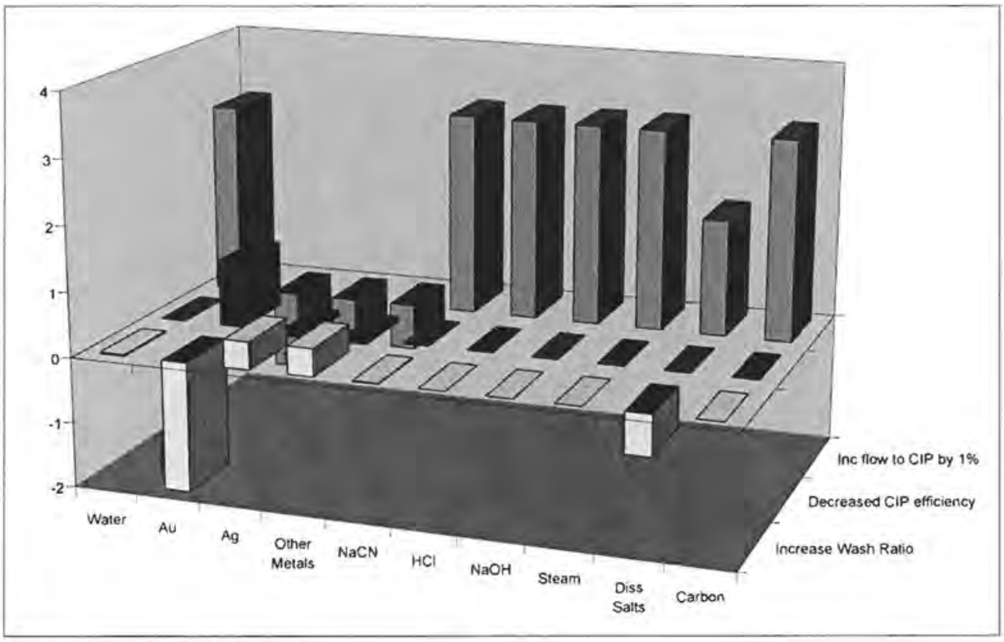


Figure 2-38 *Changes in Waste stream for different levels of decision making*

Table 2-16 *Case Studies and Generic Decision situations*

Level of Decision	Decision Process/ Cycle	Relevant case studies
Operational Level	1. Operational management	-Historical technology advances - Effect of changing operating variables
	2. Communication and marketing	- Allocation of waste stream to product
Tactical Level	3. Design and development	- Improvement in technology - Interlinking of Processes
Strategic Level	4. Capital investments and acquisition	- Relative Environmental performance of technologies - Comparison of feed materials
	5. Strategic planning	- Building Industrial developments - Economic considerations - Energy Usage

While all of these decisions are important it must be recognised that all of the case studies offered are based on existing processes and plants, i.e., they have taken place within the context of process analysis. The information structure developed has been illustrated to have application for decision support within process analysis. However, the decisions taken during process design have a profound affect on the environmental performance of a process – this will be detailed in the next section. It is for this reason that the information structure will be investigated further within the specific application of process design. In this context it will be used as a decision support tool in process synthesis.

3 Decision Making in Process Synthesis and Design

Section 2 of this thesis presented an information structure to support environmental decisions in the Minerals Industry. That section also included an indication of different contexts in which decisions can be made. While all these levels of decision are important it must be recognised that decisions at different points within the life of a project will have different effects on the overall environmental impact associated with that project.

In this section it is argued that the cumulative environmental performance of the process is most sensitive to decisions taken during process design. However, during design there is little environmental information available to support the decisions taken. This is of further significance within the minerals industry where notable environmental impacts are manifested for extended time periods after project completion. In this context the lack of information during design becomes a significant element in the decision making process. It is important to gather all significant information available during design and ensure that it is used to best effect, the so-called "planning for closure" approach.

The tools of process synthesis are commonly used to assist in decision making during design. Process synthesis is an approach to structuring and using the available information. This section also contains a literature review of current thinking on process synthesis for environmental evaluation and optimisation of technology choice.

3.1 Why the focus on Process Design and thus Process Synthesis?

The physical structure of the minerals processing industry is such that it poses a number of problems as far as planning for closure is concerned. The industry processes low concentration raw materials into higher concentration products with significant energy input. Table 3-1 shows average feed concentrations for the industry (calculated from industry averages for the 1996 financial year). As a result, significant quantities of waste materials are unavoidable. This is true both for the initial beneficiation stages where metal concentrates are produced, as well as for the various value-added stages such as the purification of metals by electrowinning. Thus adopting a waste minimisation approach to waste management problems within the minerals industry will not of itself present a comprehensive solution to environmental problems.

Sector		**Average Concentration** (mass weighted)
Gold		4 g/t
PGMs	Noble Metals	5 g/t
Base Metals	Copper	4%
	Lead	6%
	Phosphate	8%
	Zinc	5%
Ferro-Alloys	Chromium	40%
	Iron	60%
	Manganese	40%
	Vanadium*	2%
Mineral Sands		1%

*(as V_2O_5 in Fe-rich ores)

Table 3-1 *Average Feed Concentrations*

A further problem posed by the physical nature of the industry is the fact that the feed materials are thermodynamically stable. In order to impose increased order on the system (by decreasing the disorder represented by the dispersion of the metals within the ore) significant input of energy is required. This thermodynamic constraint goes beyond energy provision when opportunities for waste recovery/reprocessing are entertained. There is a need to consider explicitly "second law" inputs in terms of exergy (combined energy and entropy). This analysis is particularly relevant when examining material cascades within the minerals economy, e.g., ferro-alloys to steel to scrap to ferro-alloys.

Wastes from minerals activities are themselves usually very diverse. The waste stream from a single minerals processing plant can contain a variety of metals as well as water, sulphur, aqueous salts, organic and inert materials. Environmental liability arises from the discharge/disposal of these wastes. It is, however, not a simple matter to quantify this liability, which is determined, to a great extent, by fate and transport considerations. The liability associated with a waste is dependent also on the ability of the local environment to absorb the impacts associated with the waste; its so-called "assimilative capacity". It is not only the amount of material discharged to the environment which is important in these calculations, but also the rate of such discharge, and, in the case of metals, the rate at which these are mobilised within their environment. These factors together determine the total quantity of waste which the environment is able to absorb before a threshold level is crossed and irreparable damage is done. For these reasons the geographic location of the process is important as are waste management regimes adopted.

The previous discussion highlights the fact that it is a difficult task to assign strict environmental liability to waste management practices within the industry. It needs to be recognised also that the ability to improve the environmental performance of minerals processing activities rests principally with the companies involved. The challenge therefore is to develop a strategy for quantifying environmental liability in a manner which provides a direct link to waste generating processes. By doing so, critical points of waste generation can be identified in so far as they relate to process equipment choice, operational strategy and resource selection, which together define the ambit of technology selection.

This linkage is informed by the impact assessment stage of LCA and is described in Section 4 of this thesis. By making this express linkage, operating companies are afforded the opportunity to bring an awareness of environmental liability directly into the decision making process. This should ensure that the only limitation on the environmental performance of the process is thermodynamic rather than "artificial", as would result from inappropriate technology choice. The concepts of "artificial" and avoidable" inefficiencies are illustrated in Figure 3-1. An "artificial" waste can be defined as the difference between the best achievable performance of available technology and the design performance level of an alternative technology. In Figure 3-1 two technologies are compared. Neither achieves the thermodynamic performance limit for the system, though technology B is clearly better than technology A. Technology B is operating at the current technological limit. Our design objective is to move to a situation where the operating efficiency of our selected technology achieves the thermodynamic limit for the system, i.e., to close gap ⊗. In this context, the thermodynamic limit (which will always be less than 100%), reflects the maximum attainable conversion efficiency of primary ore to product. The aim of "clean technologies" and clean production is to drive the performance of a system towards this thermodynamic limit. This is on line with the thinking of Connelly and Koshland (1997) who present a thermodynamic argument approach to industrial ecology.

"Avoidable" wastes are those that can be overcome by good management practices. These are the wastes that are classically addressed as part of a "cleaner production" drive. Addressing them has the potential to generate significant economic returns. However, overcoming this avoidable waste

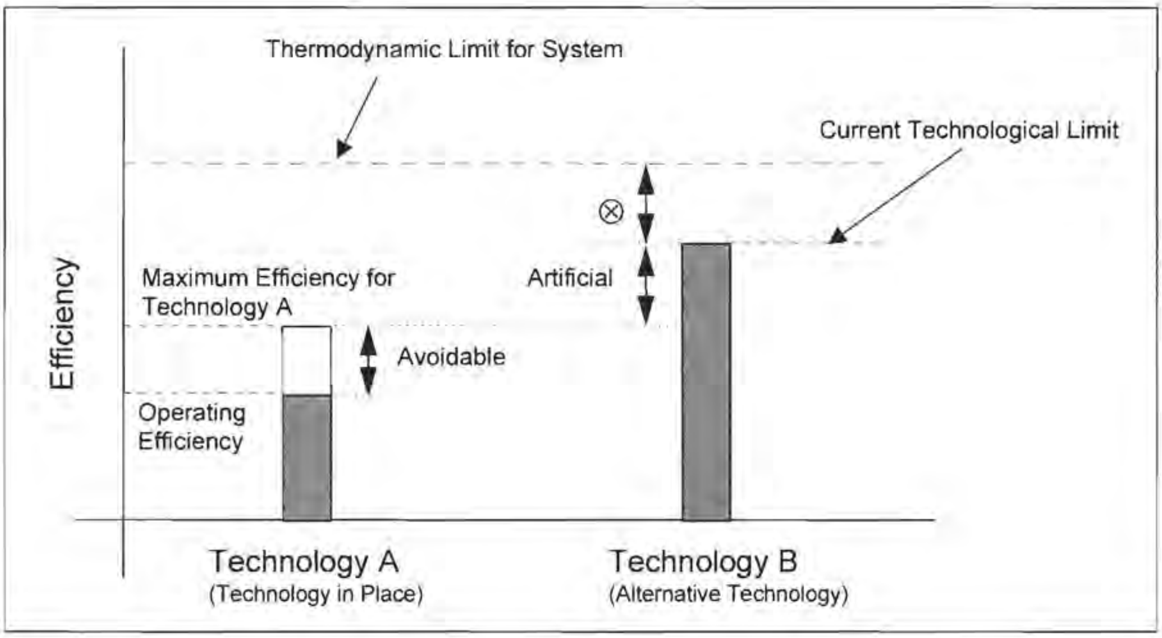


Figure 3-1 *Thermodynamic Limits to Process Efficiency*

is only good management (environmental or otherwise). The true challenge arises when the operating efficiency of the technology in place is reached. If an improvement in environmental performance is to be affected it will be necessary to re-engineer or re-design the process to improve the operating efficiency of the process. The audit trail present in Section 4 of this thesis will aid this process.

These distinctions are important in the minerals processing industry where valuable products are dispersed in the ore matrix. This can be described as a situation with high entropy. The recovery of product from the dispersed phase requires significant energy input to concentrate the material. This results in a decrease in the entropy of the product, but an increase in the entropy of the overall system due to dissipative processes including waste generation. The challenge in environmental management is to develop a systematic approach which will allow:

- the thermodynamic performance limit for the whole mineral life cycle to be identified
- an objective comparison of competing technologies to be carried out on a thermodynamic basis

While these thermodynamic concepts are not addressed directly within the information structure presented in Section 2 and expanded in Section 4 of this thesis (the completion of such a study would comprise a significant volume of work), energy considerations are included in the information structure. The design hierarchy presented in Section 5 includes an understanding of these principals in its approach to energy minimisation.

It is argued here that this strategy requires a detailed process model of the industry that embodies all material and energy resource flows. This model should be developed in a structured manner and be sufficiently detailed to make explicit the linkages between unit operations within a single process and between unit operations and waste generation. Furthermore it should have generic qualities in order to facilitate comparisons across different geographic locations and between disparate resource uses. In this way the model supports the decision making process in the broader sense (spatial, temporal and economic). The information structure presented in Section 2 of this thesis forms the basis of such a model.

The second problem facing the industry is as a result of its management structures. The size of the minerals industry has given rise to two basic corporate structures, one in which decisions are devolved to operating plant level, and the other in which the holding company retains the right to direct decisions. Quite often these are in conflict, and this is most readily apparent around environmental performance. Delegation of environmental competency to an appropriate level within operating structures is often misdirected — a case in point here is where multi-national operations fail to appreciate local conditions. The ability of either of these structures to inform the decision making process around planning for closure should be interpreted in light of the levels of decisions presented in Section 2.5. One of the main attributes of the decision levels presented denotes the feedback and feed forward of information required to ensure good decisions are made at each level. This highlights the importance of ensuring that there is adequate communication between decision makers at all levels in a corporation. It is not necessarily a lack of commitment to improving environmental performance which results in inadequate decisions being taken; communication problems within the corporate structure are often the stumbling block.

Management structures are complicated further by company networks which link suppliers and markets. There are many cases in the minerals processing industry where the economic viability of the operation is dependent upon identification of markets for various waste streams. Optimal performance of any one process (i.e., node within the network) will not necessarily ensure optimal performance for the system as a whole. Any model developed to assist in the quantification of environmental performance needs to recognise this network structure.

The previous discussion has highlighted the complexity of operational structures within the industry. The flexibility of operating companies to implement environmental improvements to any process relates to the point within the project life cycle at which such improvements are introduced (the concept of project life cycle is discussed in detail in this section).

In order to minimise the potential environmental impact associated with a new project it is important to "ask the right questions at the right time", and ensure that decisions/actions are implemented at the right time. One method which attempts to take account of this in the decision making framework is the so-called "phased demand matrix" approach, which links decisions to the technology life cycle, from project conception to closure (Coates, 1995). In this context, the phased demand matrix links technology choice to decisions required at each stage of the life cycle and traces the effects of these decisions.

A project life cycle is made up of the following periods:

- Identification of Project
- Choice of Technology
- Site Selection
- Detailed Design
- Construction and Commissioning
- Production
- Closure
- Post-closure

These periods can be plotted on a time line as demonstrated in Figure 3-2. In this figure time 0 is taken to be the time at which construction of the plant begins as it is this point at which significant economic investment starts. It is also because only at this point does the process as such actually come into existence. It is not common to see environmental assessment tools such as Environmental Impact Assessment (EIA) overlaid onto the Project Life Cycle. Including EIA on this time line is presented in Section 6 of this thesis.

This definition of a project life cycle has been used in the economic technology assessment field (Coates, 1995). Dividing the time period over which a project operates into discrete units of activity makes it possible to analyse the effect of decisions made during each segment of the project life cycle.

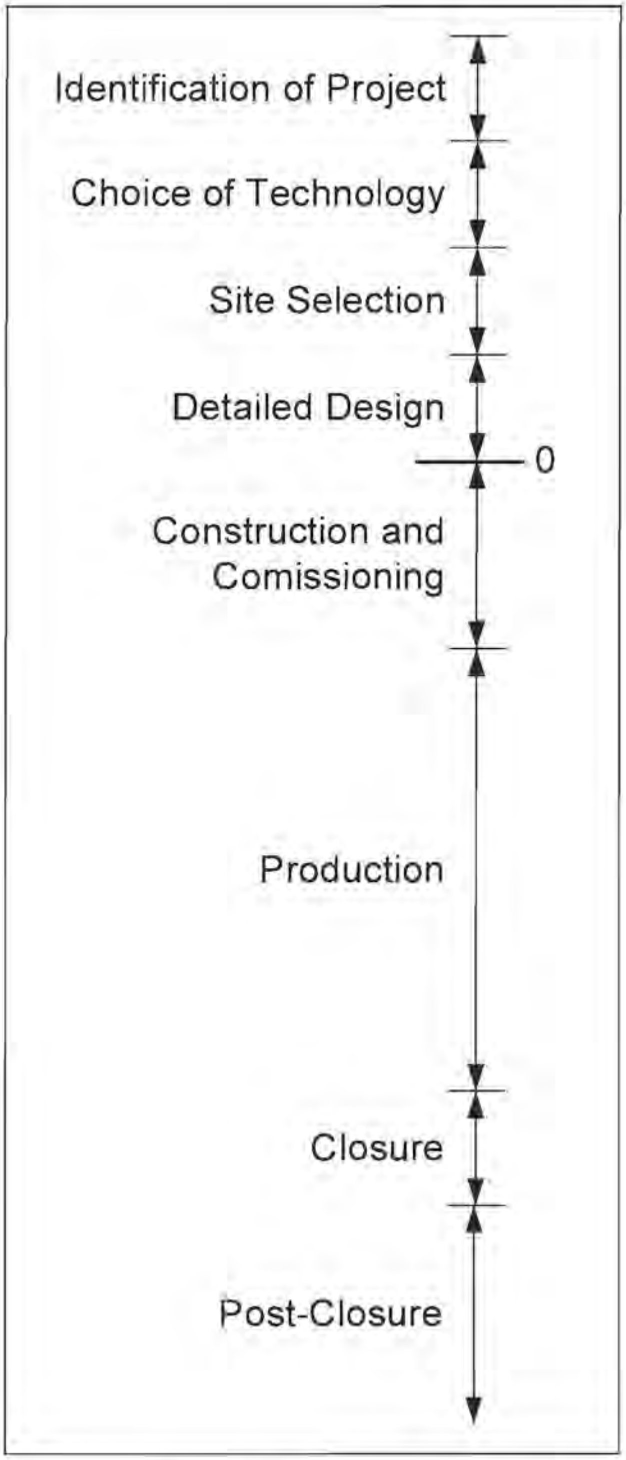


Figure 3-2 *Project Life Cycle*

Figure 3-3 is included to illustrate, qualitatively, the inter-relation between economics, production and environmental impact of a minerals processing activity. It also makes explicit the effect of decisions made at different points within the project life cycle.

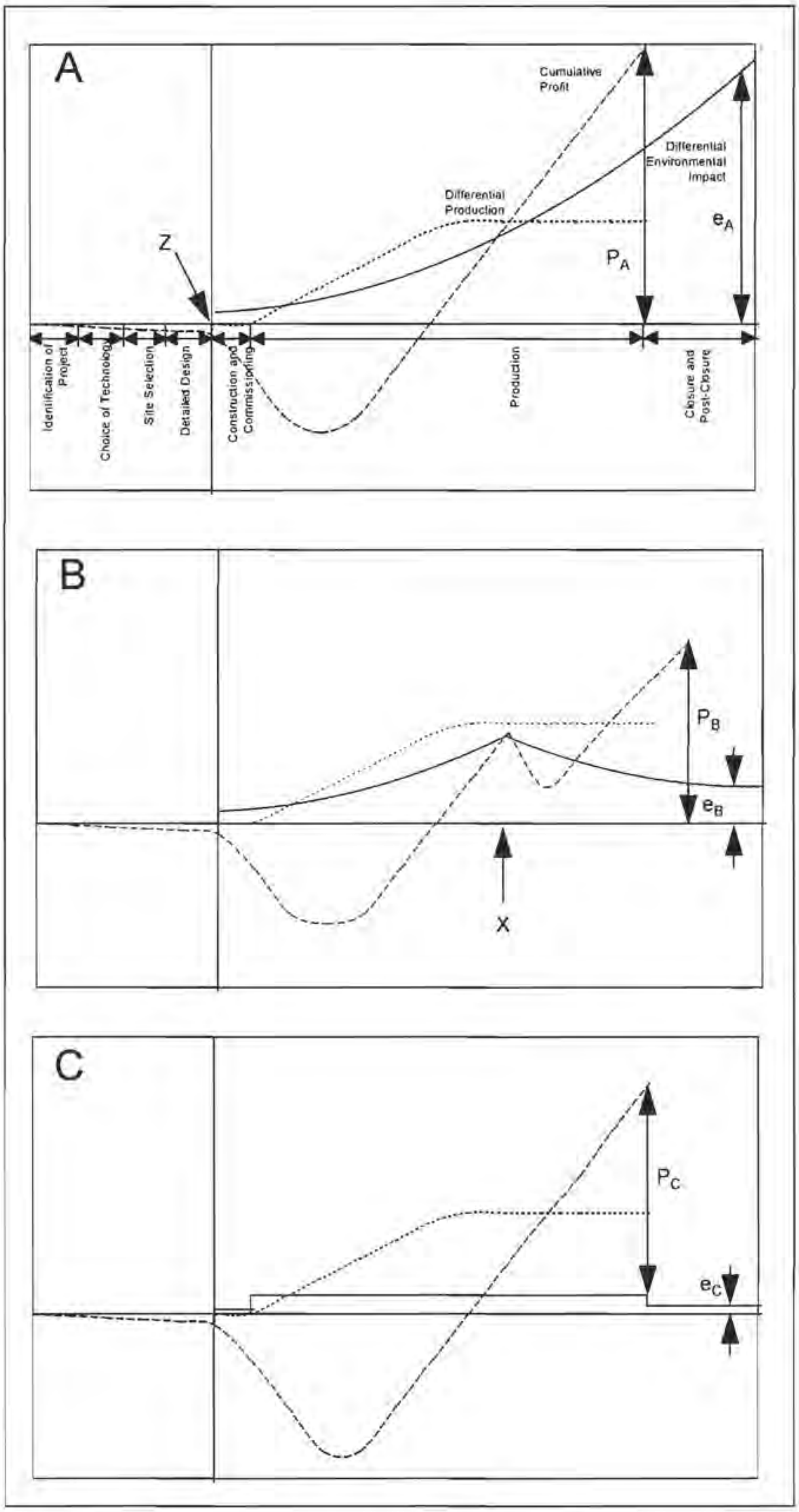


Figure 3-3 *Effect of Decisions at Different points in the Project Life Cycle*

There are three parts to this figure. Part A details the situation if there is no mitigation of environmental impact at any stage of the life of the project. In Part B the decision to remediate has been taken at some arbitrary point X during the production phase of the project. This is a common occurrence with projects; legislative or social pressures are brought to bear and a "clean-up" campaign begins. Part C illustrates the effects of including mitigation strategies in the initial stages of the project. In this case graphical trends reflect a precautionary approach; in other words, the mitigation methods included in the planning stage of the process are sufficient to foresee any changes in legislative or social requirements and to cater for these. In this scenario, no additional mitigation is necessary over the life of the project.

The value of $\boldsymbol{e}$ in each case is an indication of the differential environmental impact associated with the project. In the case of part C this is attributed only to thermodynamic limitations, i.e., all technologically possible interventions have been implemented. Figure 3-4 has been included to further explain changes in $\boldsymbol{e}$ for each of the scenarios. (Note: It is not the intention of the figure to propose that environmental impact is linear; the figure has been included for illustration only).

In the case of A, environmental impact increases throughout the life cycle of the project. For B, where a decision to reduce environmental impact is taken during the production stage of the project, the cumulative impact will be lower than for A. C illustrates planning for closure from inception of the project. This illustrates that the impact of the construction and commissioning stage can be decreased with correct planning (this is already the case in many new projects). The environmental impact of the production stage of the life cycle is limited to that dictated by thermodynamic considerations. Post-closure the impact of the process is reduced further as the impacts associated with the operation of the plant are no longer effective. The residual impact is that associated with the long-term effects of waste disposal practices. It is clear that planned mitigation results in decreased environmental impact.

The difference between the profit line and the environmental impact line in Figure 3-3 gives an indication of the ability of the process to fund post-closure mitigation. The value of $\boldsymbol{P}$ in each case is an indication of the total net profit. The challenge is to drive $\boldsymbol{P}_{\mathrm{C}}$ towards $\boldsymbol{P}_{\mathrm{A}}$ and to reduce the size of the trough in the profit curve.

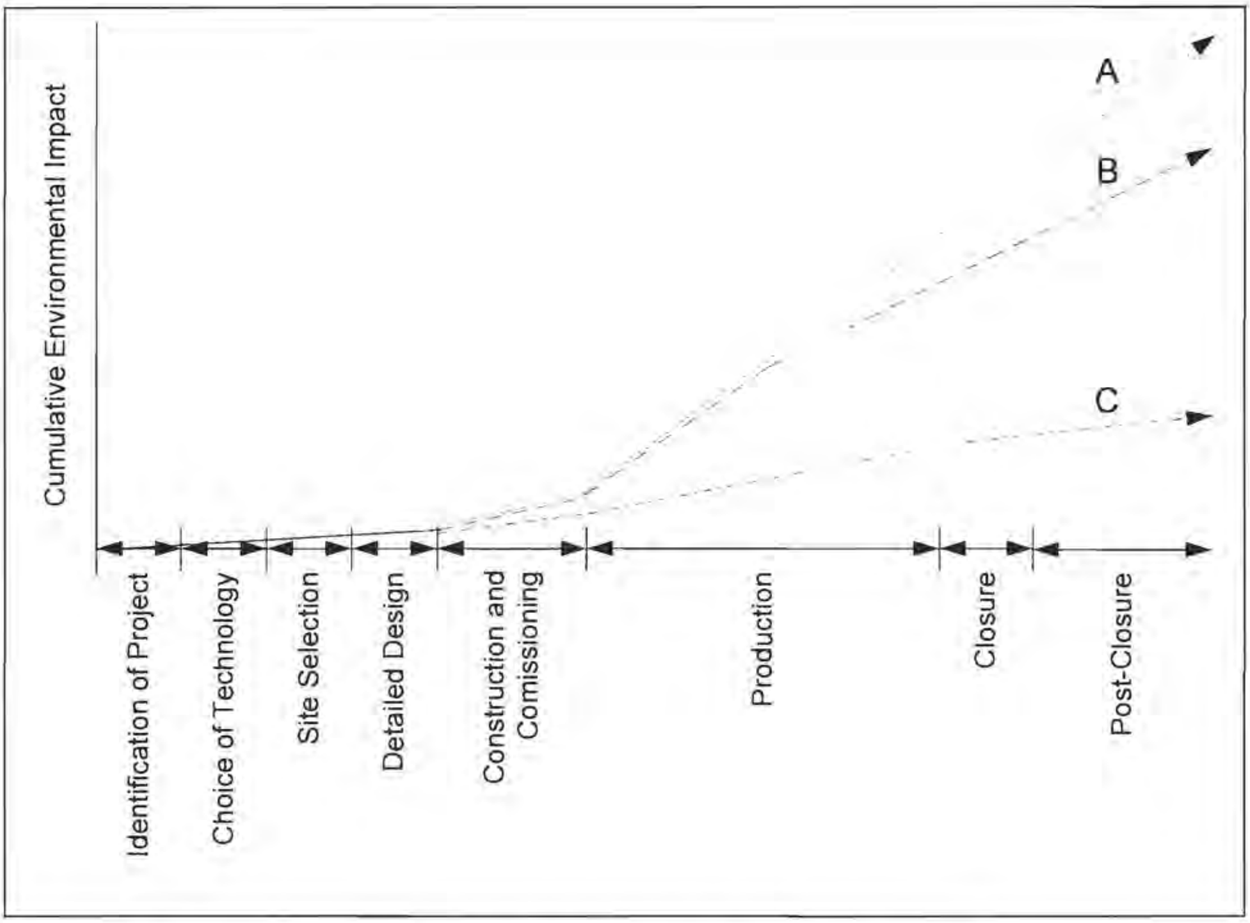


Figure 3-4 *Cumulative Environmental Impact for three decision scenarios*

These figures serve to illustrate the likely trade-off between economics and environment and show how the point at which decisions are made can affect the environmental liability associated with a process. The phased demand matrix approach overlays a matrix of impacts onto this picture in order to make transparent the effects of decisions taken at each point within the technology cycle. It highlights also the opportunities for technology intervention and, equally, quantifies the cost of delaying the recognition of environmental impacts as well as indicating the costs associated with delaying the implementation of a waste management/site remediation strategy.

Decisions made during the design phase of a project have a profound effect on the ability of the process to meet changing environmental requirements. At the outset of process design there are an infinite number of technology choices and thus an infinite flexibility to respond to changing environmental pressures. However, at this point the data set is undefined. As design progresses the data set governing technology selection is defined with diminishing variance, whilst at the same time the flexibility to respond to changes in any of the objectives decreases. It is thus important to place the process being designed within an extended time domain as this will ensure analysis of the ability of the process to respond to potential changes in objective (such as changing legislated limits, or increasing social pressure). It has to be acknowledged that these attempts to predict the future (crystal ball gazing) are carried out within the current limits of science – it is not possible to evaluate the effects of scientific and social shifts which have yet to happen.

This argument is included to highlight the importance of decisions made during design of processes. It does not incorporate design under uncertainty, which is discussed in Section 7 of this thesis.

A further reason for concentrating on the planning and design stages of the project life cycle is that these stages fix approximately 85% of the life cycle costs (Ishii *et al*, 1997). In their paper Ishii *et al* address the problems associated with operating processes within a world of mega-competition and increased market uncertainty. It develops a project life cycle oriented approach which evaluates decisions based on expected profit - here profit is determined in the context of capacity, life, availability, reliability and maintainability of each process unit. This is presented as a critical new management principle in the process industry. A heuristic procedure for process synthesis is developed in support of this concept.

The design stages of a project life cycle are critical to the environmental and economic performance of a process. This is the reason for concentrating on decisions made during the design process.

This argument illustrates the importance of decisions taken at a process design stage. The next section of this thesis uses the flowsheet structure developed here as the underlying structure upon which the flowsheets developed during process design are based.

3.2 Literature Review Process Design and Process synthesis and optimisation

In Section 1 of this thesis the environmental impact of the minerals industry was introduced as having dimensions of both time and space. Temporal and spatial effects cannot be represented as scalar quantities if their real effect is to be modelled. Thus the environmental impact associated with activities within the industry may be viewed as a vector quantity. In addition, the different elements in the LCI have different impacts on the environment (thus the need for different equivalency factors as described in Section 2.2). LCA offers a systematic approach to aggregating LCI components into impact categories. The one-to-many relationship of wastes to impacts in some cases was described in Section 2. Thus, an aggregation of impact components can result in interpretation problems when reviewing environmental performance of processes, products or services. The project life cycle presented in Section 3.1 illustrates the importance of the design stage to the environmental performance of the process over time. This section evaluates process design within the context of these issues.

This section contains a literature review in two parts; the first addresses current approaches to process design and the potential for incorporating environmental decisions into this structure. The second part contains a review of process synthesis, which is an integral aspect of process design as it is only possible to take the decisions required by process design if a sufficient understanding of the potential performance of the system is known. Thus, processes are modelled, or synthesised, supported by the decisions to be taken during design. While this review is not comprehensive in its definition of design methodologies, it is comprehensive in its review of the manner in which environmental impacts are incorporated into process design methodologies.

3.2.1 Environmental Decision Making and Process Design

Process design has depended historically on the *apriori* knowledge that design engineers have of the process to be developed. In many cases these approaches consist of a heuristic approach to design where "rule-of-thumb", proven over time, is applied. Design within this context is often referred to as knowledge-based design.

Process design is a hierarchy of decisions which start with limited information on the process to be designed. The decision hierarchy then guides the design engineer through the decisions possible within the information available. Different decisions are taken at each level of the hierarchy. In the initial stages of design there is significant uncertainty about the proposed technology. Decisions taken in the hierarchy serve to reduce this uncertainty. At the same time information detail is increased. The decision taken at one level informs the input information for the next decision level in the hierarchy. The decision taken at one level constrains the solution space for the decision taken at the next level. Decision hierarchies thus guide the development of information sets to the point where the process design is detailed explicitly, or completely constrained.

Design hierarchies developed by others offer a structured framework within which heuristic-based design decisions are made (Douglas, 1988, Biegler *et al*, 1997). Most well-represented here is the Douglas design hierarchy. This decision framework was developed for application in the petro-chemical and processing industries (dominate by liquid/gas systems) but has been extended to include decisions specific to solid/liquid systems (Douglas, 1992; Rossiter, 1994). This hierarchy follows a flowsheet based approach to process design within which it is possible to incorporate the flowsheet based approach to information structuring presented in Section 2 of this thesis into the hierarchy. This is significant in terms of the objectives of this thesis. Each level of decision within the hierarchy is linked to a certain level of detail within the flowsheet for the process. It is the purpose of the hierarchy to ensure that all possible technology combinations are evaluated at each level. There is also a feedback loop between all levels in the hierarchy. In other words it is an iterative process which narrows down the infinite possibilities to those which are most viable, and results in a final flowsheet for the proposed project.

The Douglas design hierarchy is included in Table 3-2.

In 1992, Douglas extended this hierarchy to include waste minimisation considerations (Douglas, 1992). In so doing he generated a waste minimisation hierarchy for process design. There is, however, little potential to take explicit account of environmental impacts within this hierarchy.

In the work of Rossiter (1994), pollution prevention solutions are transferred between sub-sectors within an industry, and even between industrial sectors. No indication of the applicability of that technology to application in other industries is given. The cost associated with the pollution

Table 3-2 *Douglas Hierarchy of decisions for the Process Industry*

Level	Decision
0	Input Information
1	Batch versus Continuous
2	Input-Output structure
3	Recycle Structure
4	General structure of separation system a - vapour recovery b - liquid recovery
5	Heat exchanger network

prevention solution as determined according to experience with similar technologies in place in industry. This cost is then included in the economic optimisation for the process. In this respect the environment is again viewed as an add-on running cost; and again there is no indication of how the process should be re-engineered to reduce environmental impact.

Sarigiannis (1996) states that leaving environmental considerations too late in the design methodology will result in end-of-pipe treatments being adopted. For this reason he suggests that design for environment can be divided into three sections:

- Materials selection – here he suggests beginning with an LCA of available materials and developing an LCI associated with making these materials available for processing. This LCA contains "environmental pressure indicators". He highlights processes synthesis as a powerful tool within this context as it may reveal significant information about the inherent dynamics of the material and energy flows across different sub-systems of a process plant and thus can be used to influence material selection. Process synthesis tools can also be extended to describe the interaction between production systems and the social and natural environment if it is possible to link inputs and outputs to the environmental impact which they embody. Thus it is possible to introduce a number of criteria which must be considered during material selection. He has reservations about the ability of LCA to satisfactorily describe the multi-dimensionality of industrial plant impacts due to the lack of temporal and spatial considerations within LCA, a deficiency which has already been highlighted.
- Process plant synthesis and optimisation – again synthesis is placed within the context of process design. Here process configurations are chosen to minimise economic costs. This type of approach is discussed in more detail later in this review.

- Industry-wide synthesis – in this respect he reviews the integration of a number of streams within an industry as a whole using fuzzy logic to manipulate the decision matrices.

This too can be viewed as a hierarchy of decision analysis within process design. He argues that process synthesis can be used to support environmental decisions taken during the design process. Process synthesis for environmental decision support is discussed later in this section.

Within knowledge-based approaches the emphasis is on being able to support a decision at a specific point in the design within the limits of information detail available at that point in the decision hierarchy. Much discussion on the quality of information available at each stage of the hierarchy is offered in the work of Biegler *et al* (1997). Information quality is of vital importance when taking a decision as it will determine the value of that decision. This is an important factor within a process design structure.

3.2.2 Process Synthesis and Optimisation

There are a number of approaches to process synthesis and optimisation. Included in this section are:

- Pinch analysis
- Graphical optimisation
- Numerical synthesis and optimisation

Only cases that include environmental aspects are included in the review presented in this section.

3.2.2.1 Pinch Analysis

Pinch analysis was initially developed to address design of distillation columns for complex mixtures; it was used to determine the optimum number of distillation plates within the column according to strict thermodynamic principles (Rossiter, 1994). In the field of minimising environmental impact, pinch analysis was first applied to heat exchanger networks (HENs) (Linhoff and Ahmad, 1983). This work concentrated on determining the HEN which would use available energy optimally. Sorin and Paris (1997) extended this approach by combining an exergetic analysis with a pinch approach to minimise exergy requirements within a process. In so doing they begin to address the thermodynamic considerations presented in Section 3.1 above. On the whole, using pinch analysis to minimise energy usage within a process is a very effective waste minimisation methodology.

A further aspect of pinch analysis is that it can find an optimal system while using a reduced amount of computing power (Sorin and Paris, 1997).

Pinch analyses have been extended to mass exchange networks (MENs) where "Lean" streams can be inter-changed with "rich" streams, presenting a new manner for looking at waste water treatment, (Rossiter,1994),. An elegant development of this approach is presented by Fraser (1998). This methodology has also been used to minimise waste water leaving a process. This is done by combining waste streams in ratios so that the legal requirements of the region are met. However, this does not address the environmental impacts of the process; rather it maximises the utilisation of the water within legislative requirements. Essentially the problem here is that there are many dimensions to a waste water stream, the concentration of all the components, the critical loading that the stream can absorb, the legal requirements governing the concentration of each component in the stream, as well as the impact of each of the components. For this reason pinch technology is not adequate as it models the waste water stream as a scalar quantity where a multi-dimensional matrix would be more appropriate.

Although pinch technology can show how to combine a technology suite within a known set of constraints (for example legal limits), it gives no indication of how to change the technology for optimal performance or how to choose between the different technologies or processes which are available.

3.2.2.2 Graphical and Numerical Optimisation

Flower *et al* (1993) acknowledge that data availability during the early stages of process design is the limiting factor to numerical optimisation. For this reason graphical methods have been developed. Their work presents such a graphical approach. It is assumed that this graphical approach will be used when there is very little information available. In order to increase detail in the information set, information is interpolated between known points and then extrapolated to larger plant sizes. The objective of their optimisation regime is to manipulate the mass balance in order to minimise the mass of waste being generated. Trade-offs between minimising the waste generated and maximising the profit are made explicit by mapping the graphs of reactor-separator performance on the same axis. However, this methodology only considers wastes and not impacts. Extending this analysis to a suite of impacts will introduce too many dimensions into the methodology to make graphical representation practical.

In his review paper of 1994, Rossiter defined the principle steps in a Numerical or Graphical Optimisation as:

- Evaluate emission sources, emissions rates and applicable environmental prevention and control options (establish a base case)
- Establish range of application and cost relationships for each of the waste minimisation or control technologies (establish cost versus benefit for each technology)
- Determine the mutual compatibility of each minimisation or control technology with each of the others (technologies are mutually incompatible when the joint benefits are less than the sum of the individual benefits, i.e., installing the two pieces of technology together would decrease the overall performance of the process)
- Calculate maximum reduction in emissions achievable with each technology and each permissible combination and determine the corresponding total cost
- Determine which technology or combination of technologies provides the "least cost solution" for any given reduction in emissions
- Plot results (minimum costs against emission rate)

Ciric and Huchette (1993) employed two environmental objectives which are essentially sub-sets of a single economic objective. They define two classes of environmental cost:

- Direct, which includes treatment and disposal costs
- Indirect, incorporating environmental liability, paperwork, public relations and others; this is similar to an accountant's view of indirect process costs where indirect costs are all costs associated with a project other than capital and operating ones

In order to find the optimal design they trade off treatment costs against profitability. As waste treatment costs and disposal costs are often uncertain these trade-offs can be difficult to make. However, it is possible to show the sensitivity of process profits to changes in waste treatment costs.

In the work of Ciric and Huchette, a multi-objective problem was solved for the non-inferior solution set (i.e., the one where profit cannot be increased without increasing the cost of waste treatment). This showed that any optimal solution for the problem lies on the convex hull of the surface of least trade-offs between the objective. This surface of least or minimum trade-off is also known as the non-inferior surface, or "pareto optimal" surface. The concept of a pareto optimal surface was also used by Azapagic (1996) as discussed later in this review. They then extended the work to process optimisation including discrete variables in a non-linear system. Discrete variables arise when individual technologies are evaluated with respect to others, i.e., discrete scenarios for the solution of the problem. Non-linearities are introduced when complex equation regimes are included or when unit operations do not operate in a linear fashion. Introducing recycles into a system introduces non-linearities as well. This work is very thorough in its dealing with process uncertainties. However, environmental burdens are still aggregated into a single economic cost.

Sharratt and Kiperstock (1996) added a further slant to this approach by optimising the outputs from a number of plants to ensure that the legislated limit for a pollutant in a body of water is not exceeded in any way. They determined the minimum cost (operating and capital) to achieve this limit. This could be extended to evaluating the cost required in order for a process, or a network of processes, not to exceed the potential assimilative capacity of the local environment. However, this remains a single objective optimisation.

These papers illustrate how the numerical optimisation of processes has been extended to include an indication of environmental cost. In these first attempts at "design for the environment", environmental cost was defined as an economic cost (the cost of remediation of environmental degradation or the cost of end-of-pipe treatment of wastes). In these cases the profit for a process was optimised, i.e., reducing environmental burden to have economic units of measure reduces the optimisation to a single objective. This serves to greatly simplify the problem as the information is all expressed in terms of a single unit of measure. However, converting environmental impacts to economic costs can have misleading results – it may be very expensive to remediate a fairly benign waste stream, and relatively cheap to ameliorate the effects of an extremely hazardous stream. By assigning an economic cost to a waste stream all of the impacts are reduced to the same basis, that of a monetary value. It is this monetary value which then represents the bias towards one or other waste depending on the cost of remediating that impact. Thus, reducing environmental burden to a cost can be viewed merely as a method of weighting the importance of wastes relative to each other.

The papers presented here allocated a cost to meeting environmental regulations – such as emission standards. These methods then evaluated the minimum cost required for meeting these environmental limits. While this can be viewed as a method whereby legal pressures are addressed (technologies are chosen in order that legal limits can be adhered to), the methods presented in no way reflect societal preference – rather the preferences (or weightings) which they place on impacts is based on monetary valuations. In many cases they could obscure the issue by biasing the optimisation away from a hazardous waste stream as described above.

One of the main aims of the research presented in this thesis is to address the concerns of all role-players, not only government and industry, but society as a whole. This requires a weighting or preference set other than one based on economic values. In order to address the concerns of society it is also necessary to retain information detail on all potential environmental impacts of the process and not to aggregate impacts into a single objective.

Further advances have taken place in process synthesis and optimisation in design for environment. In this more recent work the environment is no longer viewed as an add-on running cost. Diwekar *et al* (1998) state that the focus on environmental control during process design has moved away from end-of-pipe treatments and towards waste reduction or pollution prevention. In her paper she presents a framework for analysing the uncertainties introduced when this shift in perception of environmental design has been made. Uncertainties are always present in process synthesis models. There is insufficient information available on the performance of unit operations, and assumptions will always have to be made in order to establish the models. It is necessary to acknowledge and manage these uncertainties when the models are used to support decisions. Including an indication of potential environmental impact in the model greatly increases the opportunity to introduce uncertainties in these information sets. A significant example here is the ability of current scientific understanding to accurately predict the environmental impact associated with a specific component in the waste stream, i.e., the modelling of the link between a waste and an impact is not necessarily accurate.

Diwekar presents plant specific case studies which:

- Maximise profit
- Minimise emissions
- Minimise uncertainty

associated with various technology scenarios within the chemical processing industries. This introduces a multi-objective approach to optimisation of processes with respect to both environmental and economic performance.

P. Chauduri *et al* (1996) adopt a similar approach to synthesizing optimal waste blends under uncertainty. Here again the uncertainties within the models are considered overtly. Focus is placed on selecting that technology suite which will deliver waste streams which have the lowest potential environmental impact. In this work environmental impact is using an LCA approach.

Pistokopoulos *et al* (1994) acknowledge that pollution prevention at source is a process design activity. They argue that most environmental improvements postulated in guides have been qualitative and that a quantitative assessment is required. However, most systematic approaches show how to cut down emission waste but not necessarily wastes associated with inputs to the process (i.e., wastes associated with energy, capital plant, raw materials, etc.). Thus they recognise the need to group the wastes from a process in some systematic manner and state that the aggregation of wastes into impacts within LCA addresses this requirement.

They claim that the two most significant aspects of applying LCA to process synthesis are:

- Consistent boundary definition is important
- The ability to concentrate on impacts as opposed to emissions as there are a reduced number of variables and very different processes can be compared using the same "currency"

They took a "cradle-to-gate" approach "since the main direction of this work is towards process development tools for pollution prevention". The downstream use of products can be viewed as part of the background system, i.e., it is difficult to influence the use of the product during process design and thus the use of the product is taken to be independent of the process. After defining the process boundary and then the mass/energy balance and the impacts of the wastes, they evaluate an aggregate impact vector. This vector defined impacts according to Critical air mass (CTAM), Critical water mass (CTWM), Solid mass disposal (SMD), Global warming impact (GWI), Photochemical oxidation impact (POI) and Stratospheric Ozone Depletion Impact

(SODI). While these are valuable indicators, they are not consistent with the aggregations used in formal environmental management systems (such as ISO 14 040 to ISO 14 042, (ISO, 1997)). The aggregation of impacts into groups used in environmental management would make the work of this team easier to interpret with respect to other methodologies.

The equation for one of the elements in the impact vector is illustrated below:

$$\text{CTAM} = \frac{\text{Mass of Air Emissions (kg pollutant / hr)}}{\text{Standard Limit Value (kg pollutant / kg air)}}$$

which has units of kg air/hr, similarly for CTWM. SODI is determined by the equivalent mass generation of CFC11/hr; POI by the equivalent mass generation of ethylene per hour etc. Thus all impacts are reduced to the units of mass per hour. An equal weighting of 1 is then placed on each of these categories and the mass flows are aggregated to give an indication of global impact for the process.

There are three attractive features in using such a global environmental impact vector:

- The vector of waste emissions is large and can be aggregated in this manner into something manageable
- The information reflects impact on the environment rather than mass flows
- Wastes associated with inputs to a process can be accounted for on a common basis

Taking environmental performance into account in this manner transforms the process optimisation regime from a single objective one (i.e., cost/profit) to a multi-objective one. However, the placing of equal weights on each impact category does not necessarily reflect the requirements of society where some impact categories are viewed as more significant than others.

The objective of the optimisation for the process was to minimise the economic cost vector (i.e., to maximise product) within the constraints of mass and energy balance closure for the process while minimising the environmental impact vector. There are two decision sets, one relating to the structural decisions (integers relating to technology choice), the other to continuous decisions (operating variables). The integers relating to technology choice would essentially switch one or other unit operation on and off within the flowsheet and could be used to inform decisions around technology choice. The continuous variables relate to operating conditions and could be used to determine the optimal operating conditions for that selection of unit operations.

They show that LCA techniques commonly employ very simple process models that are based on data from existing industrial sites, i.e., operation and design are neither examined in detail nor improved for pollution prevention. This is no longer the case as significant steps have been taken in placing process synthesis within the inventory analysis stage of LCA (Diwekar, *et al*, 1998; Chauduri *et al*, 1996).

Stephanis *et al* (1995) incorporate LCA into a process synthesis of an ethylene production plant in order to determine the environmental impacts associated with the process in a methodology very similar to that presented in the Pistokopulos paper.

There is insufficient detail on the methodology for aggregating wastes into impacts. Neither is there an indication of how the impacts are traded off against each other. They view the inclusion of LCA as having value mainly in that it incorporates the impacts associated with inputs. However, they set these inputs to zero for most of the inputs in the example.

They state that optimising on waste generation alone leads to sub-optimal plant operation with respect to optimal environmental performance. Results show that targeting a global minimum in waste production results in cheaper plant operation. They acknowledge explicitly that there is a requirement for using formal multi-objective programming techniques within this approach to process optimisation. Multi-objective programming is presented formally and discussed in Section 4 of this thesis.

The choice of chemical process route is the key design decision defined by Cave and Edwards (1997). The focus of their work is to determine which product to make from a specific input stream. Here environmental impacts are aggregated into an Environmental Hazard Index where hazard is associated with the perceived environmental liability associated with the waste stream. This index is used to differentiate between process routes, the lower the hazard rating for the process the more preferable the process. Their approach only includes the outputs from the process. To some extent this moves process design back up the project life cycle into the project identification stage as it evaluates the potential hazards of providing different products to society.

Sharratt (1998) extends his view of design for the environment by detailing the potential tools for incorporating a measure of environmental performance into process design and optimisation. Table 3-3 below illustrates these tools. He acknowledges the difficulties in supporting decisions within the sketchy information available during process design but stresses that it is at this point where decisions are most important. While he expresses support for the developments taking place in design for environment, he also states that it will only be through legislative and economic frameworks that true innovation throughout the entire life cycle of a product will be achieved. In other words, optimising the performance of a single node in a chain of industrial activities will not optimise the entire chain.

Table 3-3 *Some process design tools and their contribution to environmental performance assessment (Sharratt, 1998)*

Tool	**Function**	**Contribution to environmental performance or assessment of process**
HAZOP	**Identification** of potential abnormal event - eg., release to environment	Accidental release identification Initiates study of potential impact
QRA	**Assessment** of likelihood of given abnormal outcomes	Control of risk of release Can be used for cost-benefit analysis of control techniques
QRA	**Assessment** of risk of outcomes	Assessment of likelihood of harm in the future, for example, from waste disposal
Optimisation-based design	**Control** Derive optimal designs within a hyperstructure of possible designs	Cheapest way to achieve required performance (or best performance at fixed cost)
ELF (Environmental load factor)	**Assessment** of waste generation (ELF = waste/product)	Approximate quatification of waste in early stages of development Local impact measure (amount of waste for disposal)
Environmental Burden	**Assessment** of contribution of process (or business) to environmental harm categories	Global assessment of environmental impact of process
Emission Factors	**Assessment** of fugitive emission	Allows contribution of fugitives to overall plant impact to be estimates

This table also serves as a summary for this section of the literature review. Optimisation tools are seen as optimising economic performance within a constrained solution space. Often these constraints are those imposed by environmental legislation. This review has shown that optimisation of processes takes place during both initial and detailed design stages of the project life cycle, i.e., at differing levels of information detail. The environment has been incorporated into these optimisation regimes. Initially the environment was reduced to an economic cost and a single objective optimisation executed. More recent work has retained the environment as a separate objective within the optimisation. However, there is insufficient detail on the environmental impacts associated with technologies. It is acknowledged that retaining more detail in environmental impacts will require trade-offs to be made between these impacts, informing these trade-offs is highlighted as an area for potential research.

The work of Azapagic (1996) and Azapagic and Clift (1999) offers a structured approach to minimising the trade-offs to be made between a number of objectives within a multi-criteria optimisation regime. They use LCA to structure the environmental objective functions. They offer a case study based on a multi-product system for boron-based products. Within their work the process is simultaneously optimised on a number of environmental objectives. This provides a range of environmental optima called the "pareto optimal" surface. This surface is drawn in many dimensions and each point on the surface represents an optimal operating point for the process. It is thus possible to determine a number of possibilities for improving the environmental performance of the system. Economic considerations are included using the definition of BPEO (Best Practicable Environmental Option) and BATNEEC (Best Available Technology Not Entailing Excessive Cost). Thus the optima within the pareto solution set could be used to evaluate the compromise between environmental and econimic costs. Multi-objective linear programming formed the basis for their optimisation regime. The value in using multi-objective optimisation is that it does not provide a single, prescriptive solution, but rather a choice which can be demonstrated to address the requirements of BPEO and BATNEEC.

While not strictly focussing on design, their work does offer an approach to process synthesis for improved environmental performance. This would infer that, within process design it should be possible to optimise the performance of the process being designed to minimise the environmental trade-offs being made. They use the tools of multi-objective linear programming to identify and evaluate the best possible options for environmental management of the system under review. They assert that LCA can be successfully combined with multi-criteria decision support tools to ensure that both the environmental and the economic performance of a system can be improved.

Multi-criteria optimisation tools are reviewed in Section 4 of this thesis.

3.3 Challenges implicit in including Environmental Decisions during design

This section has highlighted the need to include environmental considerations in decisions taken during the design stage of a project's life cycle. The value of including environmental concerns explicitly in these decisions has the potential to minimise environmental impact over the project life cycle, and to limit the cost of post-closure remediation, this is of particular significance to the minerals industry. Hierarchical decision making has been presented as the structure within which design decisions are taken. This hierarchy of decisions guides the development of information sets used to support the decisions taken during design.

To date insufficient attention has been paid to the development of information sets pertaining to environmental and social considerations during the design process. There is much support for the incorporation of these information sets into the design process (refer to the quotations from the Minerals Industry as presented in Section 1 of this thesis where commitments are made to addressing the environmental and social impacts of the industry). There are many works in literature which assert the need to include technical, environmental and social considerations into all aspects of the project's life cycle (Ehrenfeld, 1997; Anastas and Breen, 1997; Jackson, 1996; Ayres and Simonis, 1994). This material is summarised in Figure 3-5. This figure highlights the intersection of the three sets as being the solution space within which sustainable solutions will lie.

Note: it can be argued that minerals processing is, by its nature, non-sustainable as it is concerned with the exploitation of non-renewable resource. However, the dissipative use of the materials produced by the minerals industry is such that more energy is required to gather these same materials together for recycling, than is used to produce mineral products from virgin ores (Petrie and Raimondo, 1997). Thus, following the argument presented in Section 3.1 and illustrated in Figure 3-1, it can be argued that a closer approach to sustainability is reached if mining of virgin ores continues.

The challenge then is to ensure that social and environmental considerations are included in the decision hierarchy of the design process from the initiation of design. Section 5 of this thesis demonstrates how these three information sets are developed within a structured process design methodology. The aim of this methodology is to ensure that all decisions taken move the

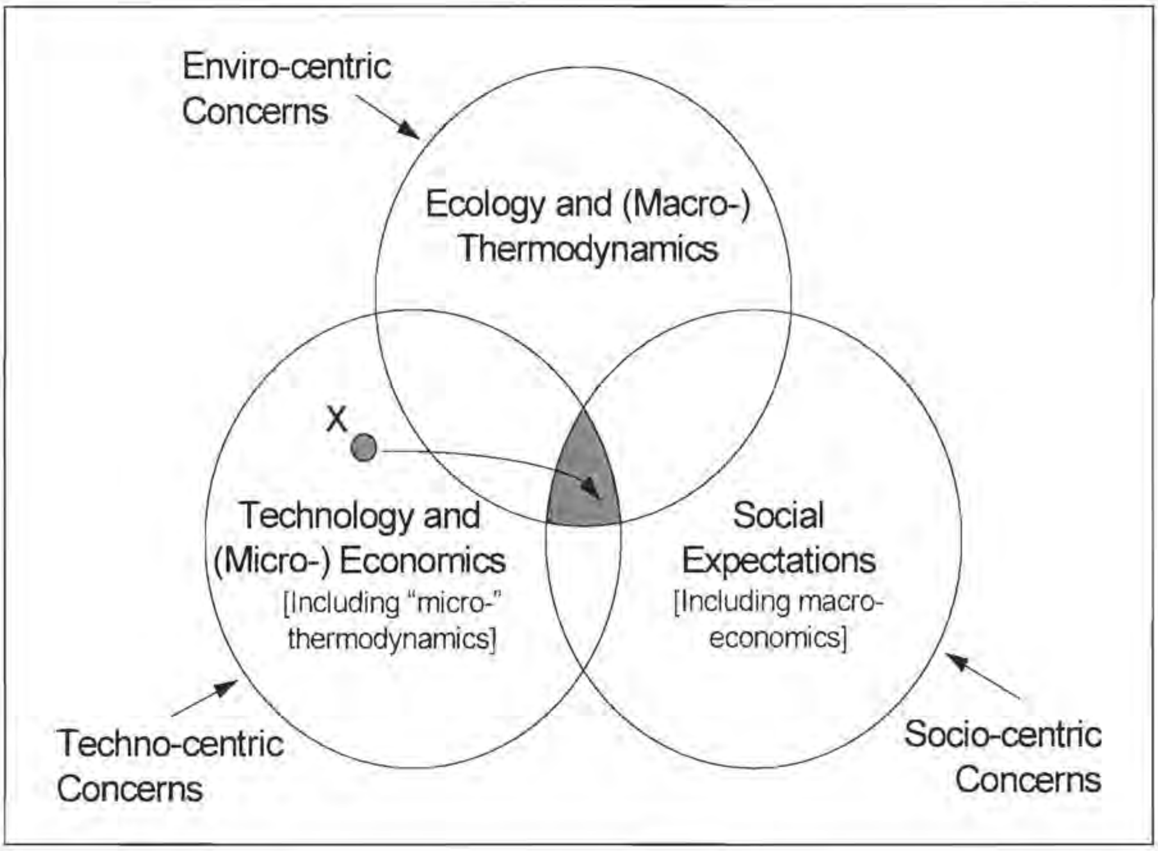


Figure 3-5 *Clean technology within the context of technological, social and economic constraints (after Clift, 1995)*

technology chosen from an arbitrary point X Figure 3-5 towards a sustainable solution within the intersection of the three sets. The optimal solution path can only be found if all three information sets are included in the decision making process from the start of design. Historically process engineers have started from "X", defined as a point within the techno-centric data set. It is necessary to gain input from the other spheres before a final decision can be made. The question is "how can this be achieved?"

In this section, process synthesis and its ability to support environmental decisions has been placed within the context of design. The current thinking on using process synthesis to minimise the potential environmental impact associated with a process has been reviewed. The potential for using multi-objective optimisation to minimise the trade-offs to be made between environmental objectives was presented in this review. This review demonstrated that it is possible to incorporate environmental considerations into process synthesis and optimisation albeit it in a somewhat limited manner in some cases.

4 Decision Making and Design for the Environment

Section 3 of this thesis highlights process design as a critical decision making point in the project life cycle. This section also presented knowledge-based design as a hierarchy of decisions used to guide the development of information sets as effectively as possible. Optimisation tools which use these information sets to optimise the process under design at each stage of the design process were also included in this section. The failure of these optimisation tools (bar those used by Azapagic (1996) and Azapagic and Clift (1999)) to address environmental objectives without an *en masse* aggregation of the impact categories was highlighted in the conclusions of Section 3. Optimisation of processes to achieve best environmental performance often reduces the optimisation to a two objective optimisation were environmental objectives are aggregated into one objective and traded-off against an economic objective. This implies that a pre-defined set (and often equal) weighting is given to each recognised environmental impact category. This does not allow for trade-offs to be made between the impact categories. Aggregating the impact categories in this manner can eliminate potential design solutions which could be found if trade-offs were allowed between the impact categories.

In order to better understand the decisions to be made in the design hierarchy a review of decision making is presented first. Multi-criteria optimisation and multi-criteria decision analysis tools which can be used to inform the decision making process are then presented and described. The value of these tools is that they make it possible to incorporate environmental objectives explicitly, as opposed to aggregating all tools.

The information structure presented in Section 2 of this thesis is then augmented so as to enable to formulation of environmental and economic objectives. Further, the information structure must direct the design process, for this reason an audit trail is constructed from unit operation, through waste to impact. This audit trail facilitates the design process by highlighting unit operations responsible for particular environmental impact. This allows critical unit operations to be highlighted and guides the re-design of unit processes as well as unit process selection.

4.1 *Review of Decision Making and Decision Analysis*

An introduction to decision making was included as part of the background context for this thesis, this can be found in Section 1. It introduced an algorithmic approach to decision structuring which can also be described as a generic decision support system (DSS). DSS is still an evolving science (Eom, 1998), thus decision support and decision structuring still reflect many contrasting views and methodologies. Essentially the aim of decision structuring is to express a number of ill-defined goals or objectives in terms of a number of potentially conflicting criteria. (Stewart, 1992). The review contained in this current section gives a more detailed understanding of tools available to structure decisions with particular application to environmental decisions. These tools are described and discussed by drawing from the analysis and review of Basson (1999). The mathematical tools used to support these decisions are also introduced. The terminology used in this section is defined in Section 4.1.2.

4.1.1 Decision support

The goal of decision making is to achieve good decision outcomes. A good decision has been defined as one which meets the requirements of all stakeholders where stakeholders are viewed as the groups which are affected by the decision outcomes (Keeney and Raiffa, 1976; von Winterfeldt and Edwards, 1986). While some decisions are "easy", others are "hard" (Clemen, 1996; Rosenhead, 1989) as detailed in the introduction to this thesis. Kleijn *et al* (1998) suggest that it is the context that will determine the complexity of the decision. This is illustrated in Table 4-1 below.

Table 4-1 *Contextual elements determining the complexity of a decision situation (after Kleijn et al, 1998)*

Context Characteristics	Simple	Complex
Time frame	Short term	Long term
Number of other aspects considered	Limited	Many
Number of Stakeholders	Few	Many
Beliefs and Preferences	Converging	Diverging

Note: The decision situation or decision context is the social, institutional and informational environmental in which the decision is made (Kleindorfer *et al*, 1993).

Exploring environmental decision making in the minerals industry with respect to this table:

- Decisions have effect over lengthy time periods (post-closure impacts)
- There are many different aspects to be considered during decision making
- There are usually a significant number of stakeholders
- The stakeholders have divergent preferences (shareholders require profit, the local community requires low environmental impact, national and international pressure groups are concerned with global environmental issues, etc.)

Thus environmental decision making in the minerals industry can be defined as "hard". However, because of the number of stakeholders involved and the time periods over which the impacts of decision taken will be felt, is it necessary to ensure that good decisions are taken. Good decisions are produced by a quality decision making process, one which (ESRC, 1998):

- Involves the appropriate stakeholder groups
- Identifies good alternatives
- Collects the right amount of information
- Is logically sound
- Uses resource efficiently
- Produces choices which are consistent with the decision maker's preferences

There is a distinction to be made between decision support tools which may be based on mathematical models; and decision support systems which encompasses all actions that assist in the decision making process (Eom, 1998). In this context, the flowsheet approach to process modelling which has been developed is the tool, while the design hierarchy presented in Section 4 is the decision support system.

4.1.1.1 Decision Structuring

There is a difference between problem solving and decision making and this is best illustrated using Figure 4-1 below. This figure demonstrates that problem solving includes the implementation of the chosen alternative and the evaluation of its success; while decision making only extends to the point where the preferred alternative is chosen. By definition, the decision making process is one which results in a decision being made (Anderson *et al*, 1991). There are a number of definitions of decisions ranging from "an intentional and reflective choice in response to perceived needs", (Kleindorfer *et al*, 1993) to "a determination arrived at after consideration… implemented through action or allocation of resources", (Turner *et al*, 1997). The latter definition which includes a commitment of resources to the actions resulting from a decision is becoming more common (Keeney and Raiffa, 1976).

It must be recognised that the decision making structure presented in Figure 4-1 is simplistic. This decision structure can only be applied to well-defined or well-structured decision contexts. However, decisions are usually based on dynamic systems which comprise a significant number of interdependent problems, described as "messes" by Ackoff (1979). Rosenhead (1989) defines problems as the simplification of these messes into more aggregated systems which are easier to quantify. Thus the first element of decision making requires the definition of the problem in such a manner as to facilitate the solution of the problem, called problem structuring. The second element of decision making is problem analysis where the alternatives available to the decision maker are evaluated on their performance relative to a set of objectives. Problem structuring ane problem analysis are demonstrated by blocks 1 and 2 on Figure 4-1 (Anderson *et al*, 1991). This figure shows that problem structuring can be divided into:

- Definition of the problem which requires that the "messy" problem be limited to one that is readily quantifiable
- Definition of the objectives of the problem solving exercise, objectives are defined by Chankong and Haimes (1983) as statements about the desired state of the system, Keeney (1992) defines objectives as statements of what is to be achieved by the system.
- Determining the complete set of alternatives which are to be considered in solving the problem
- Development of performance measures to determine how well each of the objectives have been met by each alternative

And that problem analysis includes:

- The analysis of the different alternatives which requires the performance of each alternative relative to each objective to be evaluated
- Comparison of the consequences in which the relative performance of the alternatives in each of the objectives is determined

- The choice of an alternative which out-performs the other alternatives in terms of the objectives established during problem structuring

The specification of performance measures is not a simple process as these measures must include:

- An interpretation of the values whereby alternatives will be judged
- The an understanding of the decision criteria which reflect the values of the stakeholders in the decision process
- The attributes which are used to measure the performance of each alternative relative to the selected criteria

It must be recognised that decision making processes are not linear. Perceptions of the problem may change, all the objectives may not have been evaluated, alternatives solutions identified may not be sufficient. Hence the decision process is usually viewed as iterative, and the decision process is represented as cyclical. Such a decision cycle has been included in Section 1 of this document. In the same way that objectives are specific to the problem at hand, so are decision cycles. The cycle included in Section 1 was that for business operational decisions and defined within the ISO 14 001 environmental management standard.

Table 2-15 in Section 2 of this thesis identifies different decision contexts or "levels". It also demonstrates the iterative nature of the decision process and indicates that decisions taken at one level feed into decisions taken at another.

Wrisberg and Triebswetter (1999) identify different decision cycles for each of these levels of decision making. They analyse the different decisions that can be made at each level of decision making. They propose decision situations or contexts for each decision level, define decision objects and list the main stakeholders involved in each type of decision. Table 4-2 below contains the decision situation, decision object and main stakeholders involved in design and development decisions.

While this figure details a useful generic grouping it can be argued that the stakeholders should include other groups that can potentially be affected by the impacts associated with the decision taken – local residents should be included at the very least. This discussion is extended in Section 6 of this thesis.

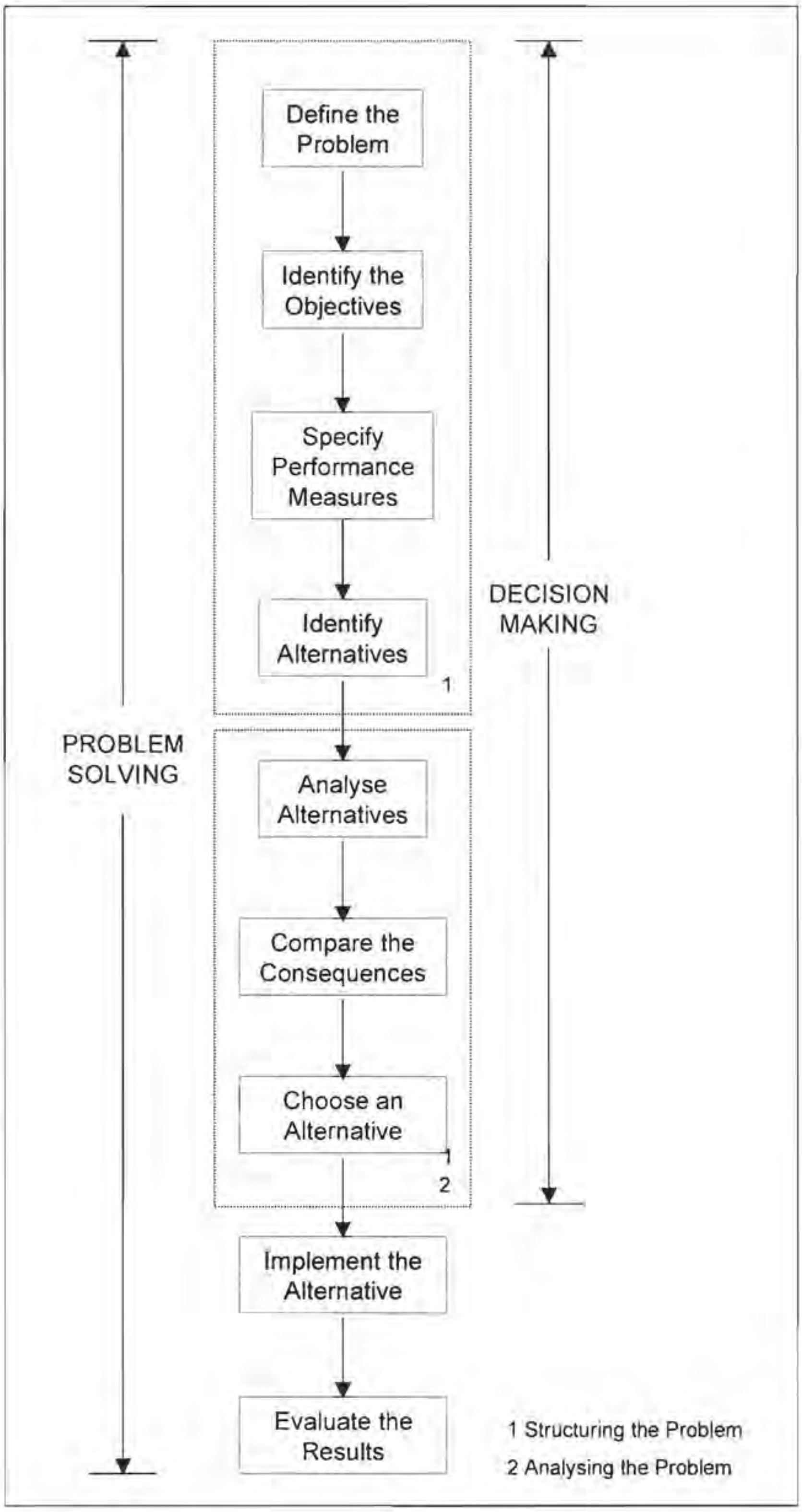


Figure 4-1 Relationship between the different aspects of Problem Solving (after Anderson et al, 1991)

Table 4-2 *The environmental and cultural context of decision situations related to design and development (after Wrisberg and Triebswetter, 1999)*

Decision Situation	Decision Object	Main Stakeholders Involved
General design and development	Material, products, processes, technologies, infrastructures	Employees
		Authorities
		Suppliers
		Customers
		Consumers
Product development	Products	Authorities
		Suppliers
		Customers
		Consumers
Process development	Processes	Employees
		Authorities
		Suppliers
		Customers
		Consumers
Technology development	Technology	Employees
		Authorities
		Suppliers
		Customers
		Consumers

In conclusion it can be stated that environmental decisions within the minerals industry are complex and hard (these include the decisions taken during design as well as those taken during other stages of the project life cycle). It is possible to structure these decisions using the four steps presented in block 1 on Figure 4-1. The decision structures will be iterative. While a decision context has been defined for environmental decisions taken during process design no indication of the decision cycle for process design has been given. These decision cycles are particular to decisions taken in specific contexts within design. The cycles developed for the design process are included in Section 6.

4.1.1.2 Decision Analysis

Decision analysis (Figure 4-1 block 2) is a well established process (Janssen, 1994; Keeney, 1992; von Winterveldt and Edwards, 1986) and takes place once the alternatives for solving a problem have been identified. From Figure 4-1 it can be seen that it is necessary for problem structuring to precede problem analysis. This implies that before alternatives are identified it is necessary to define the problem as well as the objectives to be met by preferred alternative.

It must be recognised that in the process design context there is, potentially, an infinite number of potential solutions or solutions. The aim of ordering the decisions made in process design in an hierarchical fashion is to guide the manner in which this infinite set of options is limited to the point that synthesising the remaining options becomes viable. The definition of a complete set of technology options to include as alternatives in process design is included in Section 4.1.2.1.

Decision analysis is then an evaluation of the alternatives. This evaluation follows one or other permutation of the following steps (Clemen, 1996; Keeney, 1992):

- Specifying the extent to which each alternative meets each objective, this is called the score of the alternative relative to the criteria
- Representing potential outcome for each alternative so that it is possible to determine which of the alternatives is the preferred solution
- Assessing the uncertainty inherent in the outcome for each alternative
- Reviewing the choice of preferred solution in the context of sensitivity analyses on all, or a limited set, of alternatives

Decision analysis culminates in the recommendation of a preferred solution that is robust and for which the inherent uncertainty is known. Decision analysis is iterative, and can form part of a decision cycle, or even a cycle within a cycle.

Multi-criteria decision analysis (MCDA) is the term used to define situations in which alternatives are analysed relative to their performance with respect to multiple criteria. MCDA is currently used as an over-arching term which includes multi-criteria or multiple criteria decision making (MCDM). MCDA tools were developed formally within the realm of quantitative management science to enable decision makers and decision analysts to structure and analyse multi-dimensional management problems (Stewart, 1992). MCDA is based on single objective problem solving where the objective was either maximised or minimised. In extending these tools to multiple objectives it is necessary to define the problem in terms of independent and relatively precise criteria (Stewart, 1992). By their nature these independent criteria would be in conflict, if criteria are dependant then the problem can be reduced to a single objective situation. Thus each criterion can be seen to represents a particular dimension of the problem (Bana e Costa *et al*, 1997). Within the realm of MCDA it is possible to capture the different points of view, or preferences, that stakeholders in the decision process place on different criteria. MCDA allows the decision maker to explore the interplay of these preference sets on the outcome of the problem (Bana e Costa *et al*, 1997).

The focus of MCDA is on the evaluation of alternatives and most of the discussion of MCDA has been for cases where the problem is well-defined, i.e., there is agreement on the formulation of the problem, the objectives, the available courses of action, etc. (Beinat, 1997). In the case of design for environment in minerals processing, while there are a number of different stakeholder groupings, there is a single decision maker – the group which is providing the financial backing for the project, thus the decisions taken fall into the single decision maker type. For this reason, only single decision maker algorithms have been discussed, multi-decision maker problem types have not been included in the above discussion. It must also be stated that, while environmental considerations will be included in the decision, a decision will only be taken if the proposed process is economically viable. It is possible to structure a design problem in such a manner that it becomes "well-posed" and therefore amenable to analysis using MCDA tools.

4.1.2 Terminology

Some clarification of the terminology used in MCDA is offered here.

4.1.2.1 Alternatives

$\underline{A}$ is the complete set of all possible alternatives or scenarios which can be used to solve the problem as structured. It contains elements a. The preferred solution for the problem is an element of $\underline{A}$. Identifying the set of all possible alternatives is not necessarily a trivial task (Stewart, 1992). The definition of a complete set of alternatives in the context of process design is included in this section.

There are two different types of alternative set $\underline{A}$ (Janssen, 1994):

- One which comprises discrete options, by their nature these alternative sets are finite
- One which relates to continuous decision problems which have an infinite set of possible alternatives

The terms **discrete** and **continuous** are discussed in the context of the information structure presented in Section 2 of this thesis (specifically in Section 2.5.2.1). Discrete alternatives can be viewed as separating the potential flow routes out, such as was done in evaluating the impact associated with the changes in technology in the gold industry. These are three distinct alternatives for processing the same ore body. However, a continuous solution set would result if the stream splits between the unit operations were varied while still maintaining mass balance closure. The result of this study would be a surface which would denote the trends in the waste stream which resulted as one technology was phased in and another phased out.

In using the information structure developed to support decisions in design for the environment there are two issues to consider:

- What is a complete set of alternatives?
- Is it viable to use a continuous set of alternatives?

To answer the first of these, in Section 2 of this thesis "p" was defined the number of unit operations in place in the industry. The flowsheets were then constructed by combining all of these technologies so that all possible flow routes in the industry were accounted for. In the context of process design, this value for "p" will be somewhat different as it will be necessary to include all technologies which are theoretically applicable to the process being designed.

There are a number of different technology assessment philosophies which can be used to determine where the limits of the set of alternatives lie. These include concepts such as:

- BATNEEC (Best Available Technology Not Entailing Excessive Cost)
- BPEO (Best Practicable Environmental Option)
- BPEONEEC (Best Practicable Environmental Option Not Entailing Excessive Cost)
- BDAT (Best Demonstrable Available technology)

It is necessary to state which of these concepts underpins the definition of potential technologies to be included in the design. Using BPEO as an example, BPEO was defined in the 12th report of the Royal Commission on Environmental Pollution (1988) to be that option "which, in the context, releases from a prescribed process provides the most benefit or least damage to the environment as a whole, at an acceptable cost, in the long term as well as the short term." This definition has been updated in the 21st report of the Royal Commission on Environmental Pollution (1998) to include an indication of the local conditions in the technology assessment.

This 21st report acknowledges that the application of BPEO in the United Kingdom has not paid sufficient attention to upstream impacts, or to waste management regimes as these fall outside the ambit of the legislative authority involved. The boundary drawn by LCA will ensure that these considerations are included in the decision support structure developed in this thesis. While allowing that the best option must have acceptable cost, this definition of BPEO takes no explicit consideration of technology scale. It may be necessary to include technologies which have only been demonstrated at pilot-scale in the set of alternatives.

The design alternatives should be as comprehensive a listing of potential technologies as possible within the context of the chosen technology assessment philosophy. The boundary definition used by LCA encourages innovative thought as it does not limit the scope of the problem to being within the plant boundaries (Clift and Longley, 1995). Including impacts associated with both the upstream and downstream processes places a different emphasis on the technologies under consideration. For example, in minerals processing there are various points in the production chain that require significant energy inputs – comminition, electrowinning, refining, etc. A careful assessment of how this energy is invested will lead to different approaches to developing process alternatives.

An illustrative example here is the production of pig iron from iron ore by smelting. The traditional energy source for the smelter is coal. In this respect coal is also a reagent as it functions as a reductant in the furnace. An innovative process would be using charcoal as opposed to coal as the energy source as charcoal has similar reduction properties to coal. Charcoal is also a renewable resource if the forests used for production are managed correctly. Using trees as the energy source for the smelter effectively closes the carbon cycle for pig iron production (Wibberley, 1998). This is an example of how using the LCA boundary definition can focus the design on different aspects. Previously the management of coal within pig iron production has concentrated on energy efficiency and the efficient use of this non-renewable resource, as opposed to replacing it completely. If the scope of the project were confined to the process boundary and the objective was to maximise profit then using charcoal, which is not as cost effective, would not be the preferred solution. It is only when the boundaries are expanded and the value set extended to reflect the requirements of all stakeholders as opposed to a single group, that charcoal becomes a viable energy source.

A further illustrative example is the point in the beneficiation chain where it is most effective to invest energy. This decision is discussed in depth in Section 3 where the decisions within the design hierarchy are detailed.

In conclusion, the alternative set should be as exhaustive as possible within the current understanding of available technologies. Innovative uses for traditional technologies, such as the charcoal example above, should also be included. The size of "p" will thus be larger than that used in the information structuring. However, for the sake of consistency, "p" will still be used to denote the number of unit operations in the mass balance calculation. Set $\underline{A}$ then is the total number of combinations possible with the set of unit operations "p".

To determine whether the set $\underline{A}$ is continuous for process design requires further consideration. While it can be taken as the total number of possible combinations of unit operations, consideration must also be given to the fact that best performance may result from a number of technologies in combination, as opposed to the selection of a single process route. An example here is combining a pressure leach unit with a roast-leach unit upstream of the electrowinning cells in a base metals purification circuit. Both these units have "pros" and "cons" and a combination of the two may be necessary in order to meet environmental requirements while still delivering adequate economic performance. Thus the solution space for these two technologies is continuous. Within the form of the information structure as presented in Section 2 it will be possible to combine these technologies by manipulating the stream split variables as described in this section. This will render a continuous solution space.

However, a further technology that could be considered for the refining of base metals is direct smelting. This has very few unit operations in common with the two technologies listed above and can be viewed as a discrete alternative. Thus it will be necessary to include both discrete and continuous alternatives in set A.

4.1.2.2 Criteria

The objectives for a multi-criteria problem are often articulated as relatively imprecise measures. Criteria are then developed to determine the performance of the alternatives with respect to the objective. There is no uniform definition available for a *criterion*, rather an illustrative example will be included. It is the stated goal of an enterprise to decrease the environmental impact associated with its operations. One of the impacts of the process could be a contribution to acidification effects. A major contributor to acidification is the emission of SO_2. In order to decrease the acidification effect it will be necessary to decrease the amount of SO_2 emitted by the process. Thus a criterion in the decision making process will be a decrease in SO_2 leaving the process.

The impact categories in LCA will be used to inform criteria in design for the environment in minerals processing. This has already been explored by Azapagic (1996) in the context of the analysis of a single process. Figure 1-2 in Section 1 of this thesis illustrates a hierarchy of criteria as established by Meittinen and Hamalainen (1997). In this case the stated goal is to improve environmental performance. They suggest that there are three main groups that contribute to environmental impact:

- resource depletion
- ecological impacts
- human health impacts

This suggests a further level of detail required by the hierarchy. For example, human health impacts are divided further into impact on work environment, toxicological impacts and non-toxicological impacts – all of which it is possible, in theory, to measure. In order to decrease human health impacts it will be necessary to decrease all of these. The selection of criteria will obviously be dependent on the decision context.

4.1.2.3 Attributes

While criteria are the translation of objectives into measures which are more easily calculated, it may still not be possible to evaluate the criteria explicitly. Attributes are introduced as a surrogate measure of performance. The attribute value gives an indication of the degree to which an objective has been achieved. Not all MCDA methodologies use attributes, e.g., analytical hierarchy and simple multi-attribute rating technique which are applied in cases where it is possible to determine $\underline{A}$ in terms of a set of discrete alternatives. They are not applicable to continuous variables and thus cannot be used in process design, though they can be used to assess the relative value of design alternatives in a "post-facto" sense.

There are two classes of attribute as described by Beinat (1997). In the first class are *natural* attributes which can be measured directly. The second class consists of *proxy* attributes. In cases where the natural attribute is not readily measurable, proxy attributes (which are readily measurable) are constructed. These proxy attributes are linked to the natural attributes. Again considering an example, in this case the objective is to minimise the eco-toxicity effect of a suite of technologies. It is not necessarily possible to link aqueous emission from a process directly with a toxicity effect. However, there is a link between emissions and the exposure of the natural environment to these emissions, and a toxicity effect. Thus a proxy attribute for eco-toxicity could be the amount of material emitted. The aim would then be to reduce this quantity.

4.1.2.4 Identifying the elements of the Problem

The basic elements of a decision include (Clemen, 1996):

- Values and objectives
- Decisions to be made
- Potential uncertain events
- Consequences of the decision

Two of these terms require further clarification:
Where values are taken to be an indication of the emphasis which stakeholders place on potential effects of decisions taken - the effects which matter to the stakeholders; and objectives are the specific outcomes that decision-makers want to achieve.

In this respect it could be inferred that the sum of a decision-maker's values makes up their objectives. It must be recognised that objectives are specific to the decision context (Stewart, 1992). In many ways the objectives define the decision context (Keeney and Raiffa,1976). Once the objectives have been determined it is possible to evaluate a *requisite model* – this is a model which includes all the objectives that matter, and no more. Thus the objectives for the problem can be seen as defining what "sufficient" information would be within the process design context (with "necessary" information being defined by the amount of information required to ensure mass and energy balance closure).

Once the decision context has been well-developed and the values determined, it is possible to identify specific elements which make up the decision. There is the potential to take different decisions at different times. If there is a set time-scale for solving a problem, this may generate a different solution than if more time were available for making the decision. An example here would be the purchase of stocks on the stock market. If the decision is to be taken in a single day then a different portfolio would result than if the decision were taken over a longer time period. In many ways the time scale over which the decision is taken is dictated by the amount of information available.

Decisions are often sequential. This is at the heart of the design hierarchy presented in Section 5 (which is based on the hierarchy of Douglas as presented in Section 3). In this case the decisions made in stage **n**+1 are predicated on decisions taken in stage **n** (here n is not taken to indicate the number of components in the LCI; this is purely illustrative). The iterative nature of the decision process would suggest that previous design steps be re-visited should the outcome of any decision taken further down the hierarchy show that this is necessary.

As has already been stated, decisions are often made in the presence of significant uncertainty. This is definitely the case when the environmental impact of a process is inferred during process design. One of the methods of dealing with this uncertainty within decision making is to resolve the uncertainty inherent in each decision as the decision-maker moves through sequential decisions. This is not necessarily possible in design for the environment in minerals processing where the actual impacts associated with the process may only be felt many years in the future. However, it is possible to improve on the LCA information on the potential environmental impact of the process. Current practice is to achieve this by conducting an Environmental Impact Assessment (EIA). An EIA has the potential to make the equivalency factors in the LCA methodology site specific. It may also be possible to determine the temporal and spatial domains over which these impacts have effect (Hansen *et al*, 1998). The EIA process thus has a significant role in design for the environment and has the potential to accommodate one of the sources of uncertainty. However, the impact assessments within EIA are extremely detailed and require fairly significant process detail before they can be conducted. For example, it is not possible to conduct a study on the effects of the dusts carried out of a smelter stack without having an understanding of the particle size distribution of the dust. This information, together with an understanding of the local conditions is then used to develop a temporal and spatial view of the potential impact associated with these dusts. This would infer that the timing of the EIA within the sequential design hierarchy presented is critical. This is discussed in detail in Section 6.

4.1.2.5 Normalisation and Sensitivity Analysis

In order that no single objective outweigh any other merely by virtue of the numerical range of its attribute scale, it is necessary to **normalise** the attribute scale.

The **sensitivity** of the preferred or best (within the context of the criteria identified) solution to changes in both the underlying process being modelled as well as to changing stakeholder preferences used to inform the value sets will need to be investigated for the problem at hand. This will be discussed further in the context of the development of the design decision framework as well as in the case study.

4.2 Modelling Complex Problems

Decision making models can be defined with respect to:

- The set of alternatives, $\underline{A} = (a_1, a_2, \ldots\ldots a_k, \ldots\ldots a_l)$
- The set of attributes, $\underline{B} = (b_1, b_2, \ldots\ldots b_r, \ldots\ldots b_q)$
- A performance table, $\underline{\underline{PT}}$, where $\underline{\underline{PT}}$ is defined below:

$$\underline{\underline{PT}} = \begin{bmatrix} c_{1,1} & c_{2,1} & \cdots & c_{k,1} & \cdots & c_{l,1} \\ c_{1,2} & c_{2,2} & & c_{k,2} & & c_{l,2} \\ \cdots & \cdots & & \cdots & & \cdots \\ c_{1,r} & c_{2,r} & & c_{k,r} & & c_{l,r} \\ \cdots & \cdots & & \cdots & & \cdots \\ c_{1,q} & c_{2,q} & & c_{k,q} & & c_{l,q} \end{bmatrix}$$

Equation 4-1

where $c_{k,r}$ is a measure of how well alternative a_k satisfies attribute b_r

Note: Attributes are being referred to here as the measure by which criteria are evaluated. If Criteria are directly measurable in the problem being modelled this would be the set of criteria.

Stewart (1992) uses the convention that the decision maker always prefers larger values of $c_{k,r}$. This implies that all b_r are defined in increasing sense. For two alternatives I and II, and given that $b_r(a_I) \geq b_r(a_{II})$ for all elements in the attribute set, then alternative I is said to be dominant to alternative II. Alternatives which are not dominated by another are termed **efficient** or **pareto optimal**. They are also referred to as the **best** or **preferred solution** in this thesis.

The requirement here is to choose an MCDA methodology which enables the development of this set of efficient solutions within the context of process design. As has already been stated, the decisions within process design may be regarded as well-defined. In addition, process design problems are defined as single decision maker problems as there will, ultimately, be a single decision maker - the project proponent. There is still the need for transparency and incorporation of conflict resolution possibilities in the decision structure. These are characteristics of ill-defined problems (Rosenhead, 1989) and thus a methodology that can be used for such problems should be selected from the start of the design process. The main reason for making this statement is that the information structure proposed in Section 2 will be extended to include the MCDA methodology, and it is further proposed that this extended structure can be used to inform environmental decisions during operational, closure and post-closure phases of the project life cycle. If a single information structure is to be used it must be holistic and able to manage all decision scenarios, not only those which arise during design.

Reviews of MCDA methodologies can be found in the work of Meittinen (1999), Stewart (1992) and Bana e Costa (1990). In an early work in this field, Hwang and Masaud (1979) categorised these methods relative to the participation of the decision maker in the solution process:

- *No-preference* methods - here there is no articulation of preference information
- *Aposteriori* methods - where preference are articulated after the problem has been established
- *Apriori* methods - here the preferences are articulated up front of the problem solution
- *Interactive* methods - in this case progressive articulation of the preference information is used.

Decision making during process design (using the information structure presented in Section 2 of this thesis, in conjunction with the decision hierarchy presented in Section 3), can fall into any of these categories. However, a preference set will be made known at some stage of the design and thus the first set of methodologies will not be applicable. The interactive methods usually refer to one or other algorithmically based solution approach (Meittinen, 1999). It is not the aim of this thesis to deliver a computer tool as an output and thus these will not be discussed further.

In the case of *aposteriori* methods, or methods for generating *pareto optimal* solutions, the working order is 1) analyst and 2) decision maker (Meittinen, 1999). In these methods the analyst evaluates the solutions to the problem and the decision maker chooses the preferred option (again stressing that only single decision maker problems are to be considered). In the case of process design, and more specifically in the first stages of any design hierarchy, the decision maker and the analyst are the same person/people. They are also dealing with a significant number of potential process alternatives. In order to make the design process as efficient (and thus cost effective) as possible, the team attempts to narrow down the potential number of alternatives as quickly and reliably as possible. This will be easier in the context of the *apriori* methodologies where the preferences of the decision maker are stated up front and the ability of the potential solutions to meet these preferences is evaluated. This will make the narrowing down of the potential solution set as stream-lined as possible. In addition, within process design there is the potential to have a continuous set of alternatives as discussed previously. The evaluation of the best option within this continuous set will be more efficient if the preferences are known up-front as this will guide the selection of process route within the continuous set. This compares favourably with the hit and miss approach that would result if the *aposteriori* methods were used. It is also the opinion of Stewart (1997) that the *apriori* methodologies are best suited to the decisions taken in process design.

The main shortcoming with apriori approaches is that the preferences must be stated up-front, before the solution process. However, the decision maker does not necessarily know beforehand what it is possible to attain within the problem, and thus whether the expectations of the decision maker are realistic (Miettenen, 1999). The order of working in these approaches is 1) decision maker and 2) analyst. There are three main *apriori* approaches. These are described below.

4.2.1 Value Function Method

The aim of value function modelling is to find a single value function that is the sum of the scores representing how well a single objective has achieved its goal. In the value function method, the decision maker must be able to express a mathematical form of the value function. This value function then is the total score for that alternative.

$$V(b) = \sum_{r=1}^{q} v_r(b_r)$$ **Equation 4-2**

where b is the attribute vector

v_r is the score associated with how well objective r achieves attribute b_r

In its simplest form, the value of V need do nothing other than give an order to the alternatives. The preference ordering introduced previously is referred to here, where b^a is preferred to b^b if and only if:

$$V(b^a) > V(b^b)$$ **Equation 4-3**

However, the idea of trade-offs between attribute scores is central to the understanding of a total score for an alternative. It is necessary to understand the scores being allocated to each criterion and to determine whether the trade-offs that these scores represent are acceptable to the decision maker. While there are a number of constructions that have been used to ensure that trade-offs remain within the decision maker's "tolerance" level (Keeney and Raiffa, 1976), these can be extremely complicated. It is far easier to represent the score allocated to a criterion as (Stewart, 1992):

$$v_r(b_r) = w_r\, u_r(b_r)$$ **Equation 4-4**

where u_r (b_r) is a marginal utility function

w_r is the weight associated with the importance of each criterion

The marginal utility function is calculated for each single criterion and normalised to a convenient scale. This contains no indication of trade-offs between criteria. This marginal utility function can be evaluated in a number of ways. The easiest is the direct method where the ideal (best) and nadir (worst) possible outcomes for the criterion are used to set the range within which the criterion value should fall. Other values are then fitted into this range which give an indication of how the preference for a specific criterion value changes within the ideal-nadir range.

Essentially the weight, w_r, scales the score for each criterion. The weight can be determined directly using an understanding of the importance of the outcome as the criterion value moves from the ideal value to the nadir value.

While this representation of the value function approach is potentially the simplest, it is also the most robust. Though there may be problems inherent in using the addition of scores to render a final value, any inaccuracies will be outweighed by the uncertainties inherent in the weightings and marginal value functions used. Stewart (1992) states, "This form of additive model is well-justified theoretically".

The value function approach could be seen as the optimal way of solving multi-attribute functions if the decision maker can reliably express the value function (Miettenen, 1999). In practice the use of value functions is restricted to problems with a discrete set of feasible solutions (Keeney and Raiffa, 1976).

4.2.2 Lexicographic Ordering

In lexicographic ordering the decision maker orders the objective functions according to their absolute importance. This ordering implies that the more important objective is infinitely more important than the less important objective (Meittenen, 1999).

In the context of design for the environment it is not possible to assume that any one objective is infinitely preferable to the others. If this were the case the solution to the problem would be maximising the profit for the process (bearing in mind that the decision maker will always choose a process which is profitable) within a set of environmental constraints. These constraints could be legislative limits for the process. This methodology does not allow for trade-offs between the objectives to be explored and thus lexicographic ordering is not a suitable approach.

4.2.3 Goal Programming

Charnes *et al* (1955) introduced the concepts of goal programming originally. Goal programming was one of the first methods expressly created for multi-objective optimisation (Charnes and

Cooper, 1961). In many ways goal programming can be seen as the mathematical interpretation of a decision making heuristic where a decision-maker will aim to try and satisfy all objectives as they are not able to maximise them all (Simon, 1986). Goal programming was originally developed for multi-objective optimisation and this is evident in its formulation (Miettenen, 1999)).

The idea of goal programming is that the decision maker specifies (optimistic) aspiration levels for the objective functions. Together the aspiration level and the objective function form the goal (Miettenen, 1999; Tamiz *et al*, 1996).

In goal programming the criterion is allowed to differ from the goal or target value. The sum of the differences from these goals is then minimised. It is possible to include weights in a goal programming algorithm.

There are a number of problems with the goal programming approach:

- It allows almost infinite trade-offs to be made between the criteria
- It is difficult to know what a reasonable goal is
- It may not render any easily definable alternatives

Probably the greatest deficiency in all goal programming approaches (assuming that it is possible to set realistic goals) is that fact that it will allow infinite trade-offs between the criteria. There is no indication of whether a small change in a single goal will lead to a radical improvement solution, i.e., there is no indication of how much needs to be traded-off on one criterion before it starts affecting the solution significantly.

Goal programming has an advantage over value function approaches when there are a significant number of criteria; using pair-wise comparisons within value functions becomes extremely time consuming when there is a significant number of criteria.

4.2.4 Conclusions

In this section decision structuring and decision analysis were presented and explored within the context of environmental decision making during process design. This section has shown that it is possible to structure the decisions taken during process design using formal decision structuring. While this is possible it has not been formalised as yet.

The terminology commonly used in decision analysis was presented, and some environmental examples were offered. This terminology will be used in the remainder of this section to develop environmental objectives used to inform process design.

The tools of decision analysis were then discussed in their application to design for the environment. *Apriori* methodologies were identified as being most applicable in the case of process design. The conclusions reached are that value functions and goals programming are applicable to the decisions to be taken in process design for the environment. Which of these it is possible to use will depend on the decision context.

4.3 Using LCA to Structure an Environmental Objective Function

LCA, together with the information structure presented in Section 2, can be used to formulate an environmental objective function. In this section it is assumed that the weights to be placed on each of the criteria are known. It is acknowledged that this does not necessarily reflect the "real world". However, at this stage, the weights for each criterion will be assumed to be constants values. Section 6 of this thesis deals with the case where these weights are not constant.

4.3.1 Extending the Audit Trail

An audit trail was introduced in Section 2. This audit trail links unit operations to:

- Inputs to the unit
- Products from the unit
- Wastes from the unit

Using the structure of LCA as presented in Section 2 it is possible to extend this audit trail to include the impact associated with each unit operation. Recalling Equation 2-4:

$$\underline{F}'_{j+1} = \underline{F}'_j + \underline{I}'_j - \underline{P}'_j - \underline{U}'_j$$ **Equation 2- 4**

where $\underline{F}'_j$ is the process stream to unit j

$\underline{I}'_j$ are the inputs to unit j

$\underline{F}'_{j+1}$ is the process stream exiting stream from unit j (thus the feed to unit j+1)

$\underline{P}'_j$ are the saleable products from unit j

$\underline{U}'_j$ are the unsaleable products from unit j

And recalling the three matrices constructed from the inputs and outputs to the unit operations which are all of dimension n x p:

- $\underline{\underline{I}}'$ – matrix of inputs
- $\underline{\underline{P}}'$ – matrix of saleable products
- $\underline{\underline{U}}'$ – matrix of unsaleable products

where n is the total number of components

recall that n was defined in Section 2 to be w + 2, which includes the two "non-chemical" components - energy and cost.

and p is the total number of unit operations as defined in Section 4.1.2.1

Elements within these matrices are ordered using two references; i refers to the component and j to the unit operation.

It must be accepted that wastes are not equivalent to impacts. To explore this statement more fully, a stream may have a very low flow rate but a relatively high potential impact, such as a purge stream containing a range of dissolved salts. Conversely, it is possible for streams with a large flow rate to have a relatively insignificant environmental impact. This was the reasoning behind including environmental impacts in the discussion on process synthesis in Section 3, and not merely waste flow rates. As was stated in there, if the objective of the synthesis is to minimise the mass of waste produced by the process, the problem is reduced to a single objective optimisation.

Using the impacts of the process, as opposed to merely concentrating on the wastes generated, also makes it possible to include the impacts associated with inputs to the process. If all the inputs to and outputs from the processes are analysed with resepect to their potential environmental impact, then the very significant size of information set required to support the analysis is reduced, as all the inputs and outputs can be aggregated into a reduced number of impact categories according to accepted methodology.

Thus it is necessary to evaluate the potential impact embodied by the inputs to and outputs from the process. Section 2 of this thesis contained a discussion of equivalency factors where inputs and outputs are linked to the potential environmental impact that they embody. Thus, using equivalency factors from LCA, it is possible to evaluate the environmental impact associated with the input and output matrices listed above.

In order to retain the audit trail structure it is necessary to retain information on each unit operation in the process.

4.3.1.1 Impact Profile Associated with wastes from the process

The first matrix to be evaluated is $\underline{\underline{U}}'$, the matrix of unsaleable products. This matrix can be represented:

$$\underline{\underline{U}}' = \begin{bmatrix} u_{1,1} & u_{2,1} & \dots & u_{j,1} & \dots & u_{p,1} \\ u_{1,2} & u_{2,2} & & u_{j,2} & & u_{p,2} \\ \dots & \dots & & \dots & & \dots \\ u_{1,i} & u_{2,i} & & u_{j,i} & & u_{p,i} \\ \dots & \dots & & \dots & & \dots \\ u_{1,n} & u_{2,n} & & u_{j,n} & & u_{p,n} \end{bmatrix}$$

Equation 4-5

where $u_{j,i}$ is the mass flow of unsaleable component *i* from unit operation *j*

The environmental impacts associated with the wastes from the process are evaluated using equivalency factors from LCA. An equivalency vector, $\underline{E}$ is constructed for each component in the output stream:

$$\underline{E}_i = (e_{i,1}, e_{i,2}, \dots\dots, e_{i,k}, \dots\dots, e_{i,y})$$

Equation 4-6

where: $e_{i,k}$ is the equivalency factor which determines the contribution of stream component *i* to impact category *k* expressed on a per mass of unsaleable output basis

y is the total number of impact categories

Thus it is possible to construct a matrix of equivalency vectors, $\underline{\underline{E}}'$, which has dimensions n x y, i.e., number of stream components by number of impact categories. This matrix can be represented:

$$\underline{\underline{E}}' = \begin{bmatrix} e_{1,1} & e_{2,1} & \dots & e_{k,1} & \dots & e_{y,1} \\ e_{1,2} & e_{2,2} & & e_{k,2} & & e_{y,2} \\ \dots & \dots & & \dots & & \dots \\ e_{1,i} & e_{2,i} & & e_{k,i} & & e_{y,i} \\ \dots & \dots & & \dots & & \dots \\ e_{1,n} & e_{2,n} & & e_{k,n} & & e_{y,n} \end{bmatrix}$$

Equation 4-7

Note: The equivalency factor assigned to the last component in the matrix, i.e., cost, is unity. This will ensure that the value which reports to the final objective function represents the monetary cost of the unit operations in the model.

Closer examination of the matrix in Equation 4-5, and comparing this with Equation 2-1 from Section 2 will show that a single column in $\underline{\underline{U}}$ represents a component breakdown of the unsaleable products from a single unit operation and is equal to:

$$\underline{U}'_j = (f_{j,1}, f_{j,2}, \dots\dots, f_{j,i}, \dots\dots, f_{j,n})$$

Equation 4-8

For each single component in this vector it is possible to evaluate the impact. This will be a vector, $\underline{G}_{j,i}$ which is the impact associated with component *i* leaving unit operation *j*. $\underline{G}_{j,i}$ is calculated using the relevant equivalency values from $\underline{\underline{E}}$:

$$\begin{aligned} \underline{G}_{j,i} &= (e_{i,1} . f_{j,i}, e_{i,2} . f_{j,i}, \dots\dots, e_{i,k} . f_{j,i}, \dots\dots, e_{i,y} . f_{j,i}) \\ &= (g_{1,i}, g_{2,i}, \dots\dots, g_{k,i}, \dots\dots, g_{y,i}) \end{aligned}$$

Equation 4-9

It is thus possible to construct an impact matrix for the impacts associated with the outputs from each unit operation, $\underline{\underline{G}}_j$:

$$\underline{\underline{G}}_j = \begin{bmatrix} g_{1,1} & g_{2,1} & \cdots & g_{k,1} & \cdots & g_{y,1} \\ g_{1,2} & g_{2,2} & & g_{k,2} & & g_{y,2} \\ \cdots & \cdots & & \cdots & & \cdots \\ g_{1,i} & g_{2,i} & & g_{k,i} & & g_{y,i} \\ \cdots & \cdots & & \cdots & & \cdots \\ g_{1,n} & g_{2,n} & & g_{k,n} & & g_{y,n} \end{bmatrix}$$ **Equation 4-10**

In order to evaluate the total impact vector, $\underline{S}_j$, associated with the wastes from this unit operation, it is necessary to evaluate the sum of the columns in this matrix.

$$\underline{S}_j = (s_{j,1}, s_{j,2}, \ldots\ldots, s_{j,k}, \ldots\ldots, s_{j,y})$$ **Equation 4-11**

where:

$$s_{j,k} = \sum_{t=1}^{n} g_{k,t}$$ **Equation 4-12**

and $s_{j,k}$ is the contribution of unit *j* to impact category *k*

It is thus possible to evaluate a matrix $\underline{\underline{UI}}$ which is the total impact matrix associated with the unsaleable outputs:

$$\underline{\underline{UI}} = \begin{bmatrix} s_{1,1} & s_{2,1} & \cdots & s_{j,1} & \cdots & s_{p,1} \\ s_{1,2} & s_{2,2} & & s_{j,2} & & s_{p,2} \\ \cdots & \cdots & & \cdots & & \cdots \\ s_{1,k} & s_{2,k} & & s_{j,k} & & s_{p,k} \\ \cdots & \cdots & & \cdots & & \cdots \\ s_{1,y} & s_{2,y} & & s_{j,y} & & s_{p,y} \end{bmatrix}$$ **Equation 4-13**

This matrix contains details of the impact associated with the waste streams from each unit operation in the process. In order to determine the total impact profile associated with wastes from the process it is necessary to evaluate the sum of the rows in the matrix. The waste impact vector for the process is designated $\underline{UI}$:

$$\underline{UI} = (u_1, u_2, \ldots\ldots, u_k, \ldots\ldots, u_y)$$ **Equation 4-14**

where:

$$u_k = \sum_{t=1}^{p} s_{k,t}$$ **Equation 4-15**

and u_k is the total contribution of the process to impact category *k*

4.3.1.2 Impact Profile Associated with inputs to the process

It is necessary to include the impacts associated with the inputs to the unit operation as well. Recalling matrix $\underline{I}'$ described in Section 2, this matrix is of the form:

$$I' = \begin{bmatrix} h_{1,1} & h_{2,1} & \cdots & h_{j,1} & \cdots & h_{p,1} \\ h_{1,2} & h_{2,2} & & h_{j,2} & & h_{p,2} \\ \cdots & \cdots & & \cdots & & \cdots \\ h_{1,i} & h_{2,i} & & h_{j,i} & & h_{p,i} \\ \cdots & \cdots & & \cdots & & \cdots \\ h_{1,n} & h_{2,n} & & h_{j,n} & & h_{p,n} \end{bmatrix}$$

Equation 4-16

where: $h_{i,j}$ is the mass flow of component *i* into unit operation *j*
the matrix has dimensions of number of stream components by number of unit operations

There is a vector of environmental impacts associated with each of these inputs. These impact vectors may be drawn from LCA databases. This is common practice (Jodicke *et al*, 1999; Spengler *et al*, 1998; Andersson *et al*, 1998; Hanssen, 1998). Within the discussion background and foreground systems from Section 2, LCA databases are used to determine the impacts associated with materials being brought in from, or returned to, the background system. Impacts associated with material flows in the foreground system are evaluated using equivalency factors.

These impact vectors are designated $\underline{D}_i$ where the impact for a single input component *i* is referred to as:

$$\underline{D_i} = (d_{i,1}, d_{i,2}, \ldots\ldots, d_{i,k}, \ldots\ldots, d_{i,y})$$

Equation 4-17

where: $d_{i,k}$ is expressed in contribution to impact category *k* per mass unit of input category *i*
y is the number if impact categories to be included.

Where the LCA databases are deficient, it may be necessary to collect further information. This would depend on the information detail required in the decision process, and the information detail available in the other information sets. For example, spending a great deal of time establishing impact vector $\underline{D}_i$ in detail when there is not the same level of detail in $\underline{S}_j$, the total impact vector associated with the wastes from unit operation, is not necessary. More time should be spent in ensuring that the same level of detail is available in all information sets than in gathering great detail on a single information set in the structure. As has already been stated, a complete study of what comprises comparative levels of detail in information sets is beyond the scope of this work.

For a single input component *i* into unit operation *j* it is possible to evaluate the impact vector, designated $\underline{K}_{i,j}$, where:

$$\begin{aligned}\underline{K}_{i,j} &= (h_{i,j}.d_{i,1}, h_{i,j}.d_{i,2}, \ldots, h_{i,j}.d_{i,k}, \ldots, h_{i,j}.d_{i,y}) \\ &= (k_{i,1}, k_{i,2}, \ldots, k_{i,k}, \ldots, k_{i,y})\end{aligned}$$

Equation 4-18

and $k_{j,k}$ is the contribution of the inputs to unit operation *j* to impact category *k*

$h_{i,k}$ is taken from matrix $\underline{I}'$ detailed in Equation 4-16

It is thus possible to construct a matrix $\underline{K}'_j$ which contains the information relating to the impact associated with the inputs to that unit operation:

$$\underline{\underline{K'_j}} = \begin{bmatrix} k_{1,1} & k_{2,1} & \ldots & k_{k,1} & \ldots & k_{y,1} \\ k_{1,2} & k_{2,2} & & k_{k,2} & & k_{y,2} \\ \ldots & \ldots & & \ldots & & \ldots \\ k_{1,i} & k_{2,i} & & k_{k,i} & & k_{y,i} \\ \ldots & \ldots & & \ldots & & \ldots \\ k_{1,n} & k_{2,n} & & k_{k,n} & & k_{y,n} \end{bmatrix}$$

Equation 4-19

In order to calculate the total environmental profile associated with the inputs to the unit operation it is necessary to evaluate the sum of the columns of this matrix. This will render a vector $\underline{L}_j$:

$$\underline{L}_j = (l_{j,1}, l_{j,2}, \ldots, l_{j,k}, \ldots, l_{j,y})$$

Equation 4-20

where:

$$l_{j,k} = \sum_{s=1}^{n} k_{k,s}$$

Equation 4-21

and $l_{j,k}$ is the contribution of inputs to unit operation *j* to impact category *k*

It is thus possible to construct a matrix $\underline{\underline{II}}$ which contains the total impact associated with the inputs to each unit operation.

$$\underline{\underline{II}} = \begin{bmatrix} I_{1,1} & I_{2,1} & \cdots & I_{j,1} & \cdots & I_{p,1} \\ I_{1,2} & I_{2,2} & & I_{j,2} & & I_{p,2} \\ \cdots & \cdots & & \cdots & & \cdots \\ I_{1,k} & I_{2,k} & & I_{j,k} & & I_{p,k} \\ \cdots & \cdots & & \cdots & & \cdots \\ I_{1,y} & I_{2,y} & & I_{j,y} & & I_{p,y} \end{bmatrix}$$ **Equation 4-22**

This matrix contains details of the impact associated with the inputs to each unit operation in the process. In order to determine the total impact associated with inputs to the process it is necessary to evaluate the sum of the rows in the matrix. The impact vector for the process is designated $\underline{II}$:

$$\underline{II} = (q_1, q_2, \ldots\ldots, q_k, \ldots\ldots, q_y)$$ **Equation 4-23**

where:

$$q_k = \sum_{t=1}^{p} I_{k,t}$$ **Equation 4-24**

and q_k is the total contribution of inputs to the process to impact category *k*

4.3.1.3 Impact Profile Associated with products from the process

The impact profile associated with the products from the process can be calculated in the same way as the impacts associated with the inputs to the process. Information on the impacts associated with use of each product leaving each unit operation is evaluated using information available in LCA databases. Note - these impacts are associated with the product **use** only. These are the impacts that are experienced once the product leaves the "gate" of the process. The impacts associated with the up-stream elements in the product life cycle have been accounted for in the impact matrices established above. If there is no information available in the LCA databases then it would be necessary to establish this information through further studies. The same *caveat* on information detail stated in the section on impacts associated with inputs to the process applies here.

Following the same reasoning as was applied to the development of the input impact matrix (Equation 4-16 to Equation 4-21), $\underline{\underline{\mathrm{II}}}$, it is possible to establish a product impact matrix, $\underline{\underline{\mathrm{PI}}}$:

$$\underline{\underline{\mathrm{PI}}} = \begin{bmatrix} p_{1,1} & p_{2,1} & \cdots & p_{j,1} & \cdots & pl_{p,1} \\ p_{1,2} & p_{2,2} & & p_{j,2} & & p_{p,2} \\ \cdots & \cdots & & \cdots & & \cdots \\ p_{1,k} & p_{2,k} & & p_{j,k} & & p_{p,k} \\ \cdots & \cdots & & \cdots & & \cdots \\ p_{1,y} & p_{2,y} & & p_{j,y} & & p_{p,y} \end{bmatrix}$$

Equation 4-25

And from this matrix it is possible to use an equation of the same form as Equation 4-24 to sum the impacts of the unit operations into a total impact vector for product use, $\underline{\mathrm{PI}}$:

$$\underline{\mathrm{PI}} = (z_1, z_2, \ldots\ldots, z_k, \ldots\ldots, z_y)$$

Equation 4-26

4.3.1.4 Total Impact Profile for the Process

The previous section has detailed the development of information sets which link impacts to the units which give rise to them. These impacts are quantified separately, as impacts associated with wastes, impacts associates with inputs and impacts associated with product use. In order to evaluate the total impact associated with each unit operation a further matrix is defined, $\underline{\underline{\mathrm{TI}}}$, which is calculated from matrices $\underline{\underline{\mathrm{UI}}}$, $\underline{\underline{\mathrm{II}}}$ and $\underline{\underline{\mathrm{PI}}}$ (Equation 4-13 (s), Equation 4-22 (l) and Equation 4-25(p)) :

$$\underline{\underline{\mathrm{TI}}} = \begin{bmatrix} s_{1,1}+l_{1,1}+p_{1,1} & s_{2,1}+l_{2,1}+p_{2,1} & \cdots & s_{j,1}+l_{j,1}+p_{j,1} & \cdots & s_{p,1}+l_{p,1}+p_{p,1} \\ s_{1,2}+l_{1,2}+p_{1,2} & s_{2,2}+l_{2,2}+p_{2,2} & & s_{j,2}+l_{j,2}+p_{j,2} & & s_{p,2}+l_{p,2}+p_{p,2} \\ \cdots & \cdots & & \cdots & & \cdots \\ s_{1,k}+l_{1,k}+p_{1,k} & s_{2,k}+l_{2,k}+p_{2,k} & & s_{j,k}+l_{j,k}+p_{j,k} & & s_{p,k}+l_{p,k}+p_{p,k} \\ \cdots & \cdots & & \cdots & & \cdots \\ s_{1,y}+l_{1,y}+p_{1,y} & s_{2,y}+l_{2,y}+p_{2,y} & & s_{j,y}+l_{j,y}+p_{j,y} & & s_{p,y}+l_{p,y}+p_{p,y} \end{bmatrix}$$

Equation 4-27

Entries in this matrix, $t_{j,k}$, are the total contribution of unit operation *j* to impact category *k*.

The total impact vector, $\underline{\mathrm{TI}}$, for the process is the sum of the rows in this matrix. This is equal to the sum of vectors $\underline{\mathrm{UI}}$, $\underline{\mathrm{II}}$ and $\underline{\mathrm{PI}}$.

This set of matrices establishes the audit trail illustrated in Figure 4-2 below. It is possible to trace the unit operations which gives rise to impacts of concern as illustrated below.

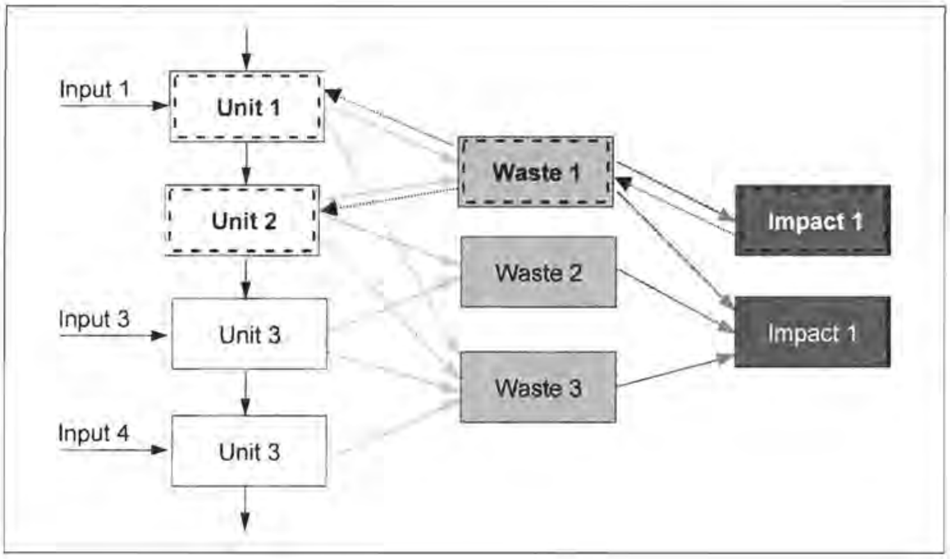


Figure 4-2 *Audit Trail in the Information Structure*

This structure informs the fourth stage of LCA, that of **improvement analysis**, as it directs attention back into the process and highlights where the process should be changed in order to address concerns around specific impacts. This is an element that has been highlighted as missing from LCA (see Section 2 of this thesis). This assertion will be explored in the context of a minerals processing example.

4.3.1.5 Structuring the Audit Trail - A Simple Case Study

Figure 4-3 below contains a very abbreviated flowsheet for the roast-leach-electrowin units in a refinery which is producing zinc from a base metal sulphide feed.

A number of gross simplifying assumptions have been made in establishing this flowsheet:

- There are no volatile metals in the metal in concentrate entering the process, if there were these would form a solid waste from the Roaster (Unit 1), or be emitted to the air
- All the O_2 required for the Roaster reaction (ZnS to ZnO) is provided by air at STP

- The coke contains only carbon, ash and sulphur. All this carbon combusts to form CO_2 in the Roaster
- There are no co-products from the system. Usually a number of base metals co-products are removed from the process stream before it enters the electrowinning process
- There is 100% regeneration of acid in the electrowinning process (Unit 3) and all the acid is recycled to the leach process (Unit 2), which implies a closed water cycle for the process.
- There is no evaporation
- There is no evolution of H_2 in the electrowinning cells
- The only wastes from the process that give rise to impacts are SO_2, acid water and solid wastes
- The only impacts of concern are acid rain (Impact category 1) and water quality impacts (Impact category 2)

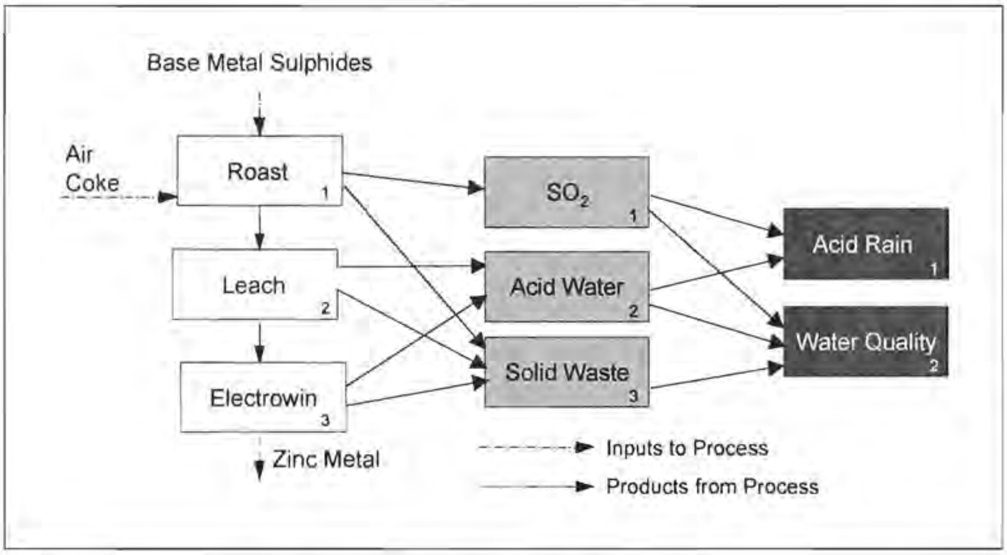


Figure 4-3 *Simplified Zinc refinery*

The main reason behind making these assumptions is in order to use as small as possible an information set that is still meaningful in the context of the example. The given information on the feed stream to the Roaster a flow rate of 100 units of mass per annum (upa) of concentrate containing 8% moisture. The composition of the solid material in the feed stream can be found in Table 4-3.

Table 4-3 *Feed to the Simplified Zinc Refinery*

Component	Mass %
Zn	50.00
S	30.00
Fe	10.00
Balance	10.00
Total	**100.00**

A complete mass balance for the process illustrated on Figure 4-3 and structured using the methodology developed in Section 2 is included in Appendix 4-1. This appendix contains details of the assumptions sets established for the three unit operations considered. There are no alternative flow routes in this process and thus there is no stream split information. The complete list of components used in this spreadsheet and the number assigned to them can be found on Table 4-4.

Table 4-4 *Complete list of component numbers*

Component Description	Component Number
Zn	1
S	2
Fe	3
H_2O	4
C	5
Ash	6
O_2	7
N_2	8
SO_2	9
CO_2	10
Balance	11

The results of the mass balance are the three matrices:

- $\underline{I}'$ – matrix of inputs which can be found on Table 4-5
- $\underline{P}'$ – matrix of saleable products on Table 4-6
- $\underline{U}'$ – matrix of unsaleable products detailed in Table 4-7

Table 4-5 *Matrix of Inputs to the Simplified Zinc Process*

	Feed	Roast	Leach	Electrowin
Zn	46.00			
S	27.60			
Fe	9.20			
H_2O	8.00			
C		12.00		
Ash		3.00		
O_2		56.79		
N_2		227.17		
SO_2				
CO_2				
Balance	9.20			
Total	100.00	298.96	0.00	0.00

Table 4-6 *Matrix of Wastes from the Simplified Zinc Process*

	Feed	Roast	Leach	Electrowin
Zn			2.30	
S				2.76
Fe			8.74	0.46
H_2O		8.00		
C				
Ash			3.00	
O_2				
N_2		227.17		
SO_2		49.63		
CO_2		44.00		
Balance			8.74	0.46
Total	0.00	328.80	22.78	3.68

Table 4-7 *Matrix of Products from the Simplified Zinc Process*

	Feed	Roast	Leach	Electrowin
Zn				43.70
S				
Fe				
H_2O				
C				
Ash				
O_2				
N_2				
SO_2				
CO_2				
Balance				
Total	0.00	0.00	0.00	43.70

Further investigations in this case study will be concerned with the wastes from the process only.

One of the assumptions made at the beginning of this case study is that there are only two environmental impact categories to be considered, i.e., contribution to acid rain and contribution to a decrease in water quality. These are purely illustrative.

The only gaseous waste contributing to acid rain is SO_2 which has an equivalency value of 1 as it is the reference substance (see Section 2), all the other components have an equivalency value of 0. There are no equivalency values for solid wastes and their contribution to a decrease in water quality is related to the temporal and spatial impacts of solid wastes. In this case, for illustration, the metalliferous wastes and sulphur are assigned a value of 1. The ash wastes (which have been assumed to have no sulphur contained in them) are assigned a value of 0.2. The balance of the feed material to the process is assumed to be metalliferous and assigned an equivalency of 1. SO_2 also contributes to a decrease in water quality and is assigned a value of 0.1. These values are purely illustrative and no claim to their accuracy is asserted. In the case studies included in Section 5 and 6 of this thesis, these equivalency factors are informed by data from the PEMS® database. Comments on improving the accuracy of equivalency factors by incorporating information from EIAs are included in Section 7.

Equation 4-6 requires a vector $\underline{E}_i$ to be drawn up which contains the equivalency values linking component *i* to each impact category. There are thus three such vectors relating to the components in the waste stream and their potential impacts. With reference to Figure 4-3, impact 1 is acid rain and impact 2 is impact on water quality.

$$\underline{\underline{E}}_{SO2} = (1, 0.1)$$

$$\underline{\underline{E}}_{Zn} = (0, 1)$$

$$\underline{\underline{E}}_{Fe} = (0, 1)$$

$$\underline{\underline{E}}_{S} = (0, 1)$$

$$\underline{\underline{E}}_{Ash} = (0, 0.2)$$

$$\underline{\underline{E}}_{Balance} = (0, 1)$$

It is then possible to construct the equivalency matrix $\underline{\underline{E}}$:

$$\underline{\underline{E}} = \begin{bmatrix} 0 & 1 \\ 0 & 1 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0.2 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0.1 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}$$

It is now possible to evaluate $\underline{\underline{G}}_j$ which is the impact matrix associated with the wastes from each unit operation (Equation 4-10).

$$\underline{\underline{G}}_{Roast} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 49.6 & 5 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \qquad \underline{\underline{G}}_{Leach} = \begin{bmatrix} 0 & 2.3 \\ 0 & 0 \\ 0 & 8.7 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0.6 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 8.7 \end{bmatrix} \qquad \underline{\underline{G}}_{Electrowin} = \begin{bmatrix} 0 & 0 \\ 0 & 2.8 \\ 0 & 0.5 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0.5 \end{bmatrix}$$

It is now possible to evaluate the total impact matrix associated with wastes from the process, $\underline{\underline{UI}}$ (Equation 4-13) which has dimensions of unit operations by impact categories:

$$\underline{\underline{UI}} = \begin{bmatrix} 49.6 & 5 \\ 0 & 20.4 \\ 0 & 3.7 \end{bmatrix}$$

This can be further aggregated to the impact vector for the process $\underline{UI}$ (Equation 4-14):

$\underline{UI} = (49.6, 29.1)$

This vector indicates that the total contribution of the process to acid rain is 49.6 on some relative scale, and the contribution to water quality loss is 29.1 on another scale.

Examining these values in more detail, and assuming that the impact of concern is water quality, Figure 4-4 and Figure 4-5 have been drawn. The first shows the relative contribution of unit operations to water quality loss and the second shows the contribution of the components in the waste stream to a decrease in water quality.

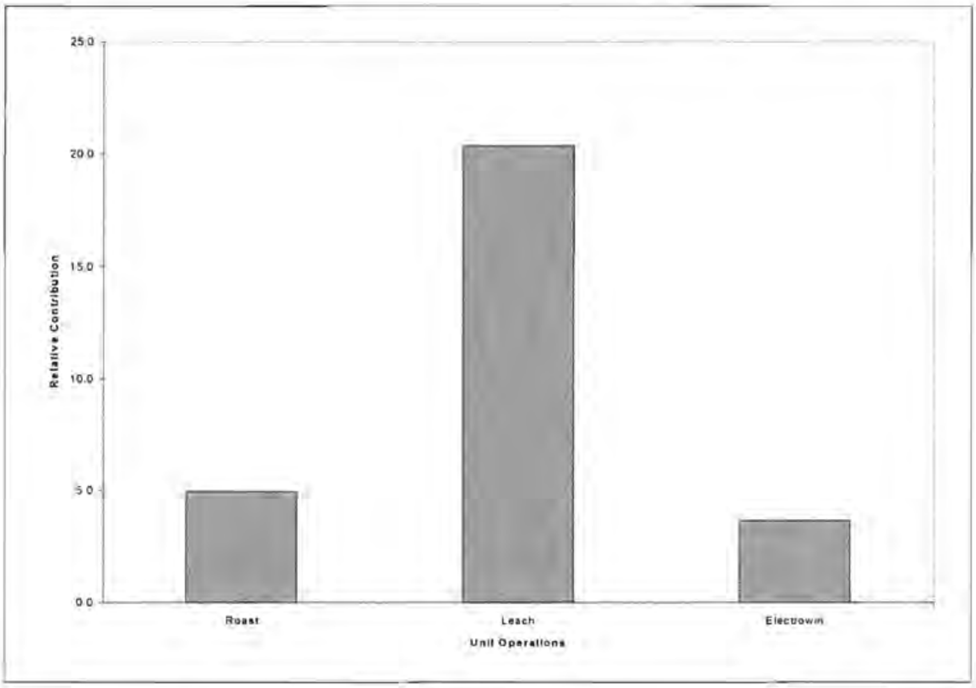


Figure 4-4 *Relative contributions of Unit Operations to Water Quality Loss*

These, and similar, figures can then be used to guide re-engineering and redesign. Figure 4-4 indicates which unit operations should be re-engineered in order to address water quality problems. Figure 4-5 can be used to support one of two actions:

- which reagents or other inputs to the process should be altered to meeting changing environmental demand
- where technology should be changed to meet requirements. A case in point here is the fact that the contribution of the SO_2 stream to water quality loss is greater that the contribution of Sulphur. While this is a function of the flow rates of each of these materials, it is also a

function of the potential impacts. This would suggest that it is better to change to a technology which reduces the amount of SO_2 generated and increases the amount of Sulphur from the process.

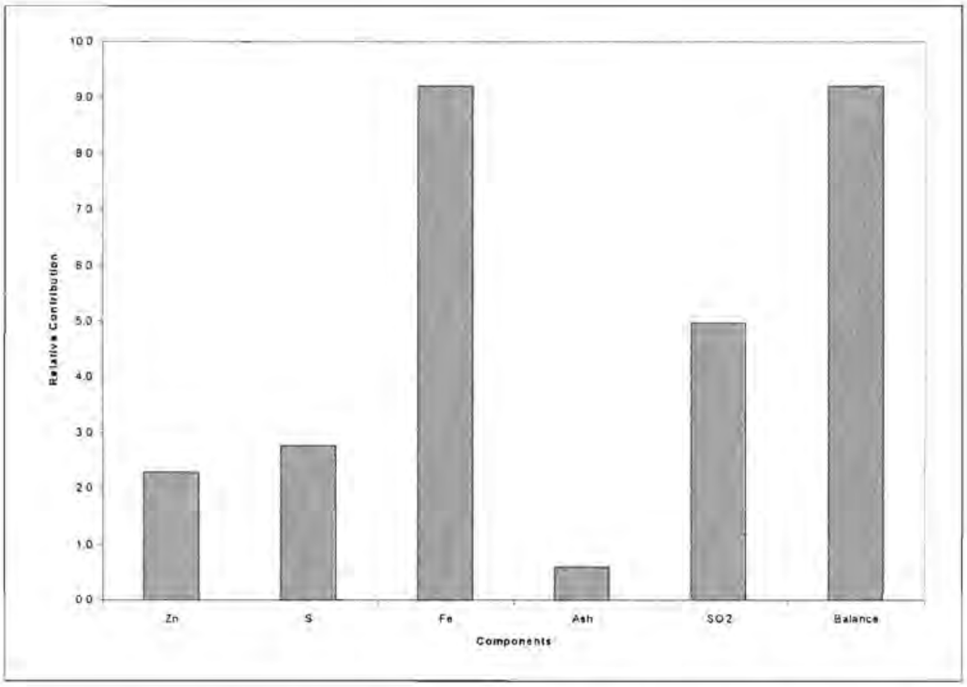


Figure 4-5 *Relative contributions of Components in the Waste Stream to Water Quality Loss*

Again it is stated that this example is purely illustrative. None of these conclusions will bear closer examination of the data and assumptions which support them.

4.3.1.6 Conclusions

The audit trail presented in Section 2 has been extended to give an indication of the impact associated with unit operations and components in the system. The information contained in the matrices established contain sufficient information to both support and direct re-engineering and re-design in the process. Thus the information structure can be used as a tool to assist in design. The information structure also has value during the life of the plant if it were implemented as part of an environmental management system (EMS). Collecting information for an EMS which contains information of the sort described in this section will support the implementation of strategies undertaken to improve the environmental performance of the process in place.

4.3.2 Optimising for both Environmental and Economic Performance

The objective function for optimising the performance of the process under scrutiny is constructed using the total impact vector, TI, Equation 4-27.

There are a number of objectives for the optimisation within the design hierarchy presented in Section 5. These objectives can be categorised into two groups:

- to achieve adequate economic performance
- to keep the potential environmental impact associated with the process as low as possible

4.3.2.1 Economic Objective Function

In order to formulate the first set of objectives within the context of the information sets developed, the economic objective is formulated using the cost "non-component" element that has been included in the matrices. An operating cost and a running cost are allocated to each unit operation. Both of these costs are evaluated as a function of the mass throughput for that unit operation. Included in the calculation for determining the value assigned to cost are considerations of (Perry *et al*, 1984):

- Interest rate payable on capital
- Time period over which the capital is repaid
- Depreciation of the assets
- Inflation
- Operating costs

There is thus a single cost value assigned to each unit operation in the flowsheet. Thus the total cost associated with the production of the process is known. The total mass of product is known and thus the profit from the process can be evaluated as income from sales less cost of production. Thus it is possible to formulate the economic objective from the matrices presented in this section.

The economic function is expressed as a total profit for the process over the life of the plant. This function includes all the considerations listed above. The form of the function is thus:

$$P = f_P(M, C, t)$$

Equation 4-28

where P is cumulative profit expressed in monetary units (P includes consideration of capital and operating costs as well as interest payable on monies borrowed)

M is the mass flow through the process expressed as weight per time period

C is the income generated by selling the product less the total cost of production expressed in monetary units

t is the time over which the process operates expressed in units of time

The form of the function is dependent on the flowsheet structure chosen. The objective of the optimisation is then to maximise P.

4.3.2.2 Environmental Objective Functions

In formulating the environmental objective functions, the assumption is made that the set of environmental goals are known. While this is a gross assumption it is made in order to demonstrate the hierarchy of design decisions included in this section. The validity of this assumption is discussed in the conclusions to the case study Section 5. A methodology for addressing the deficiencies inherent in this assumption is presented in Section 6 of this thesis.

Suffice it to say at this point that the environmental goals are known. If this is the case then preferences can be expressed as a series of weightings to be imposed on the impact categories included in the overall impact vector $\underline{TI}$. Interpreting values through a set of weights to be used in formulating the objective function requires detailed discussion. This interpretation of the values is also a function of the MCDA methodology being used. More discussion on this issue is included in the case studies in Section 5 and 6.

The values for the environmental categories included in Equation 4-27 are expressed as a quantity generated per unit time. These are in disparate units of measure, as well as disparate orders of magnitude. In order to obtain numbers which are meaningful for the optimisation it is necessary to normalise each category value. This is discussed in Section 4.3.2.3. The values reflect an actual amount of material leaving the process and entering the natural environment. Thus the smaller the impact category value, the better. The optimisation will then require that the weighted impact value be minimised. This is in contrast with the methodologies from Stewart (1992) where the aim was to maximise all values. Care needs to be taken in formulating the goals for the criteria and in determining whether the aim is to maximise or to minimise the objective function with respect to these goals.

The form of the weighted impact category function to be optimised is then:

$$I_k = wf_k \cdot f_{I_k}(M, e'_k, t) \qquad \textbf{Equation 4-29}$$

where I_k is the impact value for impact category *k* expressed in impact units

wf_k is the weighting factor for impact category *k*

e'_k is the overall equivalency factor for impact category *k* which is a function of the flowsheet structure, expressed in impact units per mass unit

The form of this function is informed by the flowsheet structure. The objective of the optimisation is then to minimise I_k for each impact category *k*. See Section 4.3.2.4 for the optimisation regime to be employed.

The sensitivity of the solution to changes in weighting factors should be explored to ascertain how robust the solution is. Marked sensitivity of the solution to the weighting placed on a single impact category would imply that the information used to calculate this impact should be verified in depth to ensure that the solution is as robust as possible. Sensitivity to changes in weighting would also imply what would happen should the current view of impact categories change. An example here is a change in the legislative limits governing a single impact category.

4.3.2.3 De-dimensionalising and Normalising the Objective Functions

The units of measure associated with each of the objective functions are not consistent. Equation 4-28 is expressed in monetary units while Equation 4-29 is expressed in impact units. In order to reduce these to values that can be included in a single function (which is the ultimate aim of the optimisation formulation), it is necessary to express all the functions in the same unit of measure. The easiest approach is to de-dimensionalise the functions. Another approach would be to transform them both to some other measure of significance such as the Unilever Overall Business Impact Assessment mentioned in Section 2.

A further consideration is that the orders of magnitude of the numbers are disparate. Acidification potential can be expressed in tens of thousands whereas a toxicity effect is measured in parts per million. It is thus necessary to normalise the values with respect to a consistent information set. One of the normalisation regimes commonly used in LCA is normalisation with respect to global emissions of that impact category (PEMS, 1998). Normalising all the values with respect to global totals reduces them all to the same basis. If the global total is formulated correctly the normalisation will also de-dimensionalise the values. It is thus possible to evaluate an environmental impact score associated with each impact category. The formula for calculating this impact score is included in Equation 4-30 below.

$$SI_k = \frac{I_k}{GI_k}$$ **Equation 4-30**

where SI_k is the impact score for impact category *k*

GI_k is the global contribution to impact category *k* for the time period under consideration expressed in impact units

In the same way it is necessary to de-dimensionalise and normalise the economic objective function, Equation 4-28. In order to maintain consistency, profit will be normalised with respect to the global value of the market in the primary commodity being produced by the process. Here the global value will be taken to be the monies generated by the total sales of that product globally for the time period under consideration. The normalised value of P will be called P'. This is not strictly consistent with the global emission values used in the normalisation of the impact objective functions as the value of sales is not the same as the profit made by the industry. However, evaluating the gross global profit for any industrial sub-sector is a major undertaking and is beyond the scope of this thesis. The sensitivity of the solutions obtained in the optimisation to this normalisation assumption will be explored for the case study.

Another approach to normalising the values which can be adopted in the context of the case studies presented in this thesis is to normalise both the environmental and the economic objectives relative to the performance of that sub-sector of the industry for an equivalent time period. This is possible as the inventories included in Appendices 2-3 to 2-8 are comprehensive inventories to the various industrial sub-sectors. This has the advantage of better consistency as the values used to normalise the environmental objectives, and the values used to normalise the economic objective have been evaluated relative to the same basis.

4.3.2.4 Optimising the Objective Functions

It is not strictly possible to evaluate the optimum for an equation set which contains multiple objectives. It is however possible to determine the solution which represents the optimal point for the sum of the objectives (be this a minimum or a maximum). This point is also called a *pareto optimal* or *efficient* solution for the equation set as discussed in 4.1.1.2. In this thesis it will also be referred to as the *best* solution. However, the solution will be the point of least trade-off between the **weighted** objectives and will thus change as these weights change.

Up to this point the objectives have been to maximise profit while minimising environmental impact. It is not a simple exercise to formulate this mathematically and thus the equation to be optimised is the one in which environmental impacts and cumulative losses are minimised. In this instance the normalised cumulative losses (L) are defined by:

$$L = -1 \times P' \qquad \textbf{Equation 4-31}$$

There is a perception problem associated with this form of the equation - including a minimisation of impacts in the same formula as a minimisation of losses would seem to imply that improved environmental performance will always cost a great deal of money. The only reason for expressing profits in terms of losses is to generate an equation that is mathematically meaningful.

The aim of the optimisation is then to manipulate the process variables which inform the functions f_P and f_{Ik} in order to minimise the impact ranking or score, IR:

$$IR = L + \sum_{i}^{w} SI_k \qquad \textbf{Equation 4-32}$$

It will thus be possible to manipulate the stream split variables in the assumption sets to facilitate the choice, either of discrete technology suites, or of a combination of technologies. For each of the technology suites selected the minimum impact ranking will be evaluated. This will be used to generate a *pareto optimal* surface.

Inherent in this equation is the acknowledgement that the decision maker is willing to accept a decrease in economic performance as long as there is an improvement in environmental performance from the process. This is not necessarily the case and will be reflected by the decision maker's choice of final solution. However, the trade off made in environmental performance for improved economic performance will be made explicit.

4.3.3 Decision support structures and aggregation levels

A decision support structure has been developed. This structure is used in formulating the environmental and economic objective functions detailed above. Figure 4-6 has been developed, together with Table 4-8, to demonstrate how the information structure presented in Section 2 of this thesis, as well as the elements of LCA, to demonstrate how the elements within the decision support structure are formulated. (Figure 4-6 is a re-working of Figure 4-2).

Together, Figure 4-6 and Table 4-8 show how LCA and the information structure are integrated to form a decision support structure. While this decision structure has been developed for environmental decisions taken during process design, the information structure was initially developed for analysis of processes and technologies. As such, the decision support structure can also form part of the analysis and improvement of existing processes. However, this activity is the intention of environmental management systems. Thus the decision support structure can be applied as a decision tool in environmental management as well as design for the environment.

The elements in the decision support structure are also an indication of information aggregation within the structure. These aggregation levels are illustrated on Figure 4-7. This figure gives an indication of the aggregation of information within each of the elements and details which elements of the LCA or information structures inform this aggregation.

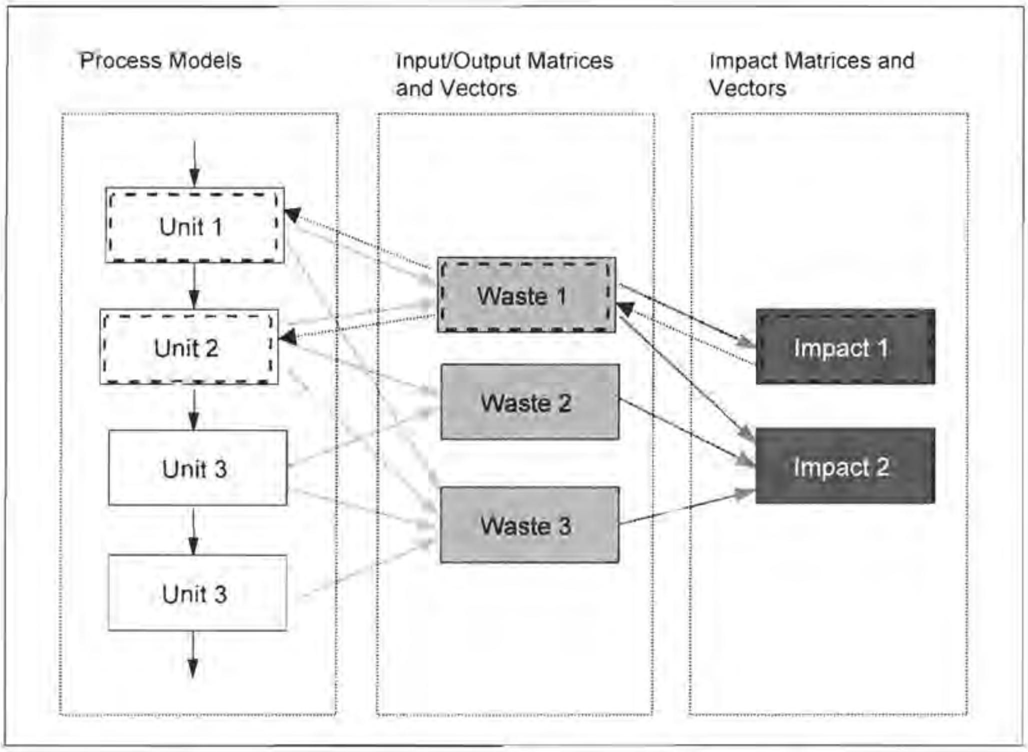


Figure 4-6 *Elements in the Decision Support Structure*

Table 4-8 *Elements from the Design Decision Support Structure, LCA and the Information Structure*

Decision Support Structure Elements	**LCA elements**	**Information Structure Elements**
Boundary around entire Structure	**First** stage of LCA - Boundary Definition	
Process Models		Assumptions governing **unit operation boundaries** used to establish flowsheets
Input-Output Matrices and Vectors	**Second** Stage of LCA - Inventory Analysis	Unit operation **assumption sets** and **stream splits** used to develop mass and energy balances
Impact Matrices and Vectors	**Third** stage of LCA - Impact assessment forms the link from wastes to impacts	These are calculated using the **augmented audit trail** developed.
Valuation of Impacts and **Improvement**	**Fourth** stage of LCA - Improvement analysis allows these vectors and matrices to be valued relative to one another; **audit trail** assists in guiding re-engineering and re-design to affect improvements	Valuation of the matrices and synthesis of optimal performance with respect to environmental and economic performance informed by **MCDA**; **assumption sets** and **stream splits** manipulated to minimise trade-off between environment and economics

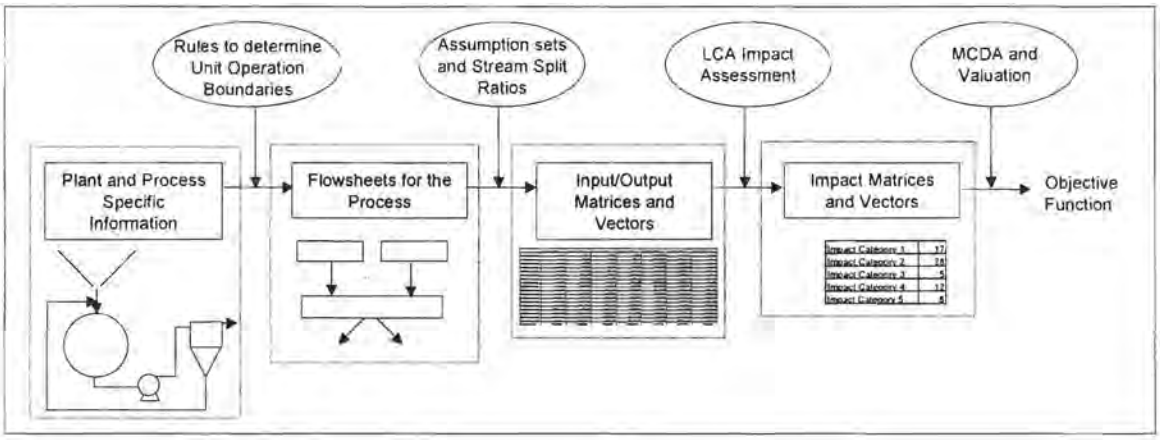


Figure 4-7 *Aggregation in the Decision Support Structure*

The approach to aggregation at all levels is structured and transparent. The amount of information detail required at each level is dependant on the decision supported by the structure. In the case of process design, the information available during the initial stages of design is limited and thus aggregation, particularly between the plant specific and flowsheet information sets, is not significant. As the plant specific information sets increase in detail the aggregation of the information becomes more marked.

4.3.4 Non-linearities and Uncertainties within the Equation Set

There are a number of sources of non-linearity within the information structure developed. The non-linearities will effect the potential use of existing optimisation routines in solving the equation set. Uncertainties are also present in the information structure. While it is not possible to rid the models of all uncertainty, it is possible to test the sensitivity of solutions to these uncertainties.

Non-linearities and uncertainties within the decision support structure illustrated on Figure 4-6 can arise either in LCA or in the information structure.

4.3.4.1 Non-linearities

While most of the equations used in developing the mathematical models, as well as those used in linking wastes to impacts, are linear, there are non-linearities inherent in the objective functions f_P and f_{Ik} defined above. The main sources of these are:

- Non-linear behavior of unit operations within the flowsheet.
- Recycles between unit operations in the flowsheet. One of the "rules" for establishing unit operation boundaries was to draw them around recycle loops. However, if this results in a loss of information as would be the case in the zinc purification process as illustrated in Figure 2-8 in Section 2, it is necessary to include recycles between unit operations. Figure 4-3 demonstrates that it is possible to chose unit operation boundaries within the zinc purification process that eliminates the need to include recycles. The level of aggregation in the mass balance for Figure 4-3 is high, thus this flowsheet can support different decisions than can be supported by the flowsheet in Figure 2-8.
- The stream split ratios in the process models
- Non-linear value functions could be applied to the objective functions if value functions are the MCDA methodology of choice. The formulation of goal programming is linear and thus the objective functions are linear. It is possible to introduce non-linearities into goal programming, however, it can be shown that these are essentially a sub-set of non-linear value functions (Meittinen, 1999).

4.3.4.2 Uncertainties

As has already been stated, there will always be uncertainties inherent in any modelled system. The main sources of uncertainty in the decision structure are:

- Inaccuracies in the assumption sets and stream splits. The case study specific appendices (Appendix 2-3 to 2-9) include an indication of the confidence placed in the information sets
- The linking of wastes to impacts in the third stage of LCA is achieved using equivalency factors as discussed in Section 2 of this thesis. There is continuing debate about the value of these equivalency factors
- There are uncertainties inherent in establishing a value function or a set of goals to be used should MCDA be used to inform the fourth stage of LCA. Most of these arise from the fact that these values are based on subjective points of view and from disparate groups in society

- The "rules" for establishing unit operation boundaries within the flowsheets could introduce uncertainties in the ability of the audit trail to direct attention back into the process if these unit operation boundaries cause the information to be aggregated to too high a degree. An example here, and with reference to Figure 2-9 and Figure 2-10 in Section 2 where a number of unit processes have been aggregated into a single unit operation called Solution Purification. The reason for this aggregation was a lack of information on the operation of each unit process. The individual unit processes each have the potential to change the wastes leaving the process as they are inside a recycle loop. In order to determine the effect of each of the unit processes on the impact associated with the unit process it will be necessary to dis-aggregate this unit operation. This is discussed further in Section 7 of this thesis where the allocation of wastes to unit processes is discussed.
- Quantifying the impact associated with a single waste is extremely complex as was discussed in Section 2.2. A waste stream which contains a significant number of components increases this complexity significantly. There are significant uncertainties associated with the assessment of impacts associated with these wastes.

It must be recognised that these uncertainties will be aggregated as the information is aggregated. Thus uncertainty will be translated through the decision support structure. It is possible to test the sensitivity of the solution to potential information uncertainties. This is achieved by conducting sensitivity analyses. It will only be possible to conduct these uncertainty analyses if the uncertainties associated with each information set is documented as the information structure is developed. The interpretation of the translation of uncertainty, and its associated risk, through the decision structure is a study that is beyond the scope of this thesis. This is highlighted as a significant study which is underway currently (Basson, 1999).

4.3.5 A structured approach to information management

The discussion included in this section has developed a particular structure for information in order to facilitate the optimisation of the process with respect to economic and environmental performance. This structure is illustrated in Figure 4-8 below. This is a uniform structure that has the potential to inform environmental decisions taken for any process, though this has still to be proven.

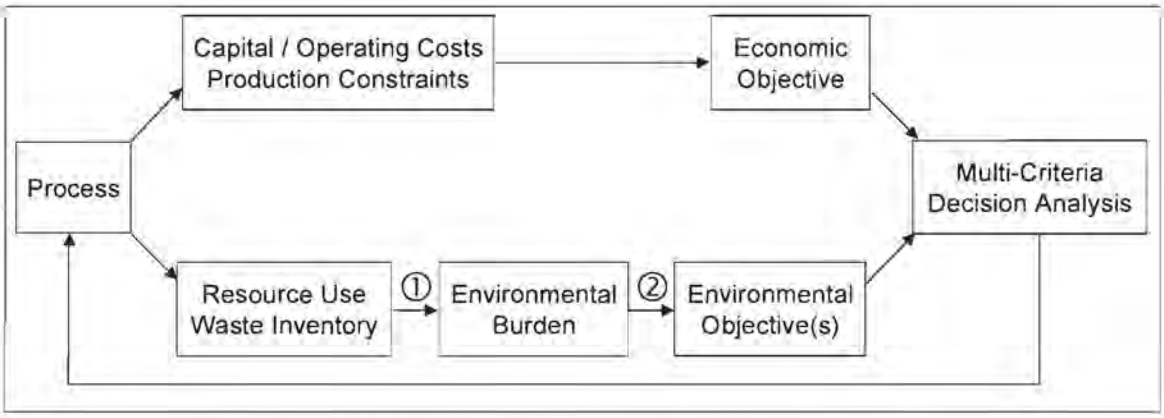


Figure 4-8 *Information flow within the Decision Support tool*

In this figure the link 1 is informed by the impact assessment stage of LCA. Link 2 is subjective and represents the valuation stage of LCA, which can be subsumed into the MCDA tool used. The feed back into the process is informed by the audit trail structure presented in this section.

5 Design for the Environment in Minerals Processing

This section of the thesis develops further the knowledge-based approach to process design known as the Douglas Hierarchy (1988). This hierarchy has been extended to include design decisions specific to the minerals industry, and further to include explicit account of environmental considerations. Process synthesis and optimisation approaches are described as required for each step of the hierarchy. The approach to process synthesis relies on the flowsheet development presented in Section 2 of this thesis. The optimisation approaches use a multi-critieria approach in order to avoid the *en masse* aggregation of impact categories. A worked case study, to determine the best technology to use for a mix of small and large-scale processes in the gold industry, is included to illustrate the extended design hierarchy. Technology choice has been optimised relative to a known set of values for each decision criterion. The integration of MCDA methodologies into the design hierarchy as outlined in Section 4 of this thesis is discussed in Section 6.

5.1 Characteristics of Design in Minerals Processing

The main issues specific to minerals processing design are identified as:

- The feed stream is extremely dilute and thermodynamically stable; thus significant energy inputs are required to achieve a pure product
- Waste streams are diverse in character
- The impacts associated with the process can be felt for extensive time periods (into the realms of geological time) after the project has been completed
- Impacts are affected by the location of the project as well as waste management regimes in place
- There are usually a number of co-products

A specific feature of design in minerals processing is that the process developed is often a combination of "off the shelf" technologies. Each technology is specified by the vendor of that particular technology and the final process is built up of these different blocks. This combination of technologies, designed in isolation, may lead to inconsistency in process performance and a mis-matching of unit processes.

Discussions in Section 3 of this thesis highlighted how sensitive the environmental performance of a process is to decisions made during the design stage. In Section 2 LCA was offered as a tool for evaluating the environmental impact of processes in a systematic manner. A link between technology selection and environmental impact was established in Section 2. This current section details how to include "environmental" decisions in a design hierarchy for minerals processes. It must be recognised that a design hierarchy offers a structured approach to the management of information generated as part of the design process. Initially, the process is seen as a "black box", where very little information is known. As steps are taken through the hierarchy, this information becomes better defined and more detailed, until the point is reached at which there is sufficient confidence in the data set to support the decision to proceed with the project.

With reference to Figure 3-5 included in Section 3 of this thesis, this figure demonstrates that there are three data sets that are used to inform decision making within the extended design mapping determined by LCA. The intersection of these data sets represents the suite of technologies that can be defined as "clean technologies". The aim of the process design methodology described in this section is to ensure that all decisions taken move the technology chosen from an arbitrary point X towards a sustainable solution within the intersection of the three sets. It must be accepted that there are a number of paths that this trajectory could follow. One of the intentions of the extended design hierarchy is to manage information efficiently; at the same time sufficient information must be available to support decisions at each step in the hierarchy. This is only possible if all three information sets are included in the decision making process from the start of design.

Historically process engineers have started from "X", defined as a point within the techno-centric data set. It is necessary to gain input from the other spheres before a final decision can be made. The question is "how can this be achieved?" As a starting point, it is argued below that the Douglas Design Hierarchy (Douglas, 1988) can be extended to provide information in a format, and at a time, which is accessible for decisions in the design process. The revised form of this hierarchical approach is demonstrated specifically for minerals processing, ensuring that the information set developed during design is not deficient in information relating to the environmental impact of the process being considered. This extended hierarchy is included in Table 5-1.

Table 5-1 *Extended Design Hierarchy*

Level	Douglas Design	Minerals Processing Design	Environmental Design
A			Background Information
B			Project Selection - comparison either of possible raw materials, or possible products
0	Input Information		
C		Establishment of Reactor-Separator train	
1	Batch vs Continuous		
2	Input-Output		LCA of raw materials; LCA of different waste streams from different trains; impact of changing quality of inputs; impacts of process efficiency
3	Recycle Structure		Differences in impacts for concentrated and dilute wastes; identification of waste management philosophies and technologies
4	Separation Systems (liquid/vapour)	Separation Systems (solid/liquid/gas)	Finalisation of Reactor-Separator couples and combinations; detailed design of separation systems
5	Heat Exchanger Network		Energy minimisation and Utilities Management

The Douglas design hierarchy is a conceptual approach to process design. The final output of the extended hierarchy described in Table 5-1 is the preferred flowsheet for the process being designed. Detailed equipment specification and design are not addressed in this hierarchy.

The intention here is to extend the Douglas Hierarchy to include these additional considerations, not to deliver a hierarchy specific to the minerals industry. For this reasons, steps that may seem superfluous in design for minerals process have not been removed from the hierarchy but rather retained to deliver a hierarchy which is applicable is a number of diverse process design situations.

It must also be recognised that, while the focus of this design hierarchy is achieving the smallest acceptable trade-off between environmental and economic performance, there are other criteria that need to be met by the process. These other criteria include (Biegler, 1997)

- Safety
- Flexibility where necessary
- Controllability

5.1.1 Level A - Background Information

This information is the set of data required to support the decisions to be taken in the Project Selection stage. It incorporates "broad brush" environmental information such as that contained in existing commercial LCA data-bases as well as that specified by legislative frameworks. Although LCA data-bases have been developed within a particular context (such as assessing the environmental impact of various types of packing material in Europe) they give a valuable starting point for a more detailed LCA to be carried out in later stages of the hierarchy. They contain sufficient information to enable comparisons in performance of different technology options to be made. This is the initial information contained in the enviro-centric information set.

In addition, some information about social arguments is required at this stage. The failure of many large-scale development projects in the past can often be traced to their inability and/or reluctance to engage with wider community interests early enough in the project planning phase. In this formative stage of design, where there is still much uncertainty over technology selection, it is still required that there be sufficient information available to give an indication of trade-offs which would ensue from a particular design choice. It is not necessary to complete a sophisticated social scoping exercise. Rather, the information elicited should be in line with the information used to evaluate the market for the proposed project. These categories of information will be refined in accuracy as decisions are made in line with the evolving design hierarchy. This is the initial socio-centric information set.

Process-specific information will be required on all process alternatives. This should be at the level of process efficiency, feed quality requirements, and waste generation. The services required (energy and water) should also be included. The accuracy of this information should be at the scale of a 'pre-design' feasibility study – which often amounts to little better than an order of magnitude evaluation. This is the starting point for the techno-centric information set, an example of the level of information that such a data set would contain can be found in the case study included in Section 5.2 and detailed in Appendix 5-1.

5.1.2 Level B - Project Selection

With reference to the project life cycle described in Section 3 of this thesis, and specifically to Figure 3-2, this decision is taken at the project selection stage of the project life cycle. It may be necessary to conduct a strategic environmental assessment. The scope of the LCA is decided at this stage.

There are two different classes of analysis that can be conducted here; these relate to the position of the proposed project in the material chain. To explain this further Figure 5-1 has been included. This figure describes a simplified material chain for aluminium. Clean product design is the design of products which have the smallest possible impact over their life cycle, are economically viable, and deliver the service required by the consumer (Jackson, 1996). This is possible in the context of design of a product or service required by society, such as the manufacture of aluminium cans. However, when design for environment is considered in the context of minerals processing where the product is not in a finished state that is available to society, but rather in an intermediate stage such as aluminium bars, it is extremely complex to include considerations of product use and disposal. The main reason for this complexity is the wide range of potential products that can be manufactured from the intermediate products. This discussion continues the argument offered in Section 2 of this thesis for drawing the boundary of the system to be a cradle-to-gate boundary.

The different focuses of product and process design (cradle-to-gate) design for the environment are illustrated in Figure 5-2. The focus of product design for the environment is on the manufacture and use of the product, processes upstream of this manufacture are aggregated. As a result there is little assistance for process re-engineering and design. Process design for the environment on the other hand requires that information detail be retained on a process level where processes are sub-divided into specific unit operations. These are two significantly different approaches.

Decisions at this level of the hierarchy (Level B) will serve to define the information sets on a macro-scale. Economic information made available at this level will be along the lines of market demand and potential selling price for the product. Environmental information will be at the level of a first order LCA for the various potential products or processes using existing databases. Social information will also be extremely aggregated.

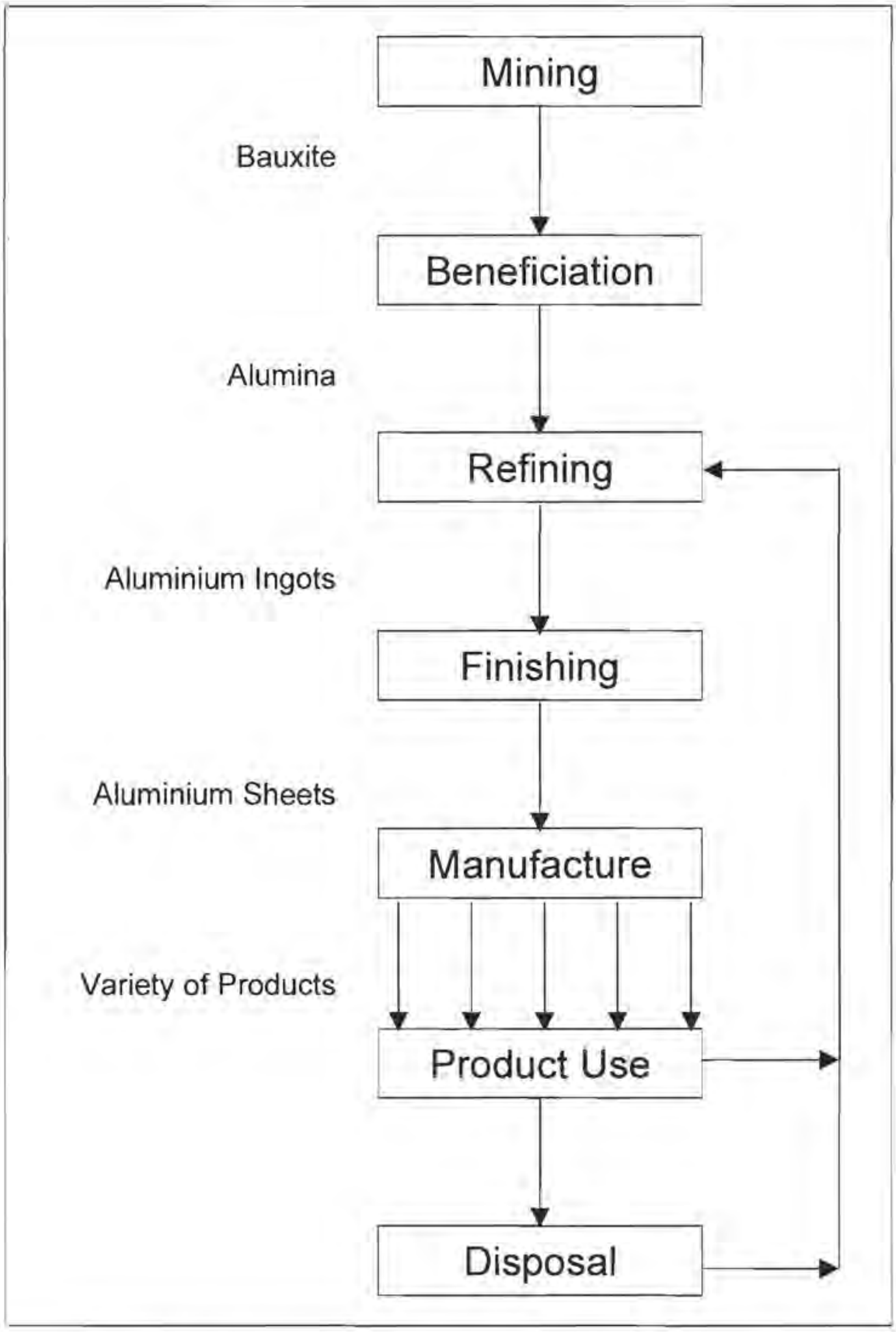


Figure 5-1 *Simplified Aluminium Material Chain*

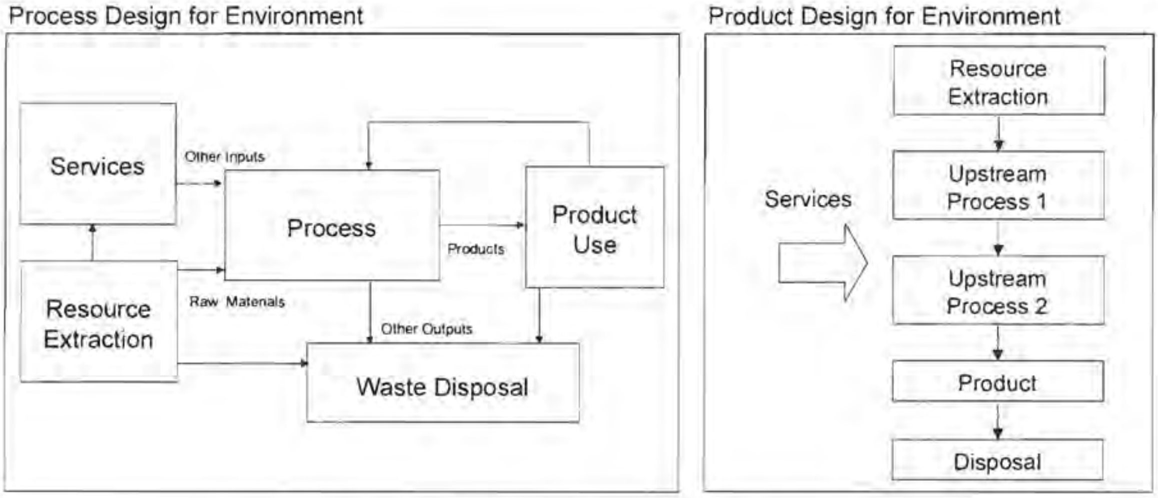


Figure 5-2 *Product and Process Design for the Environment*

The likely strategic decision to be made at this stage is whether this is the "best" use for the raw material under consideration. Calling a technology option "best" or "preferred" means that option comes closest to meeting the objectives articulated by the decision maker. Two illustrative case studies are offered here:

- The use of a natural gas field off the coast of Mozambique, together with ferrous concentrates (produced in part from one of the discard streams from a minerals processing plant in South Africa) in a proposed iron ore smelter on the Mozambique coast is being considered. The two main raw materials being supplied to this process are the natural gas and the ferrous concentrate. There are two main considerations. Is this the best use for the natural gas, or could it be used better to serve the needs of society? For example it could be used for domestic power supply. The other consideration is the fact that a "waste" material is being processed further, thus making more efficient use of a non-renewable resource.
- The proposed zinc refinery to be built on the east coast of South Africa will be drawing cheap electricity as its main South African-sourced raw material. In this case the price of electricity will be linked to the selling price of zinc on the London Metal exchange. As electricity is the largest operating cost for the process (it is used in an electro-winning plant to recover zinc from an acid leachate), fixing the cost of electricity relative to the selling price of the product will, to some extent, fix the profits for the proposed project. This in no way addresses the cost to society of the environmental management at the power stations producing this electricity. All the other major raw materials for the process will be imported. The other potential "raw material" which could be supplied by South Africa is a labour force. However, the proposed

plant is virtually fully automated and requires a small work force. The question to be asked here again, is whether this is the best use for the raw materials?

There are two concepts common to both of these examples - the first is that energy, and the effective use of that energy for the betterment of society, is a common concern. The second is the point of view that the natural resources of a country are potential credits in the national accounts. While it must be recognised that these materials have no intrinsic value when they are still in situ in the ground (Petrie and Raimondo, 1997), when they are mined and exported they represent a loss to the nation as a whole. Decision makers are honour bound to ensure that these raw materials are used in such a manner as to move the country towards a more sustainable use of its raw materials.

With reference to Table 1-14, the decision taken at this stage is a strategic decision.

5.1.3 Level 0 - Input Information

In the original design hierarchy, this input information had to be sufficient to allow an order of magnitude calculation of process performance, i.e., reaction rate, reaction extent, feed quality and major service and reagent requirements. These are required still, and should contain more detail than that used in the strategic investigation. The data set is augmented by the social and environmental information garnered during level A.

With respect to the information structure presented in Section 2 of this thesis, there should be sufficient information to ensure mass balance closure over the potential unit operations in the flowsheet developed in the next level of the hierarchy. Section 2 contains details of this information required.

5.1.4 Level 1 - Batch versus Continuous

This decision is along the same lines as for the Douglas Hierarchy. Decisions are guided by considerations of scale, operability and potential markets. The minerals processing industry in South Africa, has concentrated typically on processes with a significant throughput. Processes, consequently, have tended to be continuous. Though the environmental impact of continuous processes is often touted as being less than equivalent batch ones (due to issues of controllability, continuous process operate at almost constant conditions for great lengths of time, (Douglas, 1988)), it should be remembered that waste management is often a semi-batch process, to accommodate, amongst others, the attendant risks of process-upset conditions. The integration of batch and continuous operations requires particular attention at this stage of the hierarchical approach to design. This is particularly relevant to minerals processing, e.g., the combination of a continuous concentration process with a batch refining process. A case in point is the roast-leach-electrowin circuit commonly used to refine zinc. In this case the anodes from the electrowinning cells are removed in batches and then processed through a batch smelter.

5.1.5 Level C – Reactor-Separator Chain

There is a fundamental difference between the chemical and minerals processing industries. Feedstocks to the former are usually of a far higher purity. This suggests that minerals processes have a greater requirement for intermediate purification before achieving a final product of desired quality. There are two inter-related considerations at this level of decision. The first is that there is, potentially, an "optimal" entropy for waste streams – there is a trade-off between concentration effects and "potential to pollute". To produce a waste of desired "quality" often requires significant energy and chemical input, whose own "environmental footprint" exceeds that of the waste stream's own pollution potential. This is coupled to the second issue to be considered at this level – that of the optimum degree of recovery of co-products present as feed impurities.

This concept is developed further by way of a couple of examples. The first examines the trend to increased milling of materials in the initial concentration of base metals, while the second takes a closer look at international waste management policies.

The current trend in the initial concentration stage of the base metals industry is to mill the ore to relatively small particle sizes. This increases the recovery of the product minerals and improves the grade (concentration) of the product metal-in-concentrate. However, the milling process is extremely inefficient, a significant proportion of the energy that it draws is expended in turning the load in the mill, with only a small percentage of the energy actually being used in breaking the rock. The temptation is to design a more efficient mill. However, broadening the scope of the study means that it is possible to ask a different question, i.e., is it not more environmentally efficient to invest less energy in the milling stage while achieving the same recovery (to ensure that the non-renewable resource is utilised as efficiently as possible) but with a lower grade of product? It will then be necessary to increase the energy used in the purification process, but this is a more energy-efficient technology. This would require a paradigm shift in the industry as a whole if it were to be applied across the board. There are two issues that need to be examined here. The first is ensuring that the impact associated with energy provision is included in the decision making process in order to determine whether it is better to invest energy in milling or in smelting. In addition, acid mine drainage is recognised as a significant impact of the minerals industry (Marshman *et al*, 1998). Milling material to smaller particle sizes increases the surface area available for leaching in the waste material. Increasing the potential for leachate generation will increase the potential environmental impact associated with the process, often linked to acid mine drainage.

The second case evaluates trends in waste management policy in the context of minimising the potential environmental impact associated with a proposed project. There are two international trends in solid waste management policy at present. The first is to define the potential impact associated with metals-bearing waste according to the potential bio-availability and toxicity of the metals (Glazebrook, 1998). This impact will be a function of the concentration of the metal in the waste as well as the "entropy" associated with the form of the metal. More stable metals (or metals with a lower entropy) are less likely to become bio-available. Less concentrated metals are less likely to disperse into a pollution plume. Thus it is preferable to decrease the concentration of the metals in the waste stream and attempt to stabilise them. Using a Waelz kiln to treat wastes from an electrowinning process is an example of a technology that would be supported by this approach. The Waelz kiln both dilutes the waste stream (by adding significant quantities of flux to the kiln) and stabilises the metals (by changing their chemical form). In order to achieve this the Waelz kiln draws a significant amount of energy.

However, there is another trend in waste management at present, and that is to view the solid waste deposits not as waste dumps but rather as potential repositories which will be mined in the future. If the material is to be mined then it is preferable to keep the metals as concentrated as possible and to ensure that the entropy of the material does not decrease too much. Each "unit" of entropy decrease in the waste will require a "unit" of input energy if the material is to be concentrated. This would suggest that it is preferable to keep the metals as concentrated and as "available" as possible which is contrary to the position taken above. Far more energy would be required to recover the metals from the stablised Waelz kiln product than from the waste material which the Waelz kiln processes.

This would suggest that there is be some optimal entropy state for the waste stream, one that balances the potential for impact associated with the waste material while it is stored with the energy required to concentrate the material should the waste be processed further.

This analysis can become very intricate, and the assessment of potential environmental impact for waste streams could benefit from an industrial metabolism approach to analyse technology choice. In this way, opportunities to explore product and process interdependencies, beyond a simple production envelope, are included. Again this is a significant study in its own right. The philosophies explained above can be included in the decisions taken during design using the proposed hierarchy, but as yet no rigorous tool to support these analyses is available.

The above discussion has focussed on the integration of processes for the production "chain" of a metal from initial concentration to final purification. This is consistent with an industrial metabolism analysis approach. [The information structure developed in Section 2 of this thesis can be used to support the analysis of these "chains". The base metals case study (Appendix 2-6) is an example of an Industrial Metabolism approach.]

Similar arguments can be offered for a single unit process within the material chain. To illustrate this point the minerals processing section of the material of platinum has been included in Figure 5-3 below. This shows that there are three unit processes - initial concentration, removal of base metal co-products and final purification of the noble metals.

It is possible to examine the process units more closely. To this end Figure 5-4 has been included. Figure 5-4 shows a single base metals "reactor" coupled with three different separators which represent different potential flow routes for the removal of base metals. This figure illustrates three distinctly different reactor-separator chains within a single industry (not a common feature in design of chemical processes). The specific consideration here should be that of energy and water requirements, as well as potential reagent addition. The products from each of these separators are significantly different as are the wastes. Closer investigation of the interplay

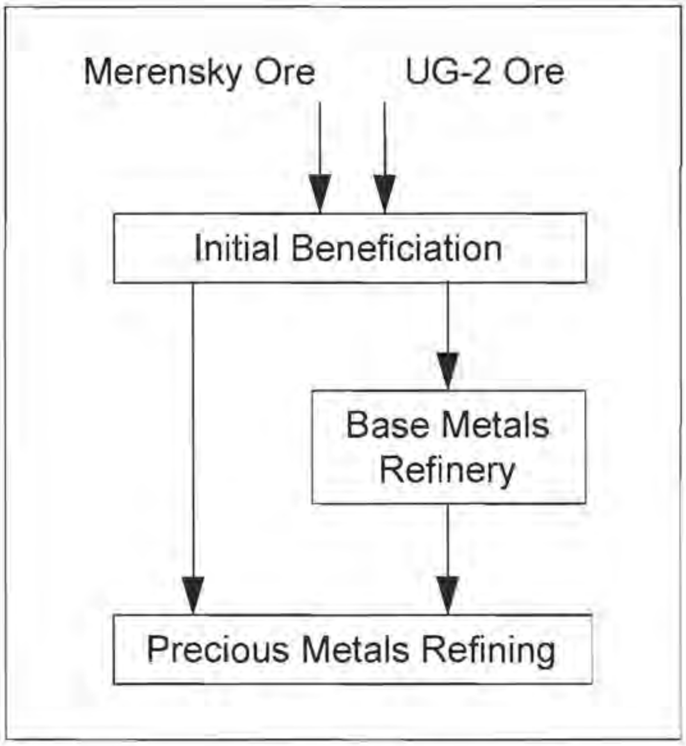


Figure 5-3 *Overall flowsheet for the Platinum Industry*

between potential environmental impact and economic performance is required to determine which of these reactor-separator couples is optimal.

There is a further issue which should not be disregarded at this point - that of "carry-through" contaminants. In minerals processing, sulphur is a notable contaminant in feed material. This element gives rise to significant environmental impacts of the form:

- Acid mine drainage in coal, gold and other sulphidic ore mining
- Acid rain generation potential from all smelters using coal as a reductant
- Sulphate /sulphur wastes from base metals processing.

There are a number of points at which sulphur can be removed from these processes (before, during, or after processing). For example, the roast-leach-electrowin process for base metals purification emits sulphur as SO_2 from the roaster while the pressure leach-electrowin process produces a solid sulphur residue from the pressure leach autoclave. This is but one example where an energy/entropy analysis, coupled with an impact assessment which reflects considerations of time-dependency. This is discussed further in Section 7 of this thesis.

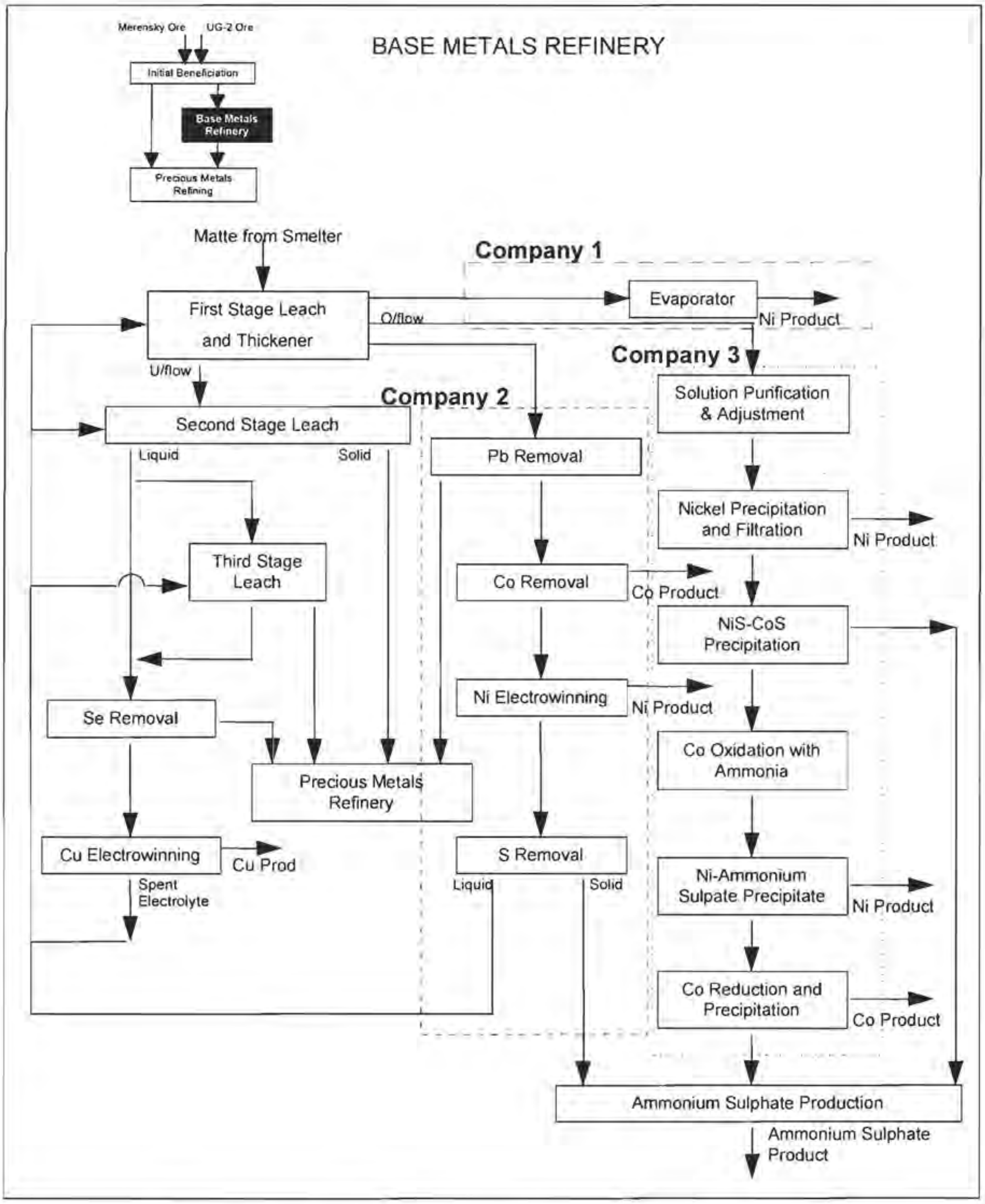


Figure 5-4 *Flowsheet for the Base Metals Refinery in the Platinum Industry*

With reference to Table 1-14 decisions from this point forward in the hierarchy can be described as tactical.

5.1.6 Level 2 - Input-Output Structure

The main aspect of this decision is to determine what the possible combinations for the reactors and separators identified in the previous step. All possible combinations of reactor-separator should be established and then analysed with respect to their potential environmental and economic performance. Some combinations of reactors and separators will not be possible.

Decisions at this level, for the first time, give detailed consideration to those streams - other than feeds and products - that cross the process boundary. It is at this point in design evaluation that the specific environmental impacts associated with technologies chosen should be evaluated in greater depth. This step determines the nature of the non-saleable streams, and determining regional and local impacts within the available data set becomes a proposition. Thus a more detailed LCA should be conducted using more detailed information in determining the environmental impact of the process (step 3 of the LCA); i.e., impact evaluation should become region specific. This exercise requires input from other environmental management tools and approaches (such as the EIA process) that can use comprehensive modelling techniques to evaluate the impact associated with different wastes from the proposed process. This is not an attempt to undersell the difficulties – merely that LCA offers a template within which other information can be interwoven. Tools such as ecological risk assessment have value here – contributing to a time dependent, site specific assessment. It will not be possible to determine the precise impact associated with the project because the information available will still be aggregated and not particularly well defined. For example, it is unlikely that the particle size distribution required for accurate air quality modelling will be available. It will, however, be possible to make a first order estimation of the potential regional and global impact of the process. This will be called the preliminary impact assessment process. Within the context of current South African environmental legislation, this could form the first round EIA called for in the Act (DEAT, 1998). In this first round impact assessment the project proposer is required to demonstrate whether the project has the potential to cause environmental impact in which case the proposer is then required to undertake a comprehensive EIA.

At this stage, determining the potential local impact associated with the proposed technology suites will not necessarily be possible. In order to determine local impacts a fairly accurate understanding of the local conditions will be required. The potential sites at which the project may be located may not have been identified at this stage of the design hierarchy.

It is also at this stage of the design exercise that a more comprehensive social scoping should exercise be conducted (beyond the market survey conducted originally). This should form the beginning of an integrated environmental impact assessment process, within which LCA forms the core of the assessment (Petrie and Raimondo, 1997). It serves the purpose of both educating the public in the project under consideration, as well as building public trust in the project and the manner in which the process is being designed.

The public scoping and preliminary EIA can be used together to inform the design process. Using the audit trail structure developed in Section 4 of this thesis, it will be possible to determine which unit operations give rise to the impacts which are of greatest concern to the constituency involved in the social scoping exercise. This serves the twofold purpose of forewarning the project proposer of potential impediments to the progress of the project, as well as guiding the design team towards a choice of technology that is most likely to meet the requirements of society.

5.1.7 Level 3 - Recycle Structure

Recycle structures have a number of implications for consideration of environmental impact. First there are the concentration effects detailed in Level C. The recycle ratio will determine the concentration of impurities in any purge stream. It may be less environmentally damaging to have a lower recycle ratio and thus lower concentration of impurities in the exit streams. In minerals processing, where the major "carrier" in the process is water this will imply that more water will be used by the process.

However, in minerals processes, the recycling of water merits special consideration. This is often linked to a preferred design option of "zero liquid effluent" which would prompt the designer to minimise the water used by the process. It would be better to fully integrate the water recycle into the recycle structure. Current approaches to design tend to view the effluent treatment plant, which is used to remove impurities from the water system before recycling the water back into the process, as a "catch all" for effluents from the process. As was stated in Section 4, minerals processing projects are often a combination of technologies specified by different vendors. In this situation the effluent treatment process is often designed last, as an add-on unit, to deal with all the waste water streams from all of the unit operations. The treatment plant is then designed to treat the total combination of water streams. In this case the effluent treatment plant is a sequence of technologies placed in series.

A different solution to the treatment of water streams would be reached if each stream were considered with respect to its utility where this utility might be defined in terms of an acceptable stream quality. This is a potential use for the pinch technology approach to water management presented in Section 3 of this thesis. Information detail on all water streams should be retained as opposed to aggregating this information together in order to establish the best possible integration of the water circuit. The size of technologies within the treatment process should be tailored to the streams that require treatment, as opposed to having to handling the entire water stream from the plant. A further advantage is that the streams being treated would be more concentrated, having not been diluted by all the other streams in the process, and thus potential treatment technologies would be different, and potentially more effective.

There is the potential that the solution to water treatment within the process will be a number of unit technologies integrated into the operation of the process. This is in contrast to the current *status quo* where the effluent treatment plant is treated as a unit process in its own right and all effluent treatment technologies are clustered together. This would have the additional advantage of removing the perception that meeting environmental requirements and regulations is an add-on cost to the process. The cost of running the effluent treatment plant is often cited as the cost of meeting environmental limits - this is the approach used in a number of the process synthesis techniques presented in Section 3 of this thesis. If effluent treatment were integrated into the process meeting environmental requirements would be seen as integral to the operation of the process as opposed to something that is tacked on at the end.

From the discussion included above it becomes apparent that the enviro-centric information set must be increased to include the waste management philosophies and technologies to be used in the process. Thus at this point in the extended design hierarchy the decision to be taken is also to determine which waste management technologies to include in the flowsheet design.

5.1.8 Level 4 - Separation Systems

It is at this point that the selection and ordering of technologies are finalised. Input will have been received from the various stakeholder groups affected by design decision outcomes. This informs the final outcome. Figure 5-4 demonstrated, by way of example, that there are a number of combinations of reactor-separator sub-systems that deliver saleable products. Uniqueness is not a selection criterion at this stage. The preferred design option requires a comprehensive LCA to be undertaken of all remaining technology options. There is the potential to use the rigorous modelling tools which inform the EIA process to inform the EIA. Still further, it is possible to integrate the EIA process with the design process. This is discussed in depth in Section 6 of this thesis. The impact assessment stage will be tailored to the potential locations for the project. Thus it will be possible to include site specific considerations, as well as the regional and global considerations which were included as of level 2, into the design.

5.1.9 Level 5 - Energy Minimisation and Utilities Management

This constitutes the final optimisation step of the design process. Energy considerations have been accounted for previously, and the most energy efficient process (on a macro-scale) should have been selected. The focus here should be on the internal integration of energy sources and sinks, in a conventional heat exchange network analysis. It is fair to say that minerals processing is a relatively untapped application area for this maturing technology.

The management of utilities relates most specifically to the management of water within the process. While placing water management this far down in the hierarchy may seem to be an undervaluing of this scarce resource, it is only at this stage that the quality and quantity of the streams is known as these are determined by the separator efficiencies. Thus it is only possible to optimise water management at this point. Different effluent treatment plant permutations as well as different water recycle structures should be considered at this point.

5.1.10 Conclusions

The intention of the design decision hierarchy presented here is to ensure that the relevant environmental considerations are included in process design decisions throughout the hierarchy. The tools of process synthesis and optimisation can be used to support decisions taken at each stage of the hierarchy. The information gathered at each stage of the hierarchy forms the input information for the next level in the hierarchy. Thus there is no duplication of effort in collecting data. The express intention of the hierarchy as developed is to select the most efficient design trajectory from point X on Figure 3-5 in Section 3 to the intersection of the three information sets. While the detail in the three information sets identified increases with each level in the hierarchy, the structure of this information remains the same. This is the structure of information represented on Figure 4-8 in Section 4.

The information gathered at each stage of the hierarchy is particular to the decision that it is required to support. The level of information detail in the techno-centric information set increases between each level of the hierarchy. The detail contained in the enviro- and socio-centric information sets only increases when it is possible to gather this information, i.e., when there is sufficient information available in the techno-centric information set. This is represented on Table 5-2 below which indicates the levels in the hierarchy in which information detail is increased for each data set.

Table 5-2 *Increase in Information Detail for different levels in the Design Hierarchy*

Step in Hierarchy	Technical Information	Environmental Information	Social Information
A	↑↑	↑	↑
B	→	→	→
0	↑↑	↑	↑
C	↑↑	→	→
1	↑↑	→	→
2	↑↑	→	→
3	↑↑	↑↑	↑↑
4	↑↑	↑	↑
5	↑↑	↑	↑

Key:

↑ Increase ↑↑ Significant Increase → No Change

The techno-centric information set increases in detail at each level of the hierarchy. The enviro-centric and socio-centric information sets remain relatively constant until the point at which it is possible to evaluate them in more detail. This is after level 2 in the hierarchy. From this point in the hierarchy onwards the detail in these information sets also increases.

5.2 Case Study of Design for the Environment with known environmental objectives

The decision hierarchy described above is now explored within the context of a case study of design for the environment in the processing of a gold ore. All of the values quoted in this case study have been rounded from the information set used to model the South African gold industry. This information can be found in Appendix 2-3. This case study is demonstrative only. For this reason it is assumed that the environmental requirements of all stakeholders are known. The complexity introduced into the design hierarchy when this is not the case is explored in Section 6.

As all case studies in this thesis pertain to the South African Minerals Industry, all economic values will be quoted in South African Rands (R) expressed in 1996 terms as this is consistent with the baseline year for the LCIs included in Appendix 2.

5.2.1 The Project

A hypothetical gold ore body is to be exploited. This ore body is on the western end of the West Wits Line, about 100km west of Johannesburg in Gauteng, South Africa. As such it is part of the Wits super-group and thus the gold is not refractory, i.e., it is easily soluable in a cyanide solution. The ore body is situated between 100 and 300 m below the surface of the earth and can thus be exploited by opencast or as a shallow underground working. However, the ore body is fractured and spread out over a significant area. The area in which the mine is placed has adequate, but not abundant, supplies of water for minerals processing. There are few processes in the area which have emissions to air.

The average grade of the ore is 4 g/t. There is a total of 40 000 kg of gold in the deposit. The rights to mining this ore body are held by the State.

5.2.2 Level A - Background Information

The information listed above is purely technical in nature and can be used to size a potential operation to exploit this ore body. However, further information is available and this is discussed below.

The policy domain for economic development within South Africa should be described. The ruling party, the African National Congress (ANC), used as its platform in the first democratic elections in 1994 a policy it called the RDP (Reconstruction and Development Program). The tenets of this document were written into national policy once the ANC came into power and can be found in the *White Paper on Reconstruction and Development* (GNU, 1994). One of the main objectives of the RDP is to integrate growth, development, reconstruction and redistribution into a unified program. One of the key methods for implementing this objective is the development of small and medium sized enterprises.

With respect to small and medium sized industries there are key areas of support offered by the RDP policy, these include:

- access to advice
- favorable amendments to legislative and regulatory conditions
- access to marketing and procurement
- access to finance
- access to infrastructure and premises
- access to training
- access to appropriate technology
- inter-firm linkages to be encouraged

Further, to place this project within the South African Minerals policy domain it is necessary to include some detail from the proposed policy framework for the minerals industry, the *White Paper: A Mining & Minerals Policy for South Africa*, (DME, 1998). This document contains details on, among other elements, the accessibility of mining rights to small and medium sized enterprises. The policy in this regard is that there should be enhanced accessibility to state-held mineral rights for small-scale ventures and that large-scale industry should be supportive of small-scale mining. However, there should be no lowering of the environmental, health and safety standards for the small-scale mining sector.

Together these policies can be used to inform the set of input information. The policy of the South African government is to support small and medium sized enterprises; they encourage co-operation between small and large operations; the environmental performance of small enterprises must be the same as large enterprises. The ore body is state-held and thus these considerations should be included in the final design.

There are two main process options for the recovery of gold - chemical and physical processes. These are discussed in detail in Appendix 5-1. The three most commonly used process routes for gold extraction are detailed in Table 5-3 below. This table includes reaction extents and typical waste materials from these processes. These figures are based on the gold sub-sectoral study included in Appendix 2-3 and represent an industry average. This case study has been limited to an analysis of technologies currently in place in the industry. None of the value of the methodology is lost in evaluating the relative performance of existing technologies, and the inclusion of as yet untested technologies (such as resin in pulp as opposed to carbon in pulp) would have resulted in the inclusion of information of differing accuracy. This would have added a further complexity to the case study without increasing the value of the study.

Table 5-3 *Background information for the Extraction of Gold*

	Amalgamation	Filtration	CIP
Water Required (tonne/tonne ore processed)			
	2.3	2.9	4.5
Recoveries (Gold in product as % of gold in ore)			
	72	87	92
Technical Expertise Required			
	Minimal	Some	Some
Potential Hazardous Wastes			
	Ore	Ore	Ore
	Mercury	Cyanide	Cyanide

Note: The judgement made on the technical expertise required is a subjective judgement based on the sophistication of the technology and its operation. Ore is classified as hazardous with respect to the proposed changes to the Basel convention where any material which has the potential to give rise to a metals-bearing leachate will be deemed hazardous (Mathebula, 1999).

The unemployment rate in the area is in excess of 30% (Editors Inc, 1998). Other information available is that the mining method does not impact significantly on the minerals processing methodology selected.

5.2.3 Level B - What is the best use for this raw material?

The raw material being discussed here is the gold ore body. The best use for the material will be decided in the context of the discussion presented in Section 4.3.

Within the policy context detailed above, and taking the unemployment rate in the area into account, it can be stated with some confidence that one of the objectives of the project will be to encourage the inclusion of small and medium-sized enterprises (SMEs) - this constitutes the best use for the raw material. The question to be asked is how to include these enterprises while still ensuring that the environmental impact associated with the processes are as small as possible.

The nature of the ore body is such that it is accessible to open-cast or shallow mines. It is spread over a significant area and thus the mining of the ore can be carried out by SMEs. It is assumed that the mines will be required to comply with the Minerals Act of 1992 (DMEA, 1992) and are therefore required to complete an environmental management program report. Thus the environmental performance of the mining and all associated processes will be quantified and monitored. In order to develop this case study further, it is first necessary to introduce some additional information. A hypothetical economic study shows that it would be most effective (with respect to ore body size and accessibility) for 15 enterprises to be given the right to mine the material. It is assumed that all 15 companies will be given the same amount of material to mine and that they will all mine at the same rate. The mines will be either open-cast or underground mines. They will mine for 40 years.

The choice of chemical based cyanide dissolution technologies is narrowed down from the four presented in Appendix 5-1 to two, i.e., CIP and Filtration. It is proposed that in-situ leaching will not be suitable in this application because of the fractured nature of the ore body (collecting the gold-bearing solution from the ore body would be well nigh impossible). Heap leaching has very slow reaction rates and the time period between investment and income being generated is deemed too long for SMEs. Thus the cyanide-based technologies which will be included are CIP and Filtration. These technologies, along with mercury amalgamation of gold, are included in Figure 2-12. For convenience, this figure is replicated on Figure 5-5 below.

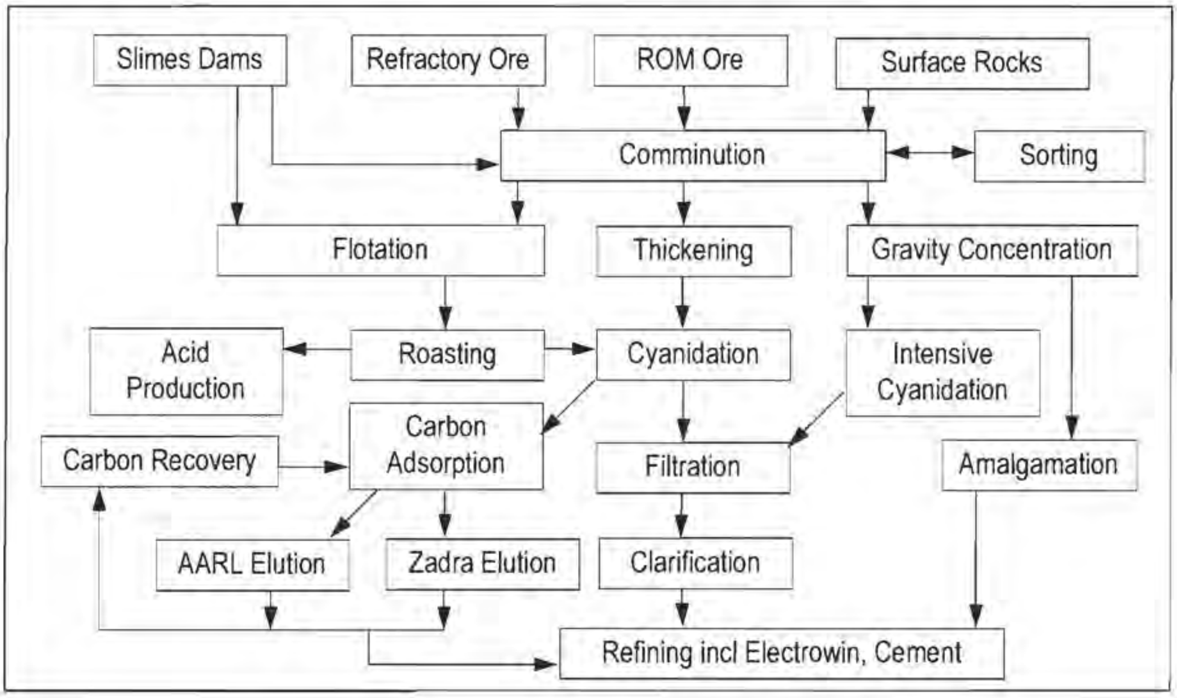


Figure 5-5 *Generalised flow diagram for Gold Processing*

As Table 5-3 shows, all three processes have the potential to impact on the aqueous system in much the same way. A comparison of the difference between these impacts will require more in depth study. CIP uses more water than the others but has a higher recovery of the gold in the ore.

It is not possible to make a decision on which technologies to concentrate on based solely on environmental considerations, within the limited amount of information available at this stage. Thus the three process routes (amalgamation, CIP and filtration) will be carried forward into the next stage of the design.

An indication of a major raw material requirement (water) is also given in Table 5-3. CIP uses significantly more water than the other technologies, but its recovery is higher. All technologies will require the ore to be milled to similar sizes and thus the mill power required by each technology suite would have roughly the same power requirement. It is not possible therefore, to differentiate between the technologies on the basis of power, and thus electricity, requirements.

The major waste from the material is the rock which bears the ore. The nature of this waste is constant, irrespective of the process route chosen. The impact associated with this waste is primarily on water quality. Using a cyanide based process will result in a waste which contains cyanide, whereas amalgamation wastes contain mercury. The cyanide waste can have impacts on the ground water, whilst the amalgamation process has the potential to impact on air quality (mercury is "boiled " off in the retorting process).

Based on the above information, the three technology suites decided on at this point are:

- Cyanide Dissolution followed by Carbon-in-pulp recovery of gold from solution (CIP)
- Cyanide dissolution followed by filtration and clarification (Filtration)
- Amalgamation and retorting (Amalgamation)

A decision has still to be made as to whether the SMEs should process the material at the mine site, or transport it to a central processing operation that can benefit from economies of scale. There is potential for the mines to undertake some beneficiation at the mine site and then capture the gold remaining in the ore in a co-operative venture.

The initial boundary of the LCA study was a cradle-to-gate approach as described in Section 4.3 of this thesis. However, the mining method will not affect the technology chosen and will be dependent on the nature of the deposit at the point at which the particular SME mines. None of the processes in contention will affect differentially the impacts associated with mining activities, and thus the LCA study may exclude the impacts associated with mining. The LCA study will include the major inputs to the process, *viz*., energy and water as well as the addition of hazardous substances, i.e., mercury and cyanide. The major impact categories to be included in the LCA are:

- Global - contribution to greenhouse gases
- Regional - potential contribution to acidification
- Local - human toxicity, water consumption, eutrophication, landfill volume

In addition, a consideration of labour utilisation will be included.

These are chosen, not as an exhaustive list, but rather to demonstrate the ability of the decision support system to account for impacts on different levels within the context of this case study.

It is also necessary to quantify the environmental objective for the process at this point. As has already been stated, it is assumed that the environmental objective is known. This implies that the weights (wf_k) assigned to the impact categories in Equation 4-29 are known. As there is no globally acceptable weighting set, nor has one been defined for South Africa, a weight of 1 will be assigned to each category (this implies that all impacts are considered equally important). The sensitivity of the solution to this assumption will be tested.

The decision taken at this stage is:

The ore body will be mined by 15 small-scale mining companies over 40 years. The ore they produce will be processed by one, or a combination of, CIP, Filtration and Amalgamation.

The scope of the LCA will include:

The LCA study will include considerations of energy, water usage and reagent addition. The boundary will extend to the "gate" of the process. The categories to be included in the study are: global warming potential, acidification, water usage, eutrophication potential, human toxicity and landfill volume. The functional unit will be one ton of gold produced.

The objective of the optimisation is:

To minimise environmental impact and maximise the return on investment when all impacts are considered equally important

5.2.4 Level 0 - Input Information

The information set that formed the background information set will be used. This information set is augmented by including the environmental impacts associated with the major inputs identified above. These impacts are detailed in Appendix 5-1.

In addition the following economic information is available:

- Pay-back period is 10 years
- The interest payable on capital is 15%, as might be the case if a preferential loan were available from the government/large industry on the grounds of the project supporting the ends of the RDP. (Prime interest averaged 18% in 1997 (Editors Inc, 1998))

- The inflation rate is variable (details can be found in Appendix 5-1). A multiplier of 4.7 is derived from interpreting the effect of the average inflation rate over the years 1995 to 1998 (Editors Inc, 1998) and applying this to the 40 year life of plant

The energy requirements of the process will be met by electricity drawn from the national grid.

5.2.5 Level 1 - Batch or Continuous

The process to be modelled will represent a continuous process; this decision is based on the amount of material to be processed. However, it will represent a combination of the processes at the mine and/or a central processing plant. There is the potential that some of these processes will be batch processes, such as the elution of gold from carbon on the CIP circuit. As was recognised in section 5.1.4, it may not be possible for processes to be operated in continuous mode, this is a distinct difference from the chemical processing industry in which it is usually possible to make the choice between operational modes.

5.2.6 Level C - Combinations of Reactors and Separators

The technology available for this process has been limited to the use of the CIP process, the filtration based process and amalgamation and retorting by decisions taken in Level B. The **reactors** within these can be identified as:
- Gravity Concentration and Intensive Cyanidation
- Cyanide Dissolution
- Amalgamation

The **separation** systems within these flow routes are:
- CIP and electrowinning
- Filtration, clarification and cementation
- Retorting

All of the processes would require upstream milling of the material and thus the comminution circuit is common to all of them. There are economies of scale associated with these depending on whether the milling is carried out at the mine site or at a central facility.

5.2.7 Level 2 - Input-output Structure

It is at this stage that all potential reactor-separator couples are modelled and analysed. The potential combinations of the reactors and separators are listed in Table 5-4 below.

Table 5-4 *Reactor-Separator Combinations*

Reactor	Separator
Intensive Cyanidation	CIP and Electrowin
	Filtration and Cementation
Cyanide Dissolution	CIP and Electrowin
	Filtration and Cementation
Amalgamation	Retorting

These reactors can run in parallel with stream splits between them being adjusted in order to minimise the environmental impact and maximise the economic benefit. There is also the possibility of running the reactors in series, i.e., with one of them being used as a "rougher" for initial concentration, followed by a "scavenger" which would remove the remaining gold from the ore. This would result in the potential flow diagram as illustrated in Figure 5-5. This figure implies that there are a number of stream splits that can be manipulated in the model to determine which combination of technologies gives the best economic and environmental performance. These stream splits are:

- the split between the Cyanidation routes and the amalgamation route
- the split between the two cyanide separation processes

A model has been developed which reflects the change in the environmental and economic performance of the process as these stream splits change. In addition, it is possible to model the effect of the ore being processed by 15 separate plants, by a combination of small and large scale operations, and finally large-scale processing only. The possible permutations are listed in Table 5-5. In this table "small" refers to the material being processed by 15 small enterprises, while "large" infers that the ore is processed centrally. It is recognised that, whilst it is unlikely that ore will be milled on a small-scale and then processed on a large-scale, this permutation has been included for completeness, and to determine whether it might not be viable to utilise small-scale milling operations.

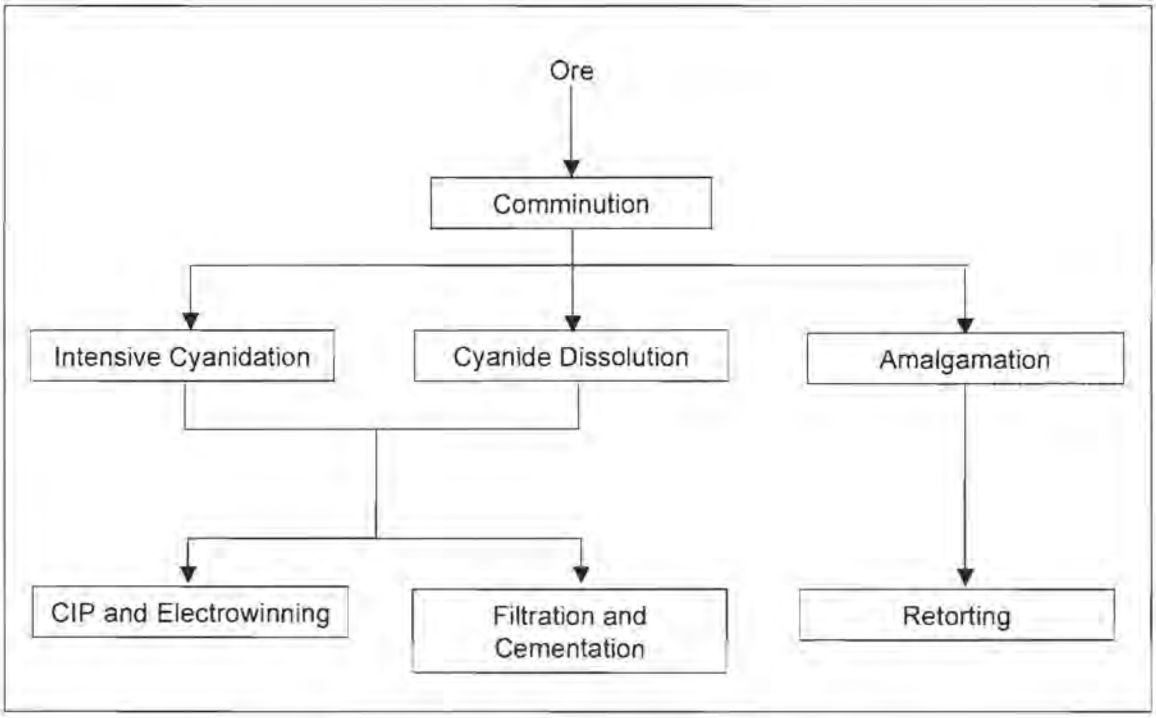


Figure 5-6 *Reactor-Seperator Combinations*

Table 5-5 *Permutations of Reactor-Separator couples, including an indication of Scale*

Number	Comminution	Reactor	Scale	Separator	Scale
1	Small	Intensive Cyanidation	Small	CIP	Small
2				Filtration	Small
3	Small	Intensive Cyanidation	Large	CIP	Large
4				Filtration	Large
5	Large	Intensive Cyanidation	Large	CIP	Large
6				Filtration	Large
7	Small	Amalgamation	Small	Retort	Small
8	Small	Amalgamation	Large	Retort	Large
9	Large	Amalgamation	Large	Retort	Large
10	Small	Cyanide Dissolution	Large	CIP	Large
11				Filtration	Large
12	Large	Cyanide Dissolution	Large	CIP	Large
13				Filtration	Large
14	Small	Cyanide Dissolution	Small	CIP	Small
15				Filtration	Small

Economic performance and labour requirements are evaluated using the cost of unit operations as detailed in Appendix 5-1. The environmental impacts are evaluated using the equivalency factors listed in the same Appendix. Each of the impact categories is given a weighting of one as discussed in Section 4.4. The models can then be evaluated to determine which flow sheet obtains the best environmental score as described in Section 4.2.

The results are presented in Table 5-6 below. This table includes a ranking of each combination relative to its environmental performance. In addition, each combination is rated relative to the cumulative profit (calculated relative to a "hurdle" rate of 20%, see Appendix 5-1 for discussion). A negative cumulative profit indicates that the relevant technology suite will deliver a rate of return less than the 20% hurdle rate. The main reason for including this factor in the table is to demonstrate that using an accepted economic measure of performance alone to rate the processes will deliver a different result to that when environmental considerations are included in the objective function. As was stated in Section 4.2, the objective is to minimise environmental impact and to minimise economic losses, thus the lower the score for the process the better. A flowsheet score is the sum of the weighted attribute scores.

The model was used to determine the optimal performance possible from the flowsheet. It was found that the optimum is represented by a large-scale CIP process as detailed in the table, it is not possible to achieve better environmental performance by combining technologies in this case. This is shown clearly in Table 5-6.

It is interesting to note that, while the two most common technology applications in the industry (cyanide dissolution followed by either CIP or filtration on a large-scale) record among the best economic performance, amalgamation on a large-scale performs better with respect to an integrated environmental/economic objective. Small-scale comminution is out-performed by large-scale comminution in all instances and will not be pursued further as a potential technology in isolation from other small-scale technologies.

Large-scale processes outperform small-scale processes but smaller plants cannot be discounted out-of-hand as they have the potential to employ more people. Ranking the technologies relative to their labour requirements (as listed in Table 5-7 below) does bear this out to some extent.

Table 5-6 *Ranking of Potential Reactors and Separators*

Number	Description	Overall Score	Cumulative Profit (R '000 000)	Economic Ranking
9	Large-scale comminution, amalgamation and retorting	-7.22	69.4	2
5	Large-scale comminution, intensive cyanidation and CIP separation	16.8	34.9	3
6	Large-scale comminution, intensive cyanidation and filtration separation	27.5	22.7	5
13	Large-scale comminution, cyanide dissolution and filtration	64.4	31.0	4
12	Large-scale comminution, cyanide dissolution and CIP	90.9	258	1
8	Small scale-comminution and large-scale Amalgamation and retorting	214	-334	6
14	Small-scale comminution, large-scale cyanide dissolution and filtration	254	-429	10
15	Small-scale comminution, large-scale cyanide dissolution and CIP	255	-407	9
3	Small scale-comminution and large-scale Intensive Cyanidation and CIP	285	-369	7
4	Small scale-comminution and large-scale Intensive Cyanidation and Filtration	320	-381	8
7	Small-scale comminution, amalgamation and retorting	401	-662	13
1	Small-scale comminution, intensive cyanidation and CIP	469	-634	12
2	Small-scale comminution, intensive cyanidation and filtration	500	-619	11
11	Small-scale comminution cyanide dissolution and Filtration	694	-1300	14
10	Small-scale comminution cyanide dissolution and CIP	2450	-5660	15

While it may be argued that maximising labour utilisation while minimising cost is a contradiction (as labour always gives rise to an operating cost), maximising on labour requirement has been included to demonstrate that objectives other than environmental and economic can be included in the MCDA framework. One of the properties of criteria is that they be independent (Stewart, 1992), however, if it is deemed important enough, a criterion which is dependant on another (in this case "loss" is dependant to some extent on "labour") can still be included.

Table 5-7 *Ranking of Technologies with respect to Number of Jobs provided (from greatest number of jobs to least number of jobs)*

Number	Description	Environmental Ranking
12	Large-scale Comminution, Cyanide dissolution and CIP separation	1
14	Small-scale comminution, carbon dissolution and CIP	3
13	Large-scale Comminution, Cyanide dissolution and Filtration separation	6
15	Small-scale comminution, carbon dissolution and Filtration	10
9	Large-scale Comminution, Amalgamation and Retorting	2
7	Small-scale Comminution, Amalgamation and Retorting	11
5	Large scale Comminution, Intensive Cyanidation and CIP separation	4
6	Large-scale Comminution, Intensive Cyanidation and Filtration separation	5
1	Small-scale Comminution, Intensive Cyanidation and CIP separation	12
2	Small-scale Comminution, Intensive Cyanidation and Filtration separation	13

As the technology which employs the most people is also the one with the best environmental/economic score the objective function was not changed to include labour intensity. However, it will be included in the next level of decision to determine whether including labour intensity in the objective changes the results in any way. Small-scale processes will still be included in the study because of other potential economic effects associated with smaller sized enterprises, and because of the political will behind the development of small businesses.

The decision taken at this stage is:

> *That a combination of small and large-scale processes will continue to be included in the study. Comminution at a small-scale is not a viable option. Amalgamation, CIP and Filtration will all be investigated further.*

5.2.8 Level 3 - Recycle Structure

There are two potential levels of recycle:

- Recycling of "tails" to further processing. It is assumed that this will only be effective on the recycling of "tails" from small-scale operations to a single, co-operative large-scale processing plant
- Recycling of inputs back into the process. The main points of focus here are on the recycling of water and the recycling of reagents.

Both of these scenarios are demonstrated in Figure 5-7.

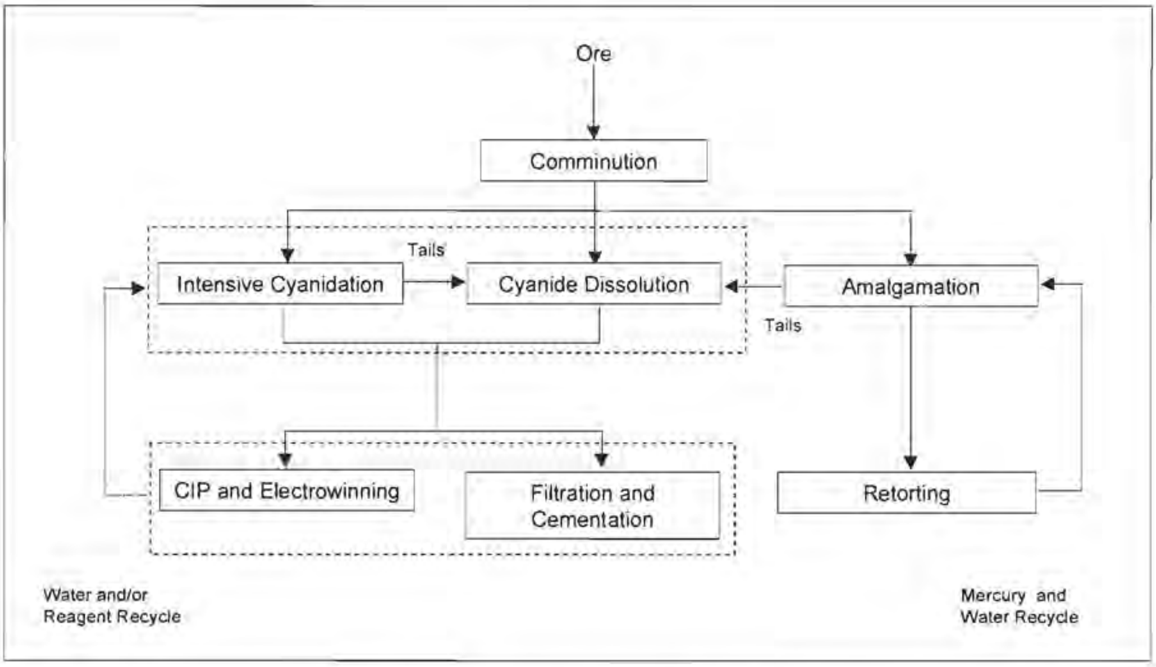


Figure 5-7 *Potential Recycle Structures*

While it is feasible to recycle mercury, the recycling of cyanide poses problems, because of its decomposition in the environment. This decomposition reaction is a function of temperature, ultra-violet irradiation and pH (Ou and Zaidi, 1996). A number of processes have been developed to reduce the cyanide concentration from minerals processing waste streams either by destroying the cyanide, or by recycling it back into the process (Norcross and Steiner, 1996; Robbins and Devuyst, 1996; Stevenson *et al*, 1996). However, it has been argued that the potential environmental impact associated with cyanide in the environment is a strong function of engineering practice, but in general is negligible (Smith and Mudder, 1995). The capital costs associated with the destruction and/or recycling of cyanide is prohibitive (Botz and Stevenson, 1995) thus recycling cyanide will not be pursued further.

Treatment and re-use of water in the minerals industry is common practice (Howard *et al*, 1986; Wates and Kelley, 1986). Thus recycling water within the process will be included in this investigation. The main recycling methodology used in the industry is to capture water leaving the slimes dam and return it as process water. Sometimes a technology is put in place to remove dissolved salts from the water. The build up of salts in the process water is as a result of the complex interaction of the performance of the process itself as well as the reactions which take place as the water filters through the slimes dam. In the context of the case study a 60% water recycle rate will be adopted. If a salt removal system is required, it will be required by all processes. These processes have been regarded as falling into the background of the study (in that they will have the same affect on all technologies and thus will not change the relative rankings of the processes) and thus have not been included in the model.

The permutations to be explored are the technology options listed in Table 5-7. All of the recycle options detailed in Figure 5-7 were explored. An optimisation was performed to determine the stream splits between unit operations that would render the best possible score for the technology. These stream splits control the material flow between the following units:

- Split of material leaving comminution over amalgamation, intensive cyanidation and cyanide dissolution
- Amalgamation "tails" to recycle
- Intensive Cyanidation "tails" to recycle
- Split between CIP and Filtration after cyanide dissolution, whether this be applied to tailings or virgin material
- Split of processing over small- and large-scale processes

Again a single technology selection (as opposed to a combination of technologies) had the best performance. [Note: this is at odds with the findings in Section 6. This point is discussed further in the conclusions to this current section.] The possible technology options are included in Table 5-8 below. The numbering system is different to that used in the previous decision level as these are essentially new technology suites.

Table 5-8 *Technology Options including Recycle*

Number	Description
A	Small-scale intensive cyanidation with central reprocessing of "tails" in a CIP plant
B	Small-scale intensive cyanidation with central reprocessing of "tails" in a Filtration plant
C	Large-scale Intensive cyanidation with "tails" processed through a CIP plant
D	Large-scale Intensive cyanidation with "tails" processed through a Filtration plant
E	Small-scale amalgamation with central re-processing of "tails" in a CIP plant
F	Small-scale amalgamation with central re-processing of "tails" in a Filtration plant
G	Large-scale Amalgamation with "tails" processed through a CIP plant
H	Large-scale Amalgamation with "tails" processed through a Filtration plant
I	Large-scale Cyanide dissolution and CIP
J	Large-scale Cyanide dissolution and Filtration

The same evaluation of the environmental score was carried out on these technology options. The results of this study are included in Table 5-9 below. This table includes an indication of the ranking of the process relative to the economic indicator, cumulative profit, as well as the ranking of the processes when labour intensity was included as a criterion to be maximised in the objective function.

With respect to the economic results, these show that the technology that will deliver the best economic performance is a large-scale CIP process. This is an expected outcome as CIP is the preferred technology in place in the industry for this very reason.

These results demonstrate that CIP outperforms Filtration on the combined environmental/economic objective. Thus Filtration will not be pursued further in this study. While the labour results are interesting, in that they deliver a different result to that obtained from an objective function that only includes environmental and economic criteria, it is the stated objective of this design to deliver the best environmental and economic performance. The integration of a further criterion into the objective function and the effect of this is discussed in the conclusions to this section.

Table 5-9 *Performance of the Technologies, including Recycles*

Number	Description	Overall Score	Economic Ranking	Labour Ranking
K	Large-scale Cyanide Dissolution and CIP	-11.3	1	9
G	Large-scale Amalgamation with reprocessing of tails through CIP	-0.52	2	3
C	Large-scale Intensive Cyanidation and recycling of Tails, CIP separation	11.4	3	1
H	Large-scale Amalgamation with reprocessing of tails through Filtration	46.5	4	7
L	Large-scale Cyanide Dissolution and Filtration	56.2	5	11
D	Large-scale Intensive Cyanidation and recycling of Tails, Filtration separation	125	6	5
A	Small-scale Intensive Cyanidation with central re-processing of tails through CIP	198	7	2
E	Small-scale Amalgamation with central re-processing of tails through CIP	252	8	4
F	Small-scale Amalgamation with central re-processing of tails through Filtration	311	10	8
B	Small-scale Intensive Cyanidation with central re-processing of tails through Filtration	336	9	6
I	Small-scale Cyanide Dissolution and CIP	475	11	10
J	Small-scale Cyanide Dissolution and Filtration	599	12	12

At this stage in the design hierarchy it is necessary to limit the number of options as the last two stages in the hierarchy involve detailed design of the flowsheets and thus carrying too many options forward will require too much work on the part of the design team.

The decision taken at this stage of the hierarchy is that the following technology suites will be carried forward into the next two stages of design:

- *Large-scale mercury amalgamation with reprocessing of the "tails" through CIP*
- *Large-scale intensive cyanidation with reprocessing of "tails" through CIP*
- *Large-scale CIP processing*
- *Small-scale intensive Cyanidation with central reprocessing of "tails" through CIP*

5.2.9 Level 4 - Separation Systems

In this stage of the design, a great deal of detail is added to the flow sheets specifically with respect to the separation systems that are going to be used. Each of the processes listed above have different separation systems that may have a significant impact both on the economic and the environmental performance of the process. The decisions taken at this point will determine the efficacy of the separation on two counts:

- The recovery of valuable product, such as in the design of the CIP elution process where gold is recovered from solution
- The recovery of reagents, such as the capture of mercury in the retorting process

In both these instances the objective can be driven by the need to maximise the economic performance of the process. While this should not take away from the importance of meeting environmental objectives, all of the stages being designed here will have an economic benefit to the operator. This may not always be the case and this will be explored further in Section 6 of this thesis. The models developed for this case study can be used to determine the sensitivy of the overall performance of the process to improved separation efficiencies. These sensitivities are discussed below. The sensitivities can be used to guide designers in the specification of unit processes. Detailed unit process optimisation has not been included in this case study as the focus of this work is the environmental decisions taken during design. Once the operation of the units has been determined is it not necessary to pursue their design further.

5.2.9.1 Sensitivity of Amalgamation to separation technology performance

Within the context of the unit operation assumption sets used in developing the models, amalgamation and retorting was found to be sensitive only to the amount of gold recovered in the retorting process. A 10% increase in the amount of gold recovered resulted in an 8% improvement in the score for the process and a 0.4% increase in cumulative profit.

5.2.9.2 Sensitivity of Intensive Cyanidation and Cyanide Dissolution to separation technology performance

The separation technology used in both of these technology options is the same, *viz.*, CIP. This sensitivity analysis also applies to the amalgamation technology suite which will use CIP in the reprocessing of the "tails". The sensitivity of the integrated environmental and economic score to changing the operation of the separator in other ways is indicated on Figure 5-8 below. This shows that the solution is most sensitive to changes in the recovery of gold. This should therefore be the point of focus for the unit technology designers.

The other factors affecting the efficiency of the unit operation performance are also included on Figure 5-8. They are included in order of the significance of their effect on the score for the process and thus the order in which they should be addressed by the design team.

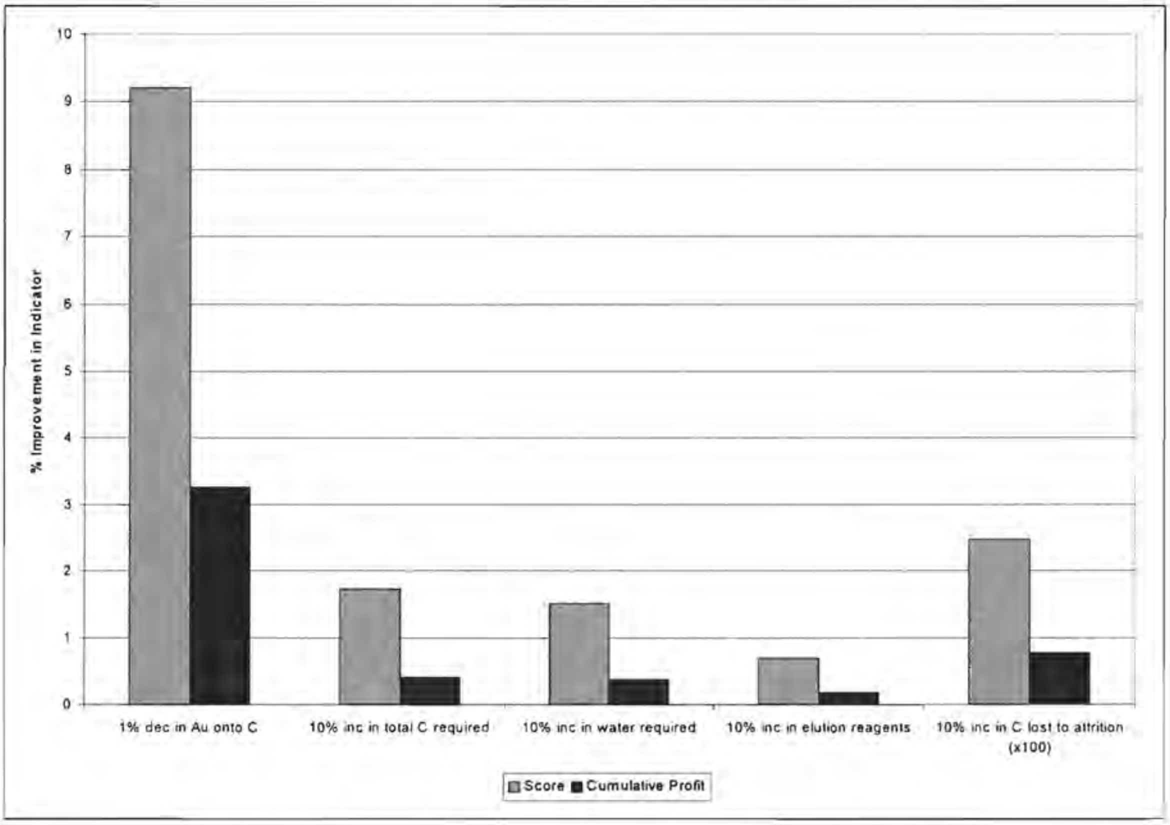


Figure 5-8 *Sensitivity of Indicators to operation of Separation Processes*

Both sensitivity analyses show that an improvement in score is linked to an improvement in return on investment, as has already been stated. Thus, it is possible to design separation systems for best economic effect and the environmental benefits would follow. Thus a single economic objective function can be used in designing this equipment at this level of the hierarchy. This is a significant finding as separation processes are typically designed by the technology vendors. Allowing technology vendors to design for least cost as opposed to having to include environmental considerations in their optimisation regimes will save time and money. However, it will only be the case when the separation technologies do not change the nature of the waste stream. In cases where separators do change the nature of the waste stream it will be necessary to optimise these unit operations with respect to the multi-objective function employed to this point in the hierarchy. This point will be investigated further in the case study in Section 6.

5.2.10 Level 5 - Energy Minimisation and Utilities Management

This final level of the design hierarchy ensures that the energy required by the process is kept to a minimum. As was the case with the design of the separators, minimising energy utilisation will minimise the economic cost of the process and again a single objective can be used.

In the case study under investigation there is no energy being generated within the process and thus an energy integration process would not be required.

There would, however, be a different conclusion if the energy requirements for the process could be met by a number of sources (as opposed to electricity as was stated in the background information). For the case of Amalgamation and retorting with "tails" reporting to a CIP process, it may be possible to integrate the recovery of gold from the amalgam with the recovery of gold from loaded carbon. This would be by burning the loaded carbon to provide energy for the retorting process. Burning the carbon would liberate the gold from the loaded carbon as well, eliminating the need for the elution process. This case was investigated and the following results found. (Note: carbon was assumed to have come from a renewable source such as coconut palms):

- The score for the basic process with electricity being the source of energy was -0.52. This changed to 5.9 for the case where activated carbon was burnt to recover gold, at the same time providing energy for the amalgamation process. This decrease in the process performance can be ascribed to the contribution that burning carbon makes to greenhouse gases.

- The cumulative profit from the process increased by 25% for the case where carbon was burnt. This increase can be ascribed to the fact that there is a reduction in the plant required as well as a reduction in the amount of reagents used.

The overall environmental performance of the process decreases when carbon is used as the energy source for the amalgamation process. However, the solution is relative to the weights placed on the impact categories. Changing these weights would change the score for the technology as is demonstrated later in this section.

Utilities management relates to the quantity of water used and the quality of the water released to the surrounding area (be this as surface runoff or groundwater). Choosing a maximum possible recycle in step 3 of the hierarchy will ensure that all surface runoff from the dump is returned to the process. Correct management of the solid waste dump will ensure that there is no release of leachate to the groundwater. Again, this can be evaluated as a cost minimisation exercise. It is directly linked to the previous step in the decision hierarchy as the more effective the separation system chosen, the more water there is to recycle and thus the lower the operating cost of the process.

5.2.11 The final decision

The final decision of what technology suite to put in place in this case study will be based on economic performance. However, the State is the holder of the rights to exploit the ore body. As such the decision that is made should reflect the development policies of the government as laid out in the RDP. Within this context it is proposed that the final decision taken will be to process the ore through small-scale intensive cyanidation processes with a central re-working of "tails".

This case study has demonstrated that it is possible to support decisions taken during process design in minerals processing to ensure that both the environmental and economic objectives for the process are met. This is achieved within an understanding of the social domain but does not address the requirements of society directly. This will be discussed further Section 6 of this thesis.

5.3 Methodological Observations

The hypothetical case study described above has demonstrated the ability of the decision support framework to support decisions taken during the design of minerals processing plant. There are a number of observations that have been made during the development of the case study. They are discussed below in order to both support the framework in its existing structure, and to comment on deficiencies within the framework.

5.3.1 Uncertainties

It must be recognised that all of the decisions taken in this case study are based upon aggregated unit operation performance for the industry. It is possible to demonstrate the ability of the decision support structure (the integration of the extended design hierarchy and the information structure) to support the types of decision to be taken in the context of this case study. However, there are uncertainties associated with the accuracy of the information used in the development of the environmental and economic objective functions. These have not been highlighted for each stage of the decision hierarchy; however, in "real" decision situations these cannot be ignored. A complete study of these uncertainties is beyond the scope of this thesis and is merely highlighted here as an area of the decision support structure which requires investigation. It is discussed further in Section 7.

5.3.2 Effects of Changing the Normalisation Regime

The normalisation regime employed in this case study relates the contribution of impact categories and profits to the mass of product from the system. To explain in more detail, the total contribution of the technology suite being modelled is normalised with respect to the total tons of gold produced by that technology option because this is the functional unit for the LCA. The baseline performance of the gold industry for the 1996 production year (as include in Appendix 2-3) was taken to be the basis for comparison of technology suites. Thus the normalised contribution to each impact category has been divided by the equivalent normalised measure for the industry. These industrial values are included in Appendix 5-2. There are two reasons for dividing by average industry performance:

- To de-dimensionalise the attribute scores for each criterion
- To ensure that the orders of magnitude of all the elements in the objective functions are similar, thereby eliminating the potential for the solution to be biased towards the elements that have the largest orders of magnitude (Stewart, 1992)

The resultant impact category score is thus a measure of the performance of that technology suite relative to the average performance of the industry.

This normalisation regime is relative to the LCA functional unit as has been stated. However, it is common to express the performance of minerals processes relative to the run-of-mine (ROM) ore milled. The effect of these different approaches to normalisation on the solution to the model has been explored below. This analysis is warranted as each technology option has a different efficiency, as detailed in Table 5-3. The different approaches to normalisation have been explored in the context of the technologies permutations compared in step 3 of the hierarchy (the recycling decision). While it can be expected that the magnitudes of the scores for each permutation will be different, this is not important. Rather it is the ranking of each technology permutation for the different normalisation regimes that is notable. The results for each normalisation regime are included in Table 5-10 below. In this table score A relates to normalising with respect to the LCA functional unit while score B relates to a normalisation against the ROM ore milled.

These results show that changing the normalisation regime will alter the relative rankings of the technology permutations only in the lower orders. As the objective for the process is to produce a desired product, normalisation with respect to the amount of product produced (i.e., the LCA functional unit) will be adopted as the normalisation regime for the information structure. This is the normalisaiton regime most commonly adopted when LCA is used to structure an environmental objective (Azapagic, 1996; Golonka and Brennan, 1996).

A further normalisation regime which it is possible to explore, is to normalise with respect to the impacts associated with the minerals industry as a whole. The impacts associated with the minerals industry are based on the sub-sectoral inventories as detailed in Appendices 2-3 to 2-9. This total impact profile is included in Appendix 5-2.

While it is possible to determine the environmental impact associated with an industrial sub-sector (based on the inventories included in Appendix 2), information is not always available on the operating profit for that sub-sector. In cases where it is not possible to determine an operating

Table 5-10 *Comparison of Rankings relative to Different Normalisation Regimes*

Number	Description	Score A (normalised relative to ton product)	Rank A	Score B (normalised relative to ton ROM ore milled)	Rank B
K	Large-scale Cyanide Dissolution and CIP	-11.3	1	-13.3	1
G	Large-scale Amalgamation with reprocessing of tails through CIP	-0.52	2	-0.62	2
C	Large-scale Intensive Cyanidation and recycling of Tails, CIP separation	11.4	3	13.4	3
H	Large-scale Amalgamation with reprocessing of tails through Filtration	46.5	4	52.5	4
L	Large-scale Cyanide Dissolution and Filtration	56.2	5	55.5	5
D	Large-scale Intensive Cyanidation and recycling of Tails, Filtration separation	125	6	129	6
A	Small-scale Intensive Cyanidation with central re-processing of tails through CIP	198	7	232	8
E	Small-scale Amalgamation with central re-processing of tails through CIP	252	8	298	7
F	Small-scale Amalgamation with central re-processing of tails through Filtration	311	9	351	10
B	Small-scale Intensive Cyanidation with central re-processing of tails through Filtration	336	10	347	9
I	Small-scale Cyanide Dissolution and CIP	475	11	558	11
J	Small-scale Cyanide Dissolution and Filtration	599	12	592	12

profit against which to normalise the economic criterion, a first assumption can be made. This assumption is that normalising the economic criterion relative to the income from sales for the industrial sub-sector is sufficient. While this is not strictly the same as the ratio that is used in the environmental objective, it is the only possible course of action within the limits of available information.

Table 5-11 below contains the results of this different normalisation regime. A comparison with the results obtained when the income from sales alone (as opposed to the cumulative profit) for the technology permutations was normalised with respect the industry average for the initial normalisation is also included.

Table 5-11 *Including industry totals in the Normalisation Regime*

Number	Description	Score A (normalised relative to ton product)	Rank A	Score C (economic objective on sales only)	Rank C	Score D (normalised relative to product mass and total performance of the industry)	Rank D
K	Large-scale Cyanide Dissolution and CIP*	-11.3	1	13.5	5	7940	3
G	Large-scale Amalgamation with reprocessing of tails through CIP*	-0.52	2	13.4	4	7910	1
C	Large-scale Intensive Cyanidation and recycling of Tails, CIP separation*	11.4	3	14.0	6	8460	8
H	Large-scale Amalgamation with reprocessing of tails through Filtration*	46.5	4	43.5	9	8360	5
L	Large-scale Cyanide Dissolution and Filtration*	56.2	5	51.2	10	9540	9
D	Large-scale Intensive Cyanidation and recycling of Tails, Filtration separation	125	6	62.0	12	9700	12
A	Small-scale Intensive Cyanidation with central re-processing of tails through CIP	198	7	6.98	3	8450	7
E	Small-scale Amalgamation with central re-processing of tails through CIP	252	8	6.48	1	7920	2
F	Small-scale Amalgamation with central re-processing of tails through Filtration	311	9	36.3	7	8370	6
B	Small-scale Intensive Cyanidation with central re-processing of tails through Filtration	336	10	54.0	11	9700	11
I	Small-scale Cyanide Dissolution and CIP	475	11	6.54	2	8020	4
J	Small-scale Cyanide Dissolution and Filtration	599	12	42.9	8	9630	10

* denotes that the technology will deliver the required 20% return on investment

This second ranking (ranking C) includes only the sales from the process in the economic objective function, no payback on capital investment is included. Although a different sequence of preferred technologies is achieved, this order is questionable as the preferred solution does not deliver the requisite return on investment. However, it is necessary to include the second ranking sequence in order to have a comparison for the third ranking sequence, ranking sequence D. In this third ranking sequence, the objective functions were normalised with respect to the total mass of products and total impacts from the minerals processing industry as a whole as opposed the only the gold sub-sector. This third ranking sequence also delivers a different preferred solution. By normalising with respect to the performance of the entire industry, the significant value of the gold product relative to the mass of the product is included in the optimisation. This shows that the preferred solution is sensitive to the normalisation regime selected.

5.3.3 Effects of Changing the Weights

There are two different effects which can be analysed by changing the relative weightings of criteria in the objective function:

- An indication of the preferred technology should the weighting of one criterion change. This will give an indication of what would happen if the preferences on the criteria in the optimisation were to change - e.g., human toxicity is twice as important to the decision maker as the other environmental impacts.
- An indication of the preferred technology should the weighting of one or more criteria in the objective function be set to zero. This is an indication of what happens if the objectives of the decision situation were to change - e.g. optimise the process for least local environmental impact as opposed to the overall environmental impact.

These effects are investigated in this section. A summary of the scores achieved by each technology for each of the weighting scenarios can be found in Appendix 5-3. Only the ranking achieved by the permutations is included in the tables in this section.

5.3.3.1 Changing the Preferences

A number of preference scenarios were investigated. These include:

- Doubling the weighting on all of the environmental criteria, which means effectively that the environment is twice as important as economic performance.
- Doubling the weighting on greenhouse impacts which is an indication that a greenhouse impact is twice as important as the other impacts.
- Doubling the weighting on human toxicity which is an indication that human toxicity effects are viewed as being twice as important as the other impacts.

- Multiplying the economic criterion by two which would imply that economic performance is twice as important any of the other criteria.

The effects of these changes are detailed in Table 5-12. This table details that no changes in the initial ranking is detected for these weighting changes.

Table 5-12 *Effect of Changing Preferences on the preferred solution*

Number	Description	Initial Weighting Set	All Impact Categories x2	Green house x2	Human Toxicity x2	Economic Objective x2
A	Small-scale Intensive Cyanidation with central re-processing of tails through CIP	7	7	7	7	7
B	Small-scale Intensive Cyanidation with central re-processing of tails through	10	10	10	10	10
C	Large-scale Intensive Cyanidation and recycling of Tails, CIP separation	3	3	3	3	3
D	Large-scale Intensive Cyanidation and recycling of Tails, Filtration separation	6	6	6	6	6
E	Small-scale Amalgamation with central re-processing of tails through CIP	8	8	8	8	8
F	Small-scale Amalgamation with central re-processing of tails through Filtration	9	9	9	9	9
G	Large-scale Amalgamation with reprocessing of tails through CIP	2	2	2	2	2
H	Large-scale Amalgamation with reprocessing of tails through Filtration	4	4	4	4	4
I	Small-scale Cyanide Dissolution and CIP	11	11	11	11	11
J	Small-scale Cyanide Dissolution and	12	12	12	12	12
K	Large-scale Cyanide Dissolution and CIP	1	1	1	1	1
L	Large-scale Cyanide Dissolution and	5	5	5	5	5

This is a surprising result. It appears that one, or more, of the criteria are dominating the solution. This will be verified in the next sub-section where the effect of changing the objectives for the problem are changed.

5.3.3.2 Changing the Objective

The objectives which define the objective function can be changed by setting the weightings applied to a specific criterion to zero. This is equivalent to discounting a particular objective. A number of different scenarios were modelled:

- Consideration of only environmental criteria
- Consideration of only economic criteria

- Optimising the model for maximum labour utilisation
- A combination of environmental, economic and labour objectives

Changing the objectives for the decision results in a different preferred technology option for each case as illustrated in Table 5-13. This demonstrates that it is important to ensure that all relevant criteria are included in the objective function. This applies to all stages of the design hierarchy and emphasises the importance of including more criteria, rather than less, in the first levels of the hierarchy. If the solutions can be demonstrated to be unaffected by one or more of the criteria in the objective function then they can be eliminated from the study. This is a significant finding as it decreases the amount of information required to support decisions.

Table 5-13 *Changing Technology Scores with changing Objectives*

Number	Description	Initial Objective	Environmental Objective only	Economic Objective only	Labour Objective only	Combined Objectives
A	Small-scale Intensive Cyanidation with central re-processing of tails through CIP	7	3	7	2	7
B	Small-scale Intensive Cyanidation with central re-processing of tails through Filtration	10	11	10	4	10
C	Large-scale Intensive Cyanidation and recycling of Tails, CIP separation	3	6	3	1	3
D	Large-scale Intensive Cyanidation and recycling of Tails, Filtration separation	6	12	6	3	6
E	Small-scale Amalgamation with central re-processing of tails through CIP	8	1	8	6	8
F	Small-scale Amalgamation with central re-processing of tails through Filtration	9	7	9	8	9
G	Large-scale Amalgamation with reprocessing of tails through CIP	2	4	2	5	2
H	Large-scale Amalgamation with reprocessing of tails through Filtration	4	9	4	7	4
I	Small-scale Cyanide Dissolution and CIP	11	2	11	12	11
J	Small-scale Cyanide Dissolution and Filtration	12	8	12	10	12
K	Large-scale Cyanide Dissolution and CIP	1	5	1	11	1
L	Large-scale Cyanide Dissolution and Filtration	5	10	5	9	5

Table 5-14 has been included to illustrate the difference in result when the process is optimised for environmental performance where spatial effects are acknowledged. This shows that a single technology may have superior performance on a global scale but unacceptable performance on a local scale. This would be supported by analysing the contribution of the various technology suites to impact categories which have different spatial effects.

Table 5-14 *Preferred solution when emphasis is placed on local, regional and global impacts*

Number	Description	Initial Weighting Set	Greenhouse x5	Greenhouse only Environmental Objective	Acidification x5	Acidification only Environmental Objective	Toxicity and Eutrophication x5	Toxicity and Eutrophication only Environmental Objectives
A	Small-scale Intensive Cyanidation with central re-processing of tails through CIP	7	7	7	7	1	5	7
B	Small-scale Intensive Cyanidation with central re-processing of tails through Filtration	10	10	10	10	10	11	10
C	Large-scale Intensive Cyanidation and recycling of Tails. CIP separation	3	3	3	3	4	3	3
D	Large-scale Intensive Cyanidation and recycling of Tails. Filtration separation	6	6	6	6	7	8	6
E	Small-scale Amalgamation with central re-processing of tails through CIP	8	8	8	8	8	7	8
F	Small-scale Amalgamation with central re-processing of tails through Filtration	9	9	9	9	9	9	9
G	Large-scale Amalgamation with reprocessing of tails through CIP	2	2	2	2	3	2	2
H	Large-scale Amalgamation with reprocessing of tails through Filtration	4	4	4	4	5	4	4
I	Small-scale Cyanide Dissolution and CIP	11	11	11	11	11	10	11
J	Small-scale Cyanide Dissolution and Filtration	12	12	12	12	12	12	12
K	Large-scale Cyanide Dissolution and CIP	1	1	1	1	2	1	1
L	Large-scale Cyanide Dissolution and Filtration	5	5	5	5	6	6	5

Technology suites A, E, G, and K have been investigated in more detail. Figure 5-9 below gives an indication of the relative significance of the contributions of each of these technology suites to local, regional and global impacts.

This figure shows that, while the local and regional impacts associated with the different technology suites are similar for all of the technologies presented, the global impacts differ with changing technology suites. This observation has value in informing the Environmental Impact Assessment process which is discussed in more detail in Section 6 of this thesis.

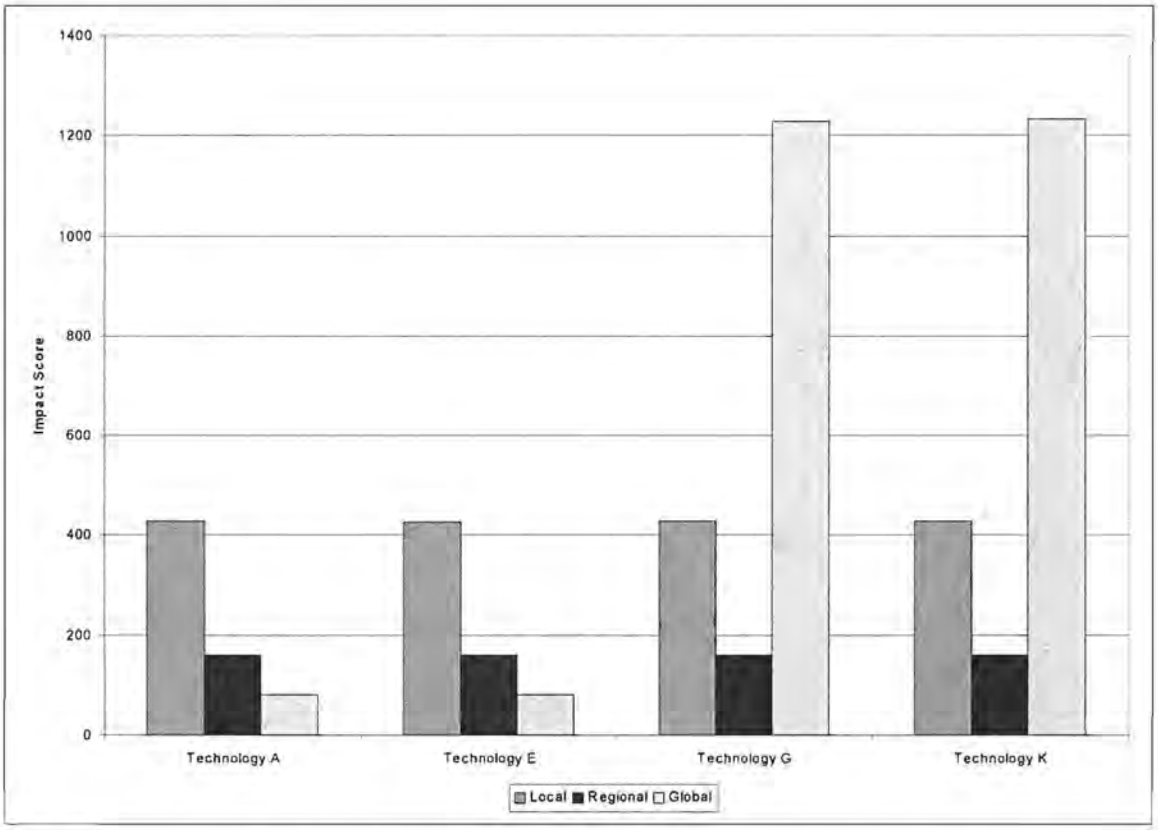


Figure 5-9 *Spatial Differences in Impacts for Different Technology Suites*

5.3.3.3 Scaling the criteria scores

The economic objective appears to be dominating the solutions (see Table 5-9, Table 5-12, Table 5-13 and Table 5-14). It is possible that there are discrepancies in the values used in the economic objective function (between the industry performance and the performance of the technology suite under investigation). There may be a greater level of detail in the economic performance for the process under design than there is in the economic performance data available for the industry. If the industry information was under-stated in any way, or the process information over-stated at all, merely ratioing the process and industry performance would not eliminate the orders of magnitude differences in the criteria scores.

In an attempt to eliminate this effect the criteria scores have been scaled. This is achieved by evaluating the best and worse scores for each of the criteria. These best and worse scores are assigned values of one and zero respectively. The criteria scores are then scaled with respect to this zero to one scale. This is an accepted methodology for overcoming dominant criteria (Beinat, 1997; Nijkamp *et al*, 1988; Keeney, 1992) and gets to the root of value function analysis as discussed in Section 4. It does however have the potential of biasing the answer away from those criteria with the smallest difference between best and worse values. It is only possible to use a scaling approach once all of the possible technology options have been established. The equation for the scaling of the criteria scores is included in Equation 5-1:

$$\text{Scale Score} = \frac{\text{Score - Best Score}}{\text{Worst Score - Best Score}} \qquad \textbf{Equation 5-1}$$

This scaling of the criteria scores has been investigated for the technologies evaluated in Step 3 of the design decision hierarchy. The scores for the permutations can be found in Appendix 5-3; only the ranking of the options is included in Table 5-15 below. This table gives an indication of how the preferred solution changes with the scaling of the criteria scores.

Table 5-15 *Comparison of Preferred Technologies for Scaled and Unscaled Scores*

Number	Description	Initial Weighting Set		All Impact Categories x2		Green house x2		Human Toxicity x2		Economic Objective x2	
		Unscaled	Scaled	Unscaled	Scaled	Unscaled	Scaled	Unscaled	Scaled	Unscaled	Scaled
A	Small-scale Intensive Cyanidation with central re-processing of tails through CIP	7	5	7	5	7	3	7	5	7	5
B	Small-scale Intensive Cyanidation with central re-processing of tails through Filtration	10	11	10	10	10	10	10	11	10	10
C	Large-scale Intensive Cyanidation and recycling of Tails, CIP separation	3	7	3	7	3	7	3	7	3	6
D	Large-scale Intensive Cyanidation and recycling of Tails, Filtration separation	6	12	6	12	6	12	6	12	6	11
E	Small-scale Amalgamation with central re-processing of tails through CIP	8	1	8	1	8	1	8	1	8	1
F	Small-scale Amalgamation with central re-processing of tails through Filtration	9	6	9	6	9	4	9	6	9	7
G	Large-scale Amalgamation with reprocessing of tails through CIP	2	3	2	3	2	5	2	3	2	2
H	Large-scale Amalgamation with reprocessing of tails through Filtration	4	8	4	8	4	8	4	8	4	8
I	Small-scale Cyanide Dissolution and CIP	11	2	11	2	11	2	11	2	11	4
J	Small-scale Cyanide Dissolution and Filtration	12	9	12	9	12	9	12	9	12	12
K	Large-scale Cyanide Dissolution and CIP	1	4	1	4	1	6	1	4	1	3
L	Large-scale Cyanide Dissolution and Filtration	5	10	5	11	5	11	5	10	5	9

There are two significant results in this table:

- The order of the technologies changes with scaling of criteria scores
- Scaling of criteria scores does not affect the response of the permutation scores to changes in preference weighting.

To address the first result, Table 5-16 below contains the top five preferred technologies (relative to the initial weighting set) as evaluated using the unscaled scores and compares these to the top five technology suites obtained using the scaled scores.

Table 5-16 *Ranking of Permutations relative to scaled and unscaled Scores*

Number	Description	Unscaled	Scaled
K	Large-scale Cyanide Dissolution and CIP	1	4
G	Large-scale Amalgamation with reprocessing of tails through CIP	2	3
C	Large-scale Intensive Cyanidation and recycling of Tails, CIP separation	3	7
H	Large-scale Amalgamation with reprocessing of tails through Filtration	4	8
L	Large-scale Cyanide Dissolution and Filtration	5	10
A	Small-scale Intensive Cyanidation with central re-processing of tails through CIP*	7	5
E	Small-scale Amalgamation with central re processing of tails through CIP*	8	1
I	Small-scale Cyanide Dissolution and CIP*	11	2

* denotes does not achieve the required 20% return on investment

These results show that the unscaled scores bias the solution towards the economic objective. Scaling the scores used to evaluate the total score for the technology permutation does affect the outcome. Thus care must be taken throughout the design hierarchy, but specifically in steps B and 2, where the normalisation and scaling regimes are chosen.

The second result from Table 5-15 is more complex. It includes considerations of the observations made in section 5.2.8 where the observation was made that the preferred solution was a single technology options (as opposed to being a combination). Both of these results related to the set of discrete, as opposed to inter-related, weights used in this case study. It is necessary to include a methodology for incorporating changing preferences into the model in order to deliver an overall objective function (the combination of environmental and economic objective functions) which is sensitive to changes in preferences placed on different criteria. This incorporation of preferences must include an indication of the willingness of the decision maker to allow trade-offs to be made between criteria. Section 6 of this thesis addresses these issues and demonstrates the methodology developed in the context of designing a zinc refinery.

6 Environmental Objectives for MCDA

Section 5 of this thesis demonstrated the application of the extended design hierarchy (Section 5) and the information structure (Sections 2 and 4) to a case study. One of the findings of this case study was that allocating discrete weights to the environmental and economic criteria in the objective function is not sufficient as there is no significant sensitivity of the preferred solution to changing these weights. It was thus concluded that it is necessary to incorporate more complex decision making tools (as described in Section 4) into the design decision hierarchy. One of the shortcomings of using these tools is that they require a significant amount of information to inform the values to be used in the algorithms - whether these be in the form of value functions (Section 4.1.3.1) or goal programming (Section 4.1.3.3). In this section it is proposed that the social scoping element of the Environmental Impact Assessment (EIA) process can be used to inform the requisite value set. However, it is not possible to conduct an EIA if there is not a technology set available to assess and, for this reason, the EIA cannot be conducted before process design has started.

This section presents an overview of the EIA process. The extended design hierarchy included in Section 5 is then analysed within the context of the information requirements of the EIA process - recognising that EIA represents a particular type of decision making context. The information requirements of EIA are identified in Section 6.1.1. A point in the design hierarchy is identified where it is possible to proceed to an EIA. This essentially moves the design process to being a three-stage hierarchy of decisions. The three stages of this design are identified as pre-design, initial design and detailed design. EIA lies between initial and detailed design. The integration of information from the EIA into design decisions is discussed. MCDA tools to inform these design decisions are presented and discussed. A worked case study on technology selection and the integration of EIA and design for a Zinc Refinery is included to illustrate the three-stage design hierarchy.

6.1 Adding detail to Design Information

The case study included in Section 5 demonstrated that it is possible to include environmental and social information in evaluating design objectives as part of process optimisation. However, there was insufficient sensitivity of the preferred solution to changes in social and environmental information. A significant deficiency is the manner in which social information was included in the objective function for Section 5. It contained no information of the potential to trade-off between different criteria - the weights allocated to the various criteria were discrete as opposed to inter-related and reflected merely the technology suite that fitted best with the environmental objectives, no sensitivity to changing environmental preferences was found. Section 4 of this thesis proposed Goal Programming and Value Functions as potential methodologies whereby social values can be included in objective functions for design. However, in order to use these methodologies more information than is usually available to the design engineer will be required. For goal programming it is necessary to be able to define goals for the criteria, while value functions require that the weights to be allocated to the criteria which have been represented by value functions be well enough understood that it is possible to interpret these relationships mathematically.

A further deficiency in the hierarchy presented to this point is that the environmental criteria are informed solely by a Life Cycle Impact Assessment (LCIA) process. While this may be sufficient for the analysis of the potential impact associated with a proposed project, it is not sufficient in the context of site selection, as it gives no indication of the real impact associated with a proposed project. It must also be recognised that different technology options may perform better at different sites. For example, there are two processes available for refining a metal - one uses a great deal of water and the other has significant gaseous emissions. There are two potential sites available for the development of the project; one that is arid but has no air pollution problems, and another that has sufficient water resources but a significant air pollution problem in the area. It is possible to determine which combination of technology and site will have the smallest environmental impact, but only if the consideration of site-specific information is included in design decisions. Making technology selections upstream of site selection has the potential to undermine the environmental performance of the proposed project.

In summary, the two main deficiencies highlighted thus far are:

- It is necessary to interpret weights in an inter-related manner
- The impact assessment lacks site-specific information

The EIA process has been developed to, among other aims, determine the real impact associated with placing a proposed project on a specific site or selection of site options, and elicit the response of society to placing the project at these sites. As such, EIA has the potential to address the two deficiencies in the hierarchy detailed above.

6.1.1 Overview of the EIA Process

Initially, EIA was seen as a tool to aid decision making on site and project selection. However, this view has been extended to include the decision making process within the ambit of EIA (Petts, 1999a). In so doing EIA has integrated a number of quantitative impact assessment tools as well as qualitative tools to address the concerns of society. A diagram of such an EIA process is included in Figure 6-1.

The elements of this process which address the information deficiencies described in Section 6.1 above are:

- The **Decision** element which has the potential to deliver a quantitative valuation of society's interests and concerns, and the **values** or goals required for value functions or goal programming; this addresses the deficiency in weighting algorithms used previously
- The **EIA report preparation** which will deliver information on the **real impacts** associated with the proposed project; this addresses the deficiency in site-specific impact assessments

For this reason these two elements within the EIA process are described in more detail.

At this point it must be stated explicitly that the decision support framework developed in this document in no way addresses the problems associated with problems that cannot be devolved from "messes" to structured problems as defined by Ackoff (1979). If it is not possible to translate the set of values expressed by society into quantitative arguments then the decision support framework developed here will not be applicable. In the instances where it is not possible to articulate societal preferences as quantities it will be necessary to use tools such as those used in conflict resolution to develop a decision structure. However, in starting the EIA before design is complete, there is greater potential to address the requirements of society actively during the design process, which has the potential to stop a conflict situation from arising. The decision space supported by the decision support framework developed in this thesis is limited to problems in which social values can be used to inform a set of weights for the various decision criteria.

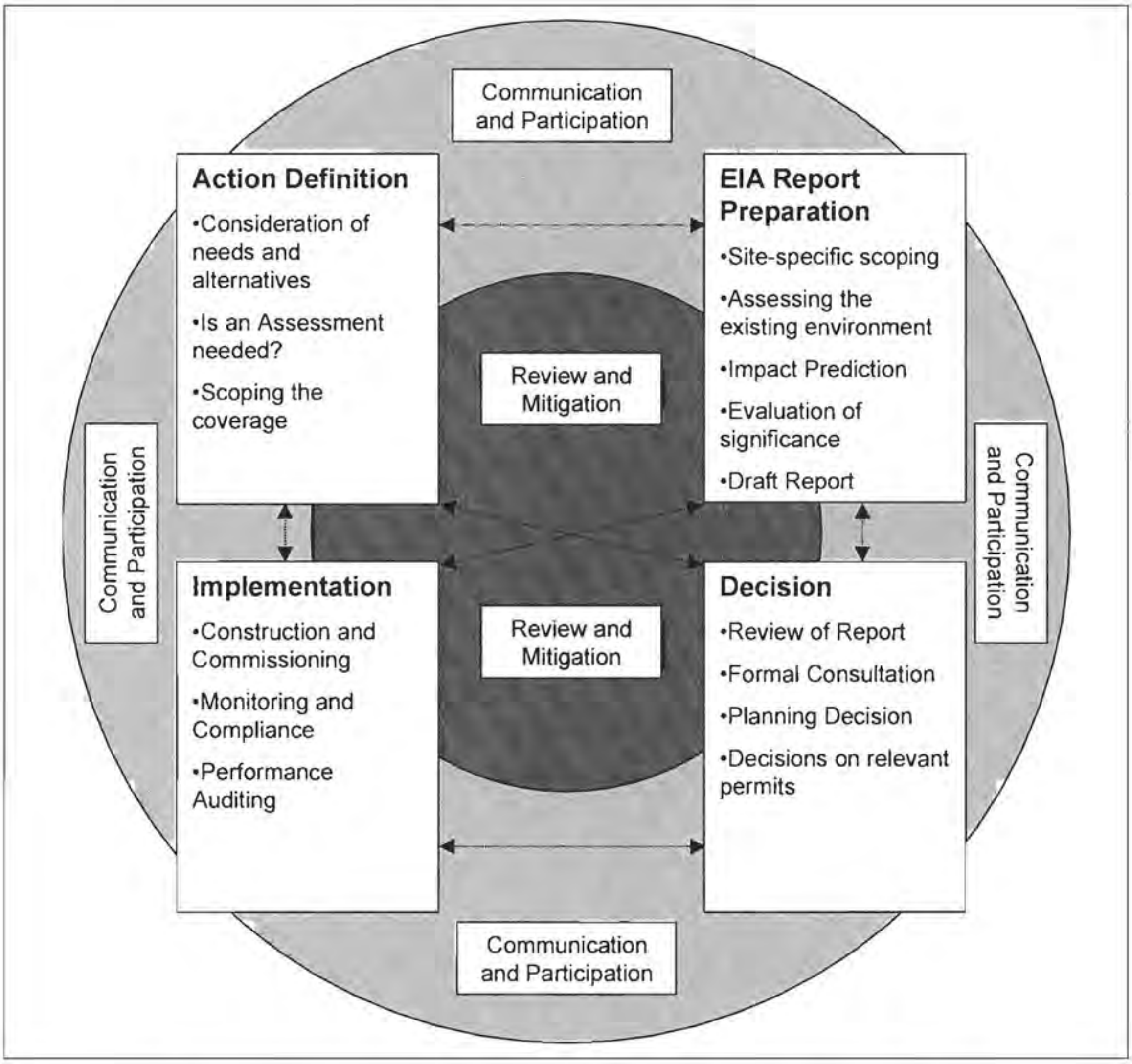


Figure 6-1 *The EIA Decision Support System (after Petts and Eduljee, 1994)*

6.1.1.1 Site specific impact assessments from the EIA process

The site specific assessment of the impacts embodied by a proposed project are usually quantified in terms of a number of specialist studies within the EIA process. These studies usually include (though not exclusively):

- Air Quality Assessment
- Water Quality Assessment (both surface and groundwater)
- Social Impact Assessment
- Ecological Impact Assessment

- Landscape and Visual Impact Assessment
- Overall Risk Assessment

While much effort has been made by EIA practitioners internationally to standardise the quality and tools used in the assessment of impacts associated with a proposed project, comprehensive guidelines have yet to be established (Petts, 1999b). Suffice it to say that the specialists' reports usually have the following generic structure:

- Baseline analysis which details the *status quo* with respect to the site(s) under consideration
- A review of the inventory from the proposed project which has the potential to impact on the medium/element which the study is focussing on
- Impact prediction, this is conducted using modelling tools were available (Air pollution modelling, modelling of potential pollution flows in ground and surface water, etc.).
- An indication of the significance of these impacts

It is thus fair to say that the output from the EIA specialist studies is a quantification of the real potential of the process to impact on the environment. The specialist studies include temporal and spatial effects. As such these specialist reports address the environmental information deficiency referred to in previous discussions.

6.1.1.2 Value sets from the EIA

The EIA process also has the potential to address the other information gap - a quantification of the values which society places on different environmental and economic criteria. A formal consultation process has the potential to deliver the requisite information. The Public participation or social scoping element of the EIA process has changed significantly and much is being written about the "new" participative approaches (Petts, 1999c; Clark, 1994). These approaches have seen the mode of interaction move from manipulation to participation on the "steps" of participation as defined by Arnstein (1969) and illustrated below.

It is within the context of participatory decision making processes that it becomes possible to develop a set of weightings which describe the concerns and interests of the parties involved. Significant development has taken place in the field of MCDA and the application of MCDA tools in the environmental field to express a qualitative valuation of different criteria in a quantitative manner (Fiala and Sauer, 1997, Hokkanen *et al*, 1997). It can be stated with confidence that this field is sufficiently well developed to be applicable in the context of a consensus-driven approach to decision making within the EIA process, thereby delivering the information required to fill the deficiencies in the information sets used in the case study detailed in Section 5.

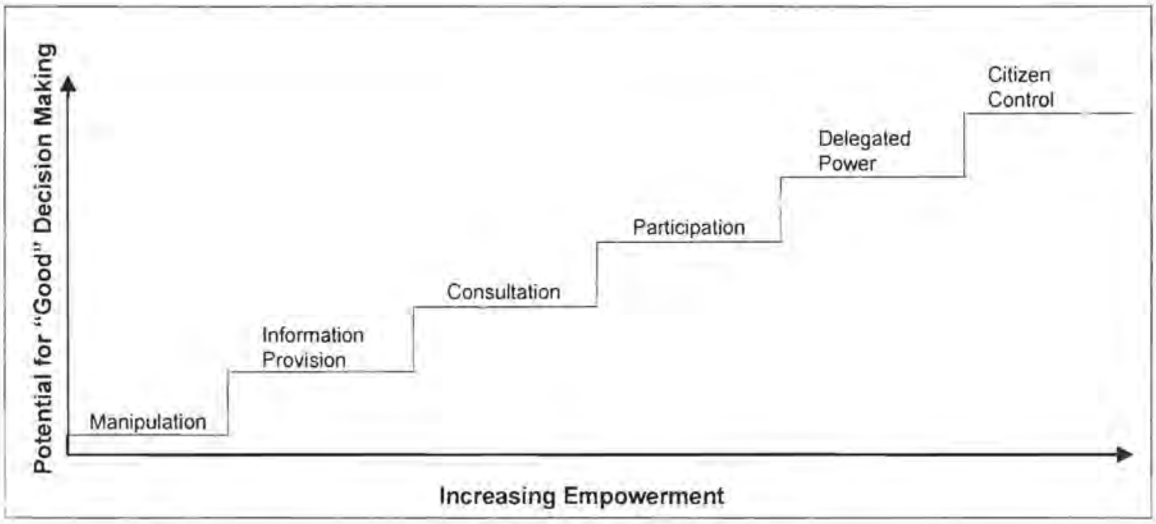


Figure 6-2 *The Participation "Steps" (adapted from Arnstein, 1969)*

6.1.2 Integrating Process Design and EIA

In order to address the statement made in Section 2 of this thesis - that it is necessary to make the right decision at the right point in the project life cycle - it must also be recognised that it is only possible to make a decision when there is sufficient information available to support that decision. The discussion presented in Section 6.1.1 suggested that it is possible for the EIA process to deliver the information required to inform the design process. This is only possible within the context of the decision structure developed in this thesis. However, it is not possible to conduct an EIA without first specifying the process and sites to be assessed. Thus, it is necessary to proceed some way through the design hierarchy both to limit the number of technologies under consideration and to ensure that enough is known about these technologies to enable the specialists' studies to be conducted. However, process design should not continue so far as to limit the ability of the design engineers to address the concerns of the public by changing the technology decisions taken within the design hierarchy.

However, specialist studies can only be conducted once the nature and quantity of streams crossing the process boundary are known. Reviewing the integrated design hierarchy presented in Table 5-1 in Section 5, this would be after, or during, step 3 of the hierarchy where the recycle structures are decided on. The reason for this is that it is at this point in the hierarchy that the nature and quantity of streams crossing the process boundary (other than feed and product streams) are calculated for the first time.

This would require a number of design decisions to have been taken before the EIA is conducted. However, at the point at which the recycles are being modelled, the design is not so constrained as to eliminate all potential to address the concerns of society. In addition, a number of technology permutations is still under consideration at this point in the hierarchy, thus it should be possible to choose the combination of technology and site that has the best performance within the value set elicited from stakeholders. This would suggest that there are a further two stages in the design hierarchy, one leading up to the EIA (steps 1 to 3) and one where process and environmental information is integrated into the EIA process (steps 4 and 5). This is not to imply that social values are not considered in the stages of the design hierarchy leading up to the EIA process, rather that in these initial stages of design the information informing the socio-centric information set is generic and aggregated. In steps 4 and 5 this socio-centric information set is developed for the proposed technology suites and sites for the project.

A more detailed analysis of the extended hierarchy presented in Section 5 would suggest that there is a further division in the types of decision to be taken and the amount of information available. Steps A and B in the hierarchy are different to the rest of the steps described. The questions which they pose are of a more strategic nature than the ensuing steps. This has been discussed in some depth in Section 3 of this thesis. Suffice it to say that the information which they use and the nature of decisions which they require are sufficiently different from the steps which follow that it has been decided that they form a further design stage in their own right.

The three stages identified are distinctly different in the quality of information available. This will have a significant effect on how the decisions are structured for each stage. However, the elements of decision structuring will still apply to each stage. The extended design hierarchy is re-stated in Table 6-1 with a modification to indicate the three-stage design process. These stages have been called Pre-, Initial and Detailed design.

Table 6-1 *Three-stage Design Hierarchy*

Stage	Level	Douglas Design	Minerals Processing Design	Environmental Design
Pre-Design	A			Background Information
	B			Project Selection - Comparison of possible products or raw materials
Initial Design	0	Input Information		
	1	Batch vs Continuous		
	C		Establishment of reactor-separation train	
	2	Input-Output		LCA of raw materials; LCA of different waste streams from different structures; impact of changing quality of inputs (feed and raw materials); impacts of process efficiency
	3	Recycle Structure		Difference in impacts between concentrated and dilute wastes
Detailed Design	4	Separation system (liquid/ vapour)	Separation of solids from liquids	Macro-scale LCA is required to show how reactor-separator couples should be linked
	5	HX network		Utility Minimisation

A detailed discussion of this three-stage design hierarchy follows in Section 6.2.

6.2 Decision Support in the Three-stage Design Process

The intention of this section is to demonstrate that the three levels of decisions identified in the design hierarchy can be described in terms of distinct decision structures. Thus the elements of decision structuring will be evaluated for each of these stages. There are a number of permutations proposed for these elements (Clemen, 1996; Janssen, 1994; Keeney and Raiffa, 1976). In this thesis the elements of decision structuring are:

- Decision situation and the values and objectives
- Development of alternatives
- Modelling and solution of models

- Sensitivity analyses and potential uncertain events
- Analysis of preferred alternative and consequences of the decision

Decisions taken at each step in the hierarchy inform the next step. The information requirements as well as the information detail added by each stage are described.

6.2.1 Pre-design

This stage incorporates the first two steps from the design hierarchy namely the gathering of background information and the selection of the project to be undertaken. The pre-design study is not seen as supplanting the pre-feasibility study, rather that the pre-feasibility study will form part of the pre-design stage. The pre-design stage as described forms part of a strategic assessment.

6.2.1.1 Decision situation and the values and objectives

The questions asked in the pre-design stage are strategic in nature. In the case of minerals processing, which inevitably exploits non-renewable resources, the primary question to ask is whether this is the most beneficial use of that raw material.

In addition, minerals processing also uses significant amounts of energy. The question to ask here is whether this is the most effective use for the energy or whether stakeholders would benefit more if that energy were used in another manner. Given the focus on Southern African case studies to support the intellectual framework developed in this these, consider as an example the use of the Pande Gas Fields gas (off the coast of Mozambique) as a gas feed to the proposed ferro-alloys plant to be constructed either in Mozambique or in Zimbabwe. Is this the best use for this raw material or would society as a whole not benefit more from using this gas to provide energy for residential or small business purposes?

Mineral deposits (and here minerals are defined to include coal and gas) can be seen as potential credit entries in the accounts of a country. If they are not exploited their value will never be reflected. However, once they are exploited they cannot be replaced thus their exploitation should be beneficial to the country as a whole.

The decision to be made here is whether the proposed project is the best use for the raw material. The objective is to achieve a sustainable society.

The criteria to be addressed at this level of decision are macro-scale. It is not possible to include consideration of, for example, water quality impacts at this stage of the hierarchy.

6.2.1.2 Development of alternatives

There are a limited number of significant inputs to a minerals processing plant. These are:

- Capital
- Mineral Reserves
- Energy
- Labour

Alternatives should be developed with these in mind. While it is recognised that a project will only go ahead if it is economically viable, different process options for a specific mineral reserve will require different permutations of these inputs.

6.2.1.3 System Model Structure

The information on the proposed technology sets for the different alternatives is extremely limited at this point. Information available is heuristic in nature and really only details conversion rates and ratios as well as energy requirements. Economic calculations will be accurate. Raw material inputs, other than the major ones listed above, are ignored at this stage; as is reagent addition. In the same way the nature of the wastes associated with the proposed technology sets is inferred from an understanding of existing processes. The calculations are, at best, an order of magnitude evaluation.

However, even at this level of information detail, it is proposed that using LCA to give an indication of the environmental impact associated with the proposed process routes has value. As information on the performance of the technology is very limited at this point, site-specific accuracy is not required from the LCA. Existing LCA data-bases are sufficient. Where information is not available it can be inferred from heuristics. LCA information is used at this point in the design hierarchy essentially to highlight the nature of potential environmental impact associated with a proposed project – not to quantify that impact. Within the context of LCA the question may be asked here whether independent peer review is possible in such an application. Independent peer review of technology assessments is seldom conducted (though there may be some in-house verification of the information), including LCA approaches in the technology assessment/selection process could require a peer review to be conducted. The main value in supporting peer review is that it increases the credibility of the design process. There are two different groups that gain value from the exercise:

- The design engineers get confirmation that what they are doing is defensible
- Stake-holder buy-in may be improved if peer review is conducted by a high profile group such as an international non-governmental organisation

Stakeholder values, the so-called "socio-centric" information set, can be informed using a number of sources – market surveys, legislative criteria, an understanding of international conventions such as the Kyoto and Basel Conventions, etc. The level of detail in the information on stakeholder preferences should be commensurate with the order of magnitude estimates that are being used to evaluate the techno- and socio-centric information sets. Thus the information need only give an expression of concern. It is not necessary to obtain more detail than this.

The information on the inputs to the process as well as how the process operates and the nature of the waste it will generate forms part of the background information (Step A); as does the LCA information and whatever stakeholder information is inferred.

6.2.1.4 Sensitivity analyses and potential uncertain events

It would be superfluous to conduct a sensitivity analysis on information which is only an order of magnitude estimate.

Inferring the impact of uncertain events on the decision made during this stage would also be superfluous due to the lack of detail in the information sets. There is more uncertainty associated with the information itself (and thus inherent in the decision reached) than in any potential application of the decision.

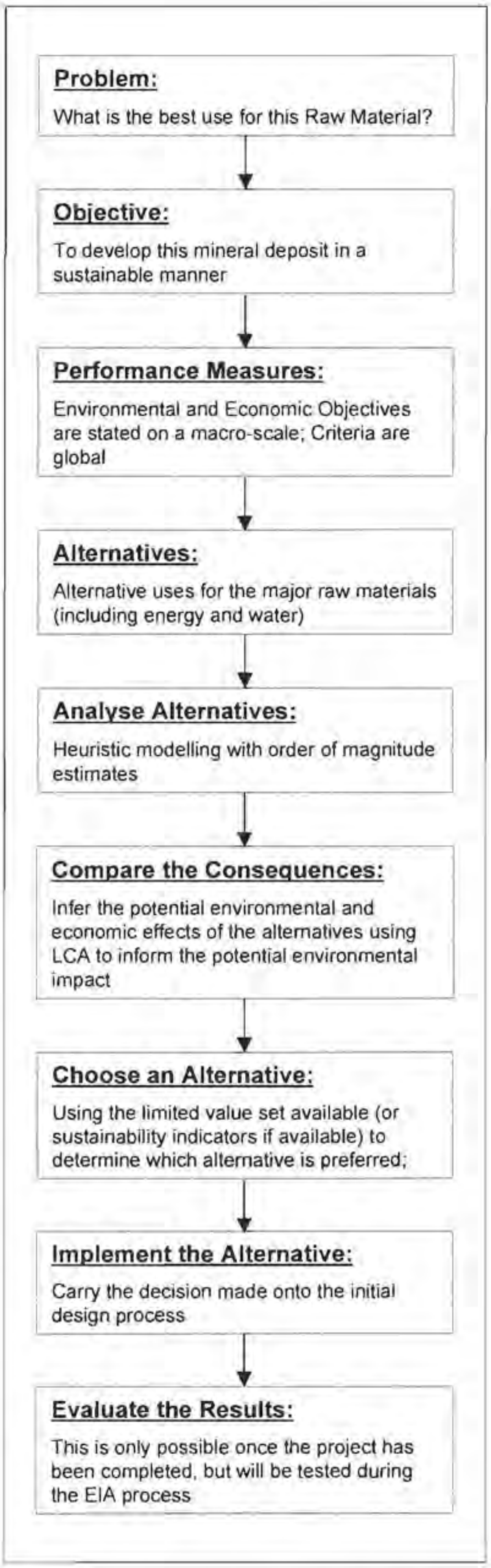
6.2.1.5 Analysis of preferred alternative and consequences of the decision

The preferred alternative will be the one which is economically viable and comes closest to meeting sustainability objectives. This however imposes the author's value set on the decision. Defining the sustainable exploitation of minerals reserves is not a trivial exercise; much of the debate focuses on the system boundary defined. Sustainability in the minerals industry is receiving much attention at present (Carbon, 1997; Miller, 1997). A definitive list of sustainability indicators for the minerals industry is not yet available. The indication of environmental impact evaluated using the LCA data-bases together with the approximated socio-centric information set used should highlight that alternative for exploiting the mineral reserve which comes closest to meeting the requirements of all stakeholders.

The final decision taken at the end of this stage of the design will be the proposed use for the mineral deposit which is carried forward into the initial design stage. In addition, the initial forms of the techno-, enviro- and socio-centric information sets will be in place. Thus, not only the final decision, but all work that goes into structuring decision itself, is of paramount importance as it will guide the design process through the next two stages. It if for this reason that this pre-design stage is seen as part of process design. If this stage were seen as being separate from process design, then there would be no way of ensuring that this information is carried forward into the next stages of design. As has been stated, the information gleaned to this point is extremely valuable in developing the decision support framework throughout process design.

6.2.1.6 Pre-design Decision Structure

This structure has been developed with reference to Figure 4-1. The generic boxes in Figure 4-1 have been specified for the pre-design decision in Figure 6-3.



Problem:
What is the best use for this Raw Material?

Objective:
To develop this mineral deposit in a sustainable manner

Performance Measures:
Environmental and Economic Objectives are stated on a macro-scale; Criteria are global

Alternatives:
Alternative uses for the major raw materials (including energy and water)

Analyse Alternatives:
Heuristic modelling with order of magnitude estimates

Compare the Consequences:
Infer the potential environmental and economic effects of the alternatives using LCA to inform the potential environmental impact

Choose an Alternative:
Using the limited value set available (or sustainability indicators if available) to determine which alternative is preferred;

Implement the Alternative:
Carry the decision made onto the initial design process

Evaluate the Results:
This is only possible once the project has been completed, but will be tested during the EIA process

Figure 6-3 *Decision Structure for Pre-Design*

6.2.2 Initial Design

Initial design includes a number of steps from the design hierarchy, Table 6-1 details these; in summary they are:

- Step 0 – Input Information
- Step 1 – Batch vs Continuous
- Step C – Establishment of reactor-separator train
- Step 2 – Input-Output
- Step 3 – Recycle Structure before EIA

Decision taken at this stage of the design hierarchy determine the structure of flowsheet inside the process boundary, i.e., none of the streams crossing the process boundary are evaluated. This does not imply that the decision scope is limited to this boundary, is it an observation on the level of information detail used at this stage. The information is on a macro-scale. Individual streams are not quantified until step 3 in the hierarchy. In step 3, streams crossing the process boundary are calculated for the first time. While some development of the enviro- and socio-centric information will be required during this stage of the design, emphasis will be placed on extending the techno-centric information set.

The main aim of the initial design stage is a pre-screening of all technology options in order to limit the total number of technologies to be included in the EIA process.

6.2.2.1 Decision situation and the values and objectives

The decision context for this stage of the design will be to determine the set of technology suites which are most likely to deliver the required economic performance while still meeting the projected requirements of stakeholders with respect to environmental performance. A single solution to the design of a process is not expected. Rather the aim is to start with the potentially infinite number of combinations of technologies available and narrow these down, using the development of process flowsheets, to a limited number of options. These technology options will form the basis of the EIA. The final result from this stage of the design will usually be between 3 and 5 potential technology options. The reason for choosing this number of options is listed below (Stewart, 1997):

- Having only one option make stakeholders feel that their input is not necessary – all important decisions have already been taken. Also, it is easier to veto a project if there is a single option available, if more that one option is offered then vetoing the project is not as simple as alternate options have been offered.
- Having only two options is also not satisfactory as it may seem that the company has only included the other option in order to make the solution which they are proposing seem better. It is difficult to place the problem in context if there is only one other solution available for contrast.
- Three is thus seen as the minimum number of potential technology options to be presented to stakeholders. Five is proposed as the maximum number of solutions as having more than this number of options has the potential of confusing the stakeholders as opposed to enlightening and empowering them to take part in the decision making process.

Having 3 to 5 options is at odds with behavioral scientists who suggest that 7 ± 2 alternatives be included in such a study (von Winterveldt and Edwards, 1986). Behavioral scientists choose this number of options as being optimal as the human mind cannot deal with more than this number of discrete options at one time. Choosing 3 to 5 options as opposed to 7 ± 2 limits the number of options to be included in the EIA process. Limiting this number then limits the amount of work required for each specialist study in the EIA which limits the cost of the EIA.

The objective is to maximise the economic performance of the proposed technology options; at the same time minimising the potential environmental impact associated with the process. In the context of the case study included in this section, the environmental objective is defined as the profit for the process (income less capital and operating costs). This is consistent with the work of Douglas (1988).

The environmental objectives are informed using the life cycle structure defined in Section 3. This makes it possible to link inputs to the process and outputs from the process to the environmental impacts which they embody. These impacts are aggregated into a number of impact categories and reported as potential contribution to global warming or acidification etc.

Legislative criteria can be used as an indication of stakeholder preferences. This is a reasonable first estimate for the socio-centric information set as, within a democratic system, it is the intention of legislation to reflect the will of the majority. However, while it is possible to use legal limits to set the weights for the environmental objectives, legislative limits do not necessarily reflect the best potential performance for the process. Constraining the solution to fall within the legislative limits may constrain the solution to be sub-optimal. To illustrate this, it may be possible that relaxing a legal limit by 1% on a single pollutant could deliver a 10% improvement in the overall environmental performance of the process. A better definition of values could be evaluated using the philosophies of, for example, "best practice" (MCA, 1995) or MIPS (Material Intensity Per unit of Service) (von Weizsäcker *et al*, 1997). Using MIPS in minerals processing may pose a problem as it is difficult to identify the service rendered by a minerals product (see the discussion included in Section 5.1.2 which discusses process design as opposed to product design). It will be necessary to formulate a different set of material intensity indicators for processes as opposed to services before this philosophy could be applied.

6.2.2.2 Development of alternatives

This set of all possible alternatives was designated $\underline{A}$ in Section 4 and is defined in that section. It is necessary to define this set of alternatives with respect to the number of processes included in the flowsheet - defined as "p" in Section 2. This is achieved by linking all processes "p" in as many technologically feasible permutations as possible. Set $\underline{A}$, the complete set of technology permutations is defined in Section 4.1.2.1.

6.2.2.3 System Model Structure

Goal programming will be used to inform the decisions at this point. There are two reasons for choosing goal programming:

- A significant number of options will be evaluated and goal programming is simpler to implement than other MCDA algorithms. This is discussed in Section 4.1.3). Using goal programming will decrease the time and effort required to formulate the model and will be less costly.
- There is insufficient information available to enable the formulation of representative value functions.

Goals for each of the objectives can be set using such philosophies as "best practice" or other bench marks for the industry (some companies are developing in-house sustainability indicators such as the ICI environmental burdens approach and the Unilever OBIA indicators included in Section 2). It will be possible to determine which of the alternatives approaches the requirements of, for example, best practice, most closely.

In order to determine the technology combination which comes closest to the required set of goals, the flowsheet is optimised. This statement is made with reference to the definition of design variables and mass balance assumption sets within the flowsheet modelling approach detailed in Section 2. The stream split ratio which dictates the split of stream between different unit operations can be taken to be a design variable. Manipulating the stream splits between unit operations is equivalent to manipulating the technology permutations, as these stream splits control the flow of material between unit operations. These streams splits can be changed in the optimisation to find that combination of technologies which comes closest to the required set of goals.

The issue of data quality needs to be addressed as there are significant differences of data quality on a number of levels:

- Information on existing technologies will be extremely detailed and accurate, while that available at pilot plant scale will be less so. Thus there are data differences between the alternatives generated within the techno-centric information set.
- The enviro-centric information set is informed by existing LCA data-bases. These are aggregated and generalised giving total potential estimates of the potential impact associated with the inputs and outputs of the process.
- The socio-centric information set will have been informed using aggregated information, such as legislative criteria, as a first guess. While this is a defensible position there is no guarantee that the stakeholders in any one area will agree with them.

In this context it is necessary to discuss data accuracy and consistency not only within the three data sets but also between the data sets. It is not necessary to make information extremely detailed. Rather it is better to define the lowest quality of information sufficient to support the decisions to be made. The reason for choosing the lowest quality of information is that this is the information set which will cost the least to generate. This is a significant study in its own right and needs to be addressed in detail. At this point of the discussion it will be highlighted as an issue. More discussion on this point is included in Section 7 of this thesis. Once a sufficient level of information has been evaluated it is necessary to ensure that there is an adequate understanding of the uncertainties inherent in the information sets.

6.2.2.4 Sensitivity analyses and potential uncertain events

One of the tools which can be used to determine whether the information quality is sufficient to support decisions is a sensitivity analysis where the sensitivity of the solution to uncertainty in the information sets is explored. This analysis would also assist in highlighting where the information sets need further development.

The sensitivity of the solution to changing preferences assigned to each of the objectives should also be conducted. This could include the sensitivity of the solution to changes in the legal limits. The main motivation for this study is an understanding of how the preferred solution will change with changing stakeholder preferences. This is valuable when embarking on the EIA as the company has a fore-knowledge of the "hot" issues associated with the proposed project. This can be used to inform the specialist studies within the EIA as well as public debate.

6.2.2.5 Analysis of preferred alternative and consequences of the decision

At the start of the initial design stage the net was cast wide to include as many technologies as was deemed to be reasonable. This vast amount of information is narrowed down as decisions are taken within each step of initial design. Information gathered in each step is used to inform the next. The final options are those which are closest to achieving the economic and environmental goals established.

The final techno-centric information set contains three to five possible options. These form the basis of the EIA. Shortcomings in the enviro- and socio-centric information sets will have been highlighted and these will need to be addressed explicitly in the EIA. Significant impacts have also been identified; these guide the specialist studies within the EIA. The project team will have an understanding of how the system will react to changing stakeholder preferences; this too has value in the EIA study.

6.2.2.6 Decision Structure in Initial Design

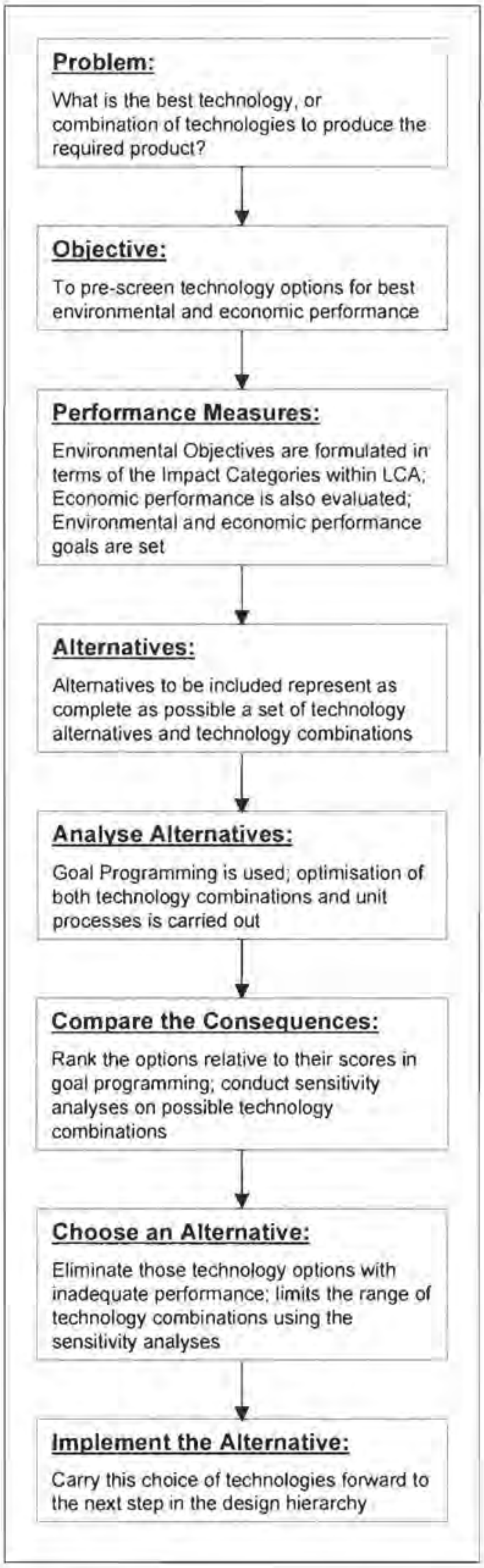
Figure 6-4 has been developed to demonstrate the structure of the decisions taken at each stage within initial design. This structure is common to all of the decisions included in this stage of the design hierarchy (steps 0 to 3 as detailed in Section 6.2.2.1). The decision taken at the end of each step is then used to inform the next step in the hierarchy. Thus it is possible to develop a decision cycle for the initial design stage. This is demonstrated in Figure 6-5.

6.2.3 Detailed Design

The detailed design stage of the decision support framework includes:
Step 3 – Recycle Structure after EIA
Step 4 – Integrated Separation System
Step 5 – Utilities Minimisation and Management

There is an overlap with the previous stage. Step 3 is included in both initial and detailed design. In the initial design stage the recycle structure is established and optimised according to specific goals set for economic and environmental objectives. This then is the information which forms the basis for the first iteration of the EIA process. It should be stressed that, in integrating the EIA process into the iterative design process, the EIA process also becomes iterative. The stakeholder preferences elicited in the EIA process are used to inform the development of the process from this stage forward. This infers that, while the process alternatives under design will have been optimised prior to being presented to the stakeholders, they will have to be optimised again once the stakeholder preferences (the socio-centric information set) and the specialists studies (the enviro-centric information set) have been completed.

While all effort would have been expended in the previous stages of the design hierarchy to ensure that the processes presented in the EIA are the "best" for that application according to pre-defined goals, there is the potential that the decision made during the initial design may have been biased by incorrect estimates in the enviro- and socio-centric information sets. There is thus the potential for design to return to the decisions made in the first step of the initial design and for the entire process to have to start from the beginning again. This should not be unnecessarily time-consuming if all the information gathered is passed on to the following stage.



Problem:

What is the best technology, or combination of technologies to produce the required product?

Objective:

To pre-screen technology options for best environmental and economic performance

Performance Measures:

Environmental Objectives are formulated in terms of the Impact Categories within LCA; Economic performance is also evaluated; Environmental and economic performance goals are set

Alternatives:

Alternatives to be included represent as complete as possible a set of technology alternatives and technology combinations

Analyse Alternatives:

Goal Programming is used; optimisation of both technology combinations and unit processes is carried out

Compare the Consequences:

Rank the options relative to their scores in goal programming; conduct sensitivity analyses on possible technology combinations

Choose an Alternative:

Eliminate those technology options with inadequate performance; limits the range of technology combinations using the sensitivity analyses

Implement the Alternative:

Carry this choice of technologies forward to the next step in the design hierarchy

Figure 6-4 *Decision Structure for Initial Design*

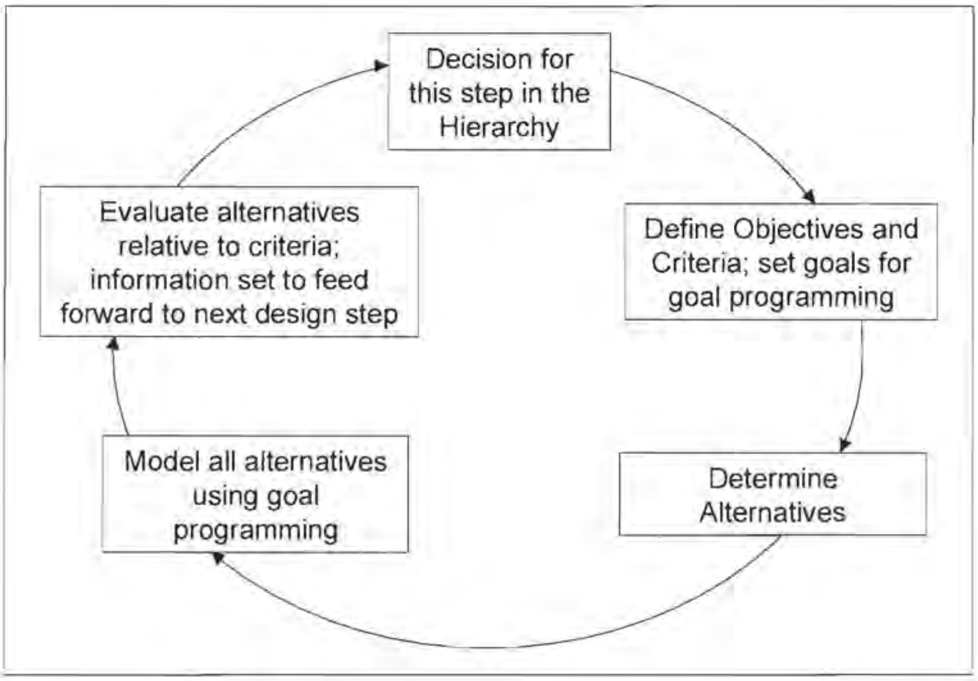


Figure 6-5 *Decision Cycle for Initial Design*

There should be no need for the design to revert to the pre-design stage. This is a strategic assessment stage and consensus should have been reached between all stakeholders before any specific project was proposed. There are two reasons for design to return to steps 0 or 1:

- The pre-design stage was not conducted satisfactorily.
- Information arising in these later stages of design change the outcomes resulting from different alternatives so dramatically that the decision taken during steps 0 and 1 of the hierarchy need to be revisited

There are two main aims for this stage of design:

- To choose that technology option or combination which meets the requirements of society
- The ensure that the final stages of design optimise technology choice (around separation equipment and utilities mangement) and process conditions (for the process as a whole) within the value set elicited during the EIA process

6.2.3.1 Decision situation and the values and objectives

The decision context for the Detailed Design stage should not differ considerably from that identified in the Initial Design stage. The aim will be to reach consensus between the stakeholders on the final technology suite and its siting. The structure of the information will not change significantly from that used in initial design. The information sets will be defined more accurately:

- The specialist studies within the EIA develop the environmental impact assessments fully. They move the environmental impacts from being an aggregated indication of the potential of the process to impact on the environment on a global scale to the impact the process will have at a regional and local level. This is used to inform both the siting of the process as well as the technology chosen.
- The social scoping phase of the EIA informs the value set. This set should reflect total stakeholder concerns.

These may change the objectives and the value set but this should not be significant if the initial design has been conducted satisfactorily.

6.2.3.2 Development of alternatives

All alternatives should have been included by this stage in the design. If it is not possible to address the concerns of society within the constraints of the technology options included in this stage of the design, it may be necessary to revert to earlier steps in the design and re-visit alternatives which had been discounted previously. This should only be necessary if the criteria used in the initial design stages did not reflect the requirements of society adequately. New criteria introduced into the models by the results of the social scoping process may highlight technologies which have been discounted in previous stages of the design hierarchy.

It is important that all concerns expressed by the stakeholders be investigated in full both to ensure that all possible alternatives have been assessed and to ensure stakeholder participation in the EIA process.

6.2.3.3 System Model Structure

The enviro-and socio-centric information sets will have been developed fully by this stage. In addition, the number of technologies under investigation will have been narrowed to a relatively small number (3-5). Thus more rigorous preference modelling methodologies can be used. The use of Value Function Analysis is proposed for the case study. The preferences expressed by stakeholders within the EIA process are used to inform the shape of value functions for each criterion. The technology options under consideration are guided by the desire to minimise trade-offs between economic and environmental criteria.

6.2.3.4 Sensitivity analyses and Uncertainties

At this stage in design sensitivity analyses reflect the robustness of the design to the stakeholders. The uncertainties which can be addressed in the context of the model are systemic uncertainties. A full Risk Assessment for the project should still be conducted.

6.2.3.5 Analysis of preferred alternative and consequences of the decision

The preferred alternative will be the technology option which minimises the trade-offs made between criteria. The minimisation is informed by the values gleaned in the social scoping exercise. However, it must be recognised that the final decision does lie with the developer. If they are not able to make a profit from the process it will not go ahead. If there is sufficient stakeholder scoping early enough in the design process it is unlikely to result in a "no go" answer.

The consequences of the decision will be reflected in the EIA. Main consequences will be impacts in both the environmental and social domains. By evaluating the position of least trade-offs between all objectives the final process will, at least, have the positive aspects equaling the negative aspects, if not outweighing them considerably.

6.2.3.6 Decision Structure in Detailed Design

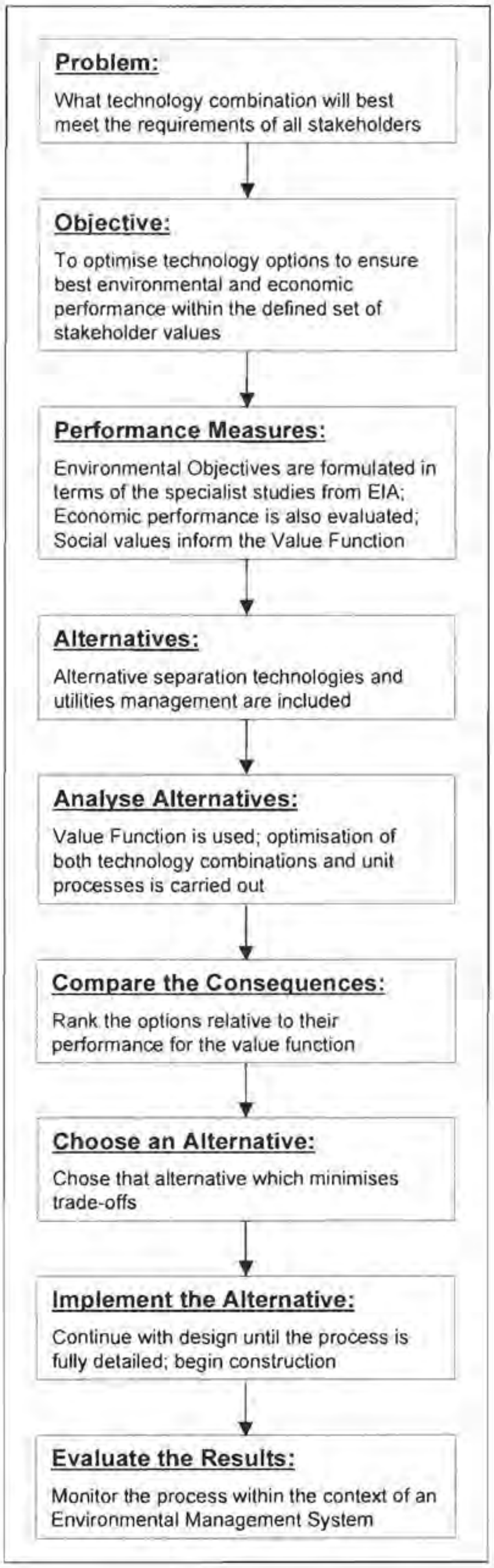
The decisions taken during this last stage of the design process have been structured and are illustrated in Figure 6-6. This structure is common to all of the decisions included in this stage of the design hierarchy (steps 3 to 5 as detailed in Section 6.2.3.1). As was the case for initial design, decisions taken inform the next step in the hierarchy. Again it is possible to construct a decision cycle for these decisions. This cycle included in Figure 6-7.

6.2.4 Conclusions

The decision hierarchy presented in Section 5 has been integrated into the EIA process. Information from the EIA process has been used to augment the information sets used in the design of processes. Three distinct stages in the design hierarchy have been evaluated. Generic decision structures for these stages have been developed. Decision cycles have also been presented for initial and detailed design.

The mathematical formulation for goal programming and value functions can be found in Section 4 of this thesis. The two methodologies chosen, namely goal programming for the pre-screening of options during initial design, and value functions for optimisation in detailed design, have been chosen because of their applicability to these stages of the design hierarchy. However, more complex MCDA tools are available which may have more value in these applications. This is discussed in more detail in Section 7 of this thesis.

The balance of this section contains a case study on designing a Zinc refinery using the three-stage design hierarchy developed above.



Problem:

What technology combination will best meet the requirements of all stakeholders

Objective:

To optimise technology options to ensure best environmental and economic performance within the defined set of stakeholder values

Performance Measures:

Environmental Objectives are formulated in terms of the specialist studies from EIA; Economic performance is also evaluated; Social values inform the Value Function

Alternatives:

Alternative separation technologies and utilities management are included

Analyse Alternatives:

Value Function is used; optimisation of both technology combinations and unit processes is carried out

Compare the Consequences:

Rank the options relative to their performance for the value function

Choose an Alternative:

Chose that alternative which minimises trade-offs

Implement the Alternative:

Continue with design until the process is fully detailed; begin construction

Evaluate the Results:

Monitor the process within the context of an Environmental Management System

Figure 6-6 *Decision Structure for Detailed Design*

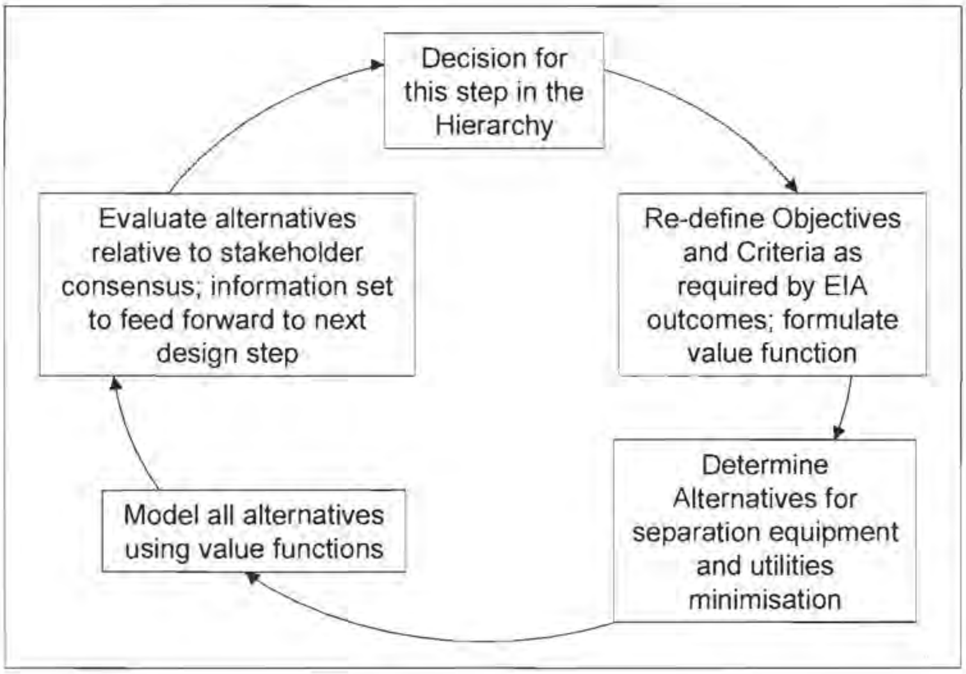


Figure 6-7 *Decision Cycle for Detailed Design*

6.3 *Case Study of Design for the Environment with environmental objectives being informed by social preferences*

This case study has been included to demonstrate the application of goal programming and value functions to the decision making processes of the extended design hierarchy. This case study also demonstrates the integration of EIA into the design process.

6.3.1 The Project

This case study relates to a proposal for a zinc plant to be developed for the toll refining of zinc concentrates. (Toll refining implies that the plant will not be developed for feed material from a single ore body, but rather that the plant is flexible and can be used to refine material from a number of different ore bodies.) The plant will be built in South Africa. The feed to the plant will be zinc concentrate from the initial concentration stage of the base metals industry as illustrated in Appendix 2-6. As the focus of the design is to deliver a plant that is capable of processing material from a number of sources, it is assumed that the feed to the plant is not necessarily drawn from South Africa. These assumptions are based on those used in support of the proposed Zinc plant to be built at Coega in the Eastern Cape in South Africa. In that instance the project proposer was Billiton Pty Ltd. The Coega project was the subject of a detailed and extensive Environmental Impact Assessment (EIA) process (including a significant and thorough Social Scoping exercise) before the decision was made that the plant would not go ahead. All EIA documentation is available from African Environmental Solutions (AES, 1997 and 1998).

The purpose of this case study is to investigate the potential technology that could have been used in the development of the flowsheet for the Coega plant. The social preferences from the EIA will be used to inform the socio-centric information set within the design hierarchy. The question that will be asked is whether there are existing technologies that could have better met the requirements of all the stakeholders than the technology suites that were proposed for the project. Details of these technologies are included in the discussion which follows.

6.3.2 Level A - Background Information

The main motivation for the project is the potential over-supply of electrical energy in South Africa. Currently, there is greater generating capacity than consumption in South Africa. It is only by "moth balling" a number of power stations, and running other stations below their design capacity that the electricity requirements of the country are not exceeded. However, it is not cost effective for the electricity generation company (Eskom) to have capital plant standing idle. For this reason Eskom has been a catalyst in proposing a number of projects which have a significant electrical energy requirement. Most notable among those in the South African minerals industry are:

- the development of the Hillside Aluminium Smelter in Richards Bay (on the north east coast of South Africa) which uses electrical energy in purifying alumina to aluminium. This plant came on stream in July 1996 (DME, 1997)
- the proposed zinc refinery for Coega

It must be noted at this point that aluminium purification has the highest electrical energy requirement of all minerals processing technologies. The next most electrical energy intensive process in minerals processing is the *en masse* electrowinning of metals from an aqueous solution (i.e., electrowinning of base metals; electrowinning of precious metals, while as energy intensive, does not have the same throughput as the base metals industry and thus the total electricity required is not significant). It is for this reason that Eskom approached Gencor Pty Ltd (now Billiton Pty Ltd) with the proposal that Gencor investigate the development of an electrowinning process. As was the case with the aluminium smelter, Eskom offered the company a special arrangement as concerns the cost of the electricity for the plant. The selling price of electricity to the plant would be linked to the selling price of the commodity on the London Metal Exchange (be that commodity aluminium or zinc). In so doing the profits for the process would essentially be fixed irrespective of the selling price of the metal on the open market. To explain this statement, the cost of electricity is the most significant running cost for the proposed technologies. In the case of the aluminium smelter, the cost of electricity represents more than 50% of the running costs for the plant. Electricity and labour costs together represent more than 75% of the running costs of the plant. Thus, if it is possible to fix the labour cost and then to link the cost of electricity to the selling price of the metal, it is possible to essentially "fix" the profit for the process. In so doing the risks associated with the plant are reduced significantly, in spite of potential fluctuations in the market price for the commodity. While the contribution of the cost of electricity in the electrowinning of zinc is not as significant as is the case with aluminium, it is still a significant proportion of the running costs (Green, 1997).

Further background information is that the unemployment rate in the proposed project area was 19% in 1996 (CSS, 1998).

6.3.3 Level B - Project Selection

The arguments included in Section 6.3.2 are, essentially, qualitative. They have been included to give a better understanding of the context in which the zinc refining process is to be developed. From this discussion, as well as the description of the project, it is possible to state that the three main inputs (or raw materials) to the process to be drawn from within South Africa are:

- Electricity
- Labour
- Capital investment

The metals-in-concentrate will be imported.

Within the context of the extended design hierarchy the question that needs to be asked at this point is: "Is developing a zinc plant the best possible use for the raw materials, or would the South African public, economy and environment not be better served if these raw materials were invested in a different project?"

In order to answer this question with any confidence it would be necessary to carry out a Strategic Environment Assessment (SEA) for the area. This assessment would need to investigate other projects that would provide the same number of jobs as the proposed project, while drawing less than or the same amount of electricity and requiring the same or less capital investment. In order to answer this question it would be necessary to include order of magnitude estimations of the number of jobs to be provided as well as the capital investment required for the proposed projects (be they minerals processing based or otherwise). The requirements and preferences of society, both in the area and in South Africa as a whole would need to be included in this decision. It is proposed that the tools of multi-criteria decision analysis be used in this respect. These tools were discussed in Section 4 of this thesis. Two of them will be used in this case study.

For the sake of continuing with this case study it has been assumed that using the raw materials to establish zinc toll refinery in the Eastern Cape region of South Africa was shown to be the best option available.

The decision taken at this stage is:

A process for the toll refining of Zinc will be developed to be placed in the Eastern Cape region of South Africa

The scope of the LCA will include:

The LCA study will include considerations of energy, water usage and reagent addition. The boundary will extend to the "gate" of the process. The functional unit will be one ton of zinc produced The impact categories to be included will be developed within the context of social preferences and may change through the hierarchy.

The objective of the optimisation is:

> *To minimise environmental impact while still delivering a required return on investment within the context of values placed on the impact categories by all stakeholder groupings*

6.3.4 Level 0 - Input Information

All the plant specific information (feed composition, concentrate quality, etc can be found in the EIA for the proposed project (AES, 1997)).

The feed stream to the process will be 440 000 tonnes per year of zinc sulphide concentrate. The feed composition is included in Table 6-2 below. The information on the feed stream has been aggregated according to their deportment in the system, and not according to rigorous definitions. For example, silver and lead are grouped together (as light metals) in spite of the fact that silver is a precious metal and lead is a base metal, as they behave in a similar manner within the plant. This device of grouping metals to simplify calculation is discussed further in Section 6.3.7. The feed stream contains 7% moisture by mass. The required product purity is 99.9%.

Table 6-2 *Initial Estimate of Feed Stream to the Zinc Plant*

Component	**Mass Percent**	**Aggregation**	**Mass Percent**
Zn	52	Zn	52
S	32	S	32
Fe	10	Fe	10
Cu	1	Base Metals	1.3
Cd	0.2		
Ni	0.1		
Ag	0.1	Light Metals	1.9
Pb	1.8		
Hg	0.1	Volatile Metals	0.1
Balance	2.7	Balance	2.7
Total	**100**	**Total**	**100**

The following economic information is available:

- The final process must be paid back in 10 years
- The interest payable on capital is 15%, as might be the case if a preferential loan were available from the government/large industry on the grounds of the project supporting the ends of the RDP. (Prime interest averaged 18% in 1997 (Editors Inc, 1998))
- The inflation rate is variable. Details can be found in Appendix 5-1. A multiplier of 4.7 is derived from the available inflation information (Editors Inc, 1998)
- The plant life will be 40 years

The energy requirements of the process will be met by electricity drawn from the national grid.

6.3.5 Level 1 - Batch versus Continuous

Table 6-3 has been included to give an indication of those technologies which can be operated in continuous mode, and those technologies which are purely batch. For the purpose of design the operation of batch processes will be averaged out over the year of operation and will be modelled within the steady-state mass balance. It is assumed that if it is possible to operate a technology in continuous mode, then this mode is chosen. This decision is based on the scale of the process.

Table 6-3 *Operational Mode of Unit Processes*

Unit Process	Operational Mode
Reactors	
Roast-Leach	Continuous
Roast	Continuous
Pressure Leach	Continuous
Separators	
Solution Purification and Electrowinning	Continuous Purification; Batch Electrowinning
Imperial Smelting Process	Semi-Batch

The decision taken at this stage is:

> *Processes will be operated in continuous mode if at all possible*

6.3.6 Level C - Reactor-Separator Chain

The technologies available for the refining of zinc sulphide ores, broken down into reactors and separators as required by the design hierarchy, are listed below. All possible combinations of these technologies are included in Section 6.3.7 where the potential input-output structures for the process are established. A more complete description of these technologies can be found in Appendix 6-1, Section 6.1.1:

- **Reactors**

Roast-Atmospheric Leach: the kinetics of leaching of any sulphide ore are slow at atmospheric temperatures and pressures. For this reason the ores are first roasted to form oxides, the sulphur being converted to SO_2 and leaving the roaster in the off gases. The solid waste from the leaching process is a complex material containing significant quantities of iron and zinc in different ratios. These ratios depend on leaching conditions and the ratio of zinc to iron in the feed material. The solid wastes from roast-leach circuits are hazardous in nature and require further processing or disposal in a landfill that is able to manage hazardous materials. Technologies for the management of these solid wastes are discussed below.

Pressure Leach: pressure leaching has been developed to overcome the environmental impact associated with roasting sulphide ores. In pressure leaching the unit processes are pressurised and operated at higher temperatures in order that the kinetics of leaching are adequate. The main difference between pressure leaching and the conventional roast-leach process is that the sulphur is reduced in the pressure leach and reports to the output stream as a solid sulphur co-product. The solid waste from this process is similar in nature to that generated by the Roast-Leach process, except in that it will also contain the reduced sulphur.

Roast: the Imperial Smelting Process® (ISP) requires the zinc to be in an oxide form (see below for a discussion of the ISP), thus a roaster on its own has been included as a potential reactor. The solid waste from this process does not leave the system at this point, rather it leaves the separator unit process, the ISP.

Bacterial Leaching: Essentially the bacterial leach operates in the same manner as the Pressure Leach, except that in this case the kinetics of reactions are accelerated by the presence of bacteria which assist in the Fe^{2+} to Fe^{3+} switch. This ionic switch is involved in the leaching of Zn via a complex (and not completely understood) mechanism. However, the bioleaching of zinc has not been developed on an industrial scale as yet. In addition, there is very little information available in the open literature. For these reasons it will not be included in this case study.

- **Separators**

Solution Purification and Electrowinning: Electrowinning is used to recover the zinc from the aqueous leach solution. In order to deliver a product of the required purity it is necessary to first purify the aqueous solution to remove other components which may have been leached such as copper, cadmium, cobalt etc. Iron removal is integrated into the leaching circuit.

Imperial Smelting Process® (ISP): The ISP takes advantage of the different boiling points (or vapour pressures) of the various oxides in the stream from the roaster. It can be used for processing zinc as zinc has a fairly low vapour pressure. Essentially it is a sequential distillation process where metals of different boiling point are separated at different temperatures. The feed under consideration for this process has a number of components which would boil-off before zinc - Arsenic, Lead, Silver, Selenium and Mercury. Halides would also be removed from the feed material before zinc. The solid waste from this process would contain zinc and iron in a less hazardous form than from the Leach unit process (Woollacott and Eric, 1994).

Within the context of the discussion included in Section 2 of this thesis (with respect to determining the alternative technology suites to be included in the development of the flowsheet), the technologies listed above represent both existing technologies and new technologies. The ISP was historically used to purify zinc but few plants of this type have been built in recent years. The Roast-Leach-Electrowin process is the process that is currently most common in the industry. There are different permutations within the leaching circuit, most of which determine the nature of the iron-bearing waste (the ratio of Fe:Zn:O) and thus its potential environmental impact. The purification processes are also present in a number of permutations, a representative (as opposed to exhaustive) number of these have been included in this case study.

Thus the technologies included in the case study are representative of all the technologies available to the industry at present, and determine the value for "p" which was defined in Section 2 as being the total number of unit operations to be included in the flow sheet.

6.3.7 Level 2 - Input-Output Structure

The possible permutations of reactor-separator chains are illustrated on Figure 6-8, which includes an indication of where bioleaching would be placed in the flowsheet were it to be considered. These permutations are modelled according to the methodology developed in Section 2 and extended in Section 4 of this thesis. Assumption sets upon which the operation of unit processes are based are included in Appendix 6-1, Section 6.1.2. These assumption sets are based on averaged industrial performance data. A full reference list is included in Appendix 6-1.

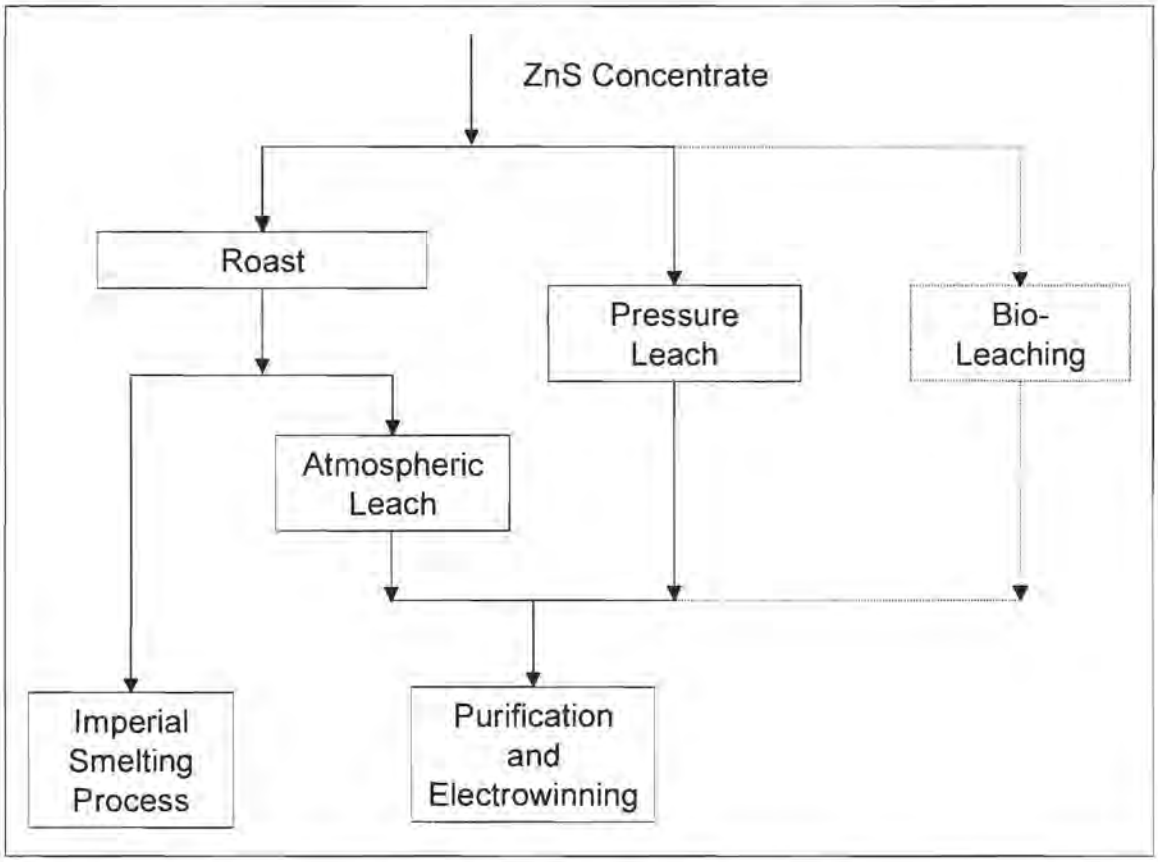


Figure 6-8 *Technology Alternatives for the Purification of Zinc*

As with the gold case study included in Section 5, the stream splits between these unit operations are allowed to change in order that the "best" combination of technologies can be chosen.

6.3.7.1 Aggregation of initial information

The information on the feed stream as included in Table 6-2 has been aggregated into a number of generic groupings. The reason for grouping the information in this manner is to keep the information set required at this point of the design hierarchy as small as possible while still supporting the requisite decision, i.e., which combination of reactors-separators should be carried forward to the next stage in the design hierarchy. In order to make this decision it is necessary to trace where the major components in the stream are going within the flowsheet. However, tracing each component individually will require a relatively detailed information set. A number of the metals behave in a fairly similar manner within the process - they can be seen to "follow" each other. An example here is that the volatile metals such as mercury and selenium will behave in a similar manner and the majority of these compounds will report to the same process streams. While a term like "majority" may not suffice for more detailed design decisions, it is sufficient at this point to assume that, for example, all the base metals behave in the same manner. Thus, in order to keep the information required for modelling to a minimum, a number of elements have been aggregated into categories of elements which behave in a similar manner. In so doing, only a single piece of information is required to model the behaviour of lead and silver in the leaching circuit, as opposed to having to evaluate different information for each element individually. This is significant in that it limits the amount of information required to model the process. The amount of information required for mass balance closure is detailed in Section 2.

6.3.7.2 Objectives, Criteria and Attributes

In order to determine which is the best combination of technologies it is necessary to define the objectives, criteria, and attributes whereby these technologies will be compared.

Section 6.3.4 contains the economic assumptions that will be used to evaluate the **economic** objective function. The return on investment required is at least a 20% hurdle rate as discussed in Section 5 of this thesis. Thus the economic objective is that a minimum hurdle rate of 20% be achieved. The criterion to be used to determine whether this objective has been met is the profit from the process over its 40 year design life. As this profit is directly measurable it is not necessary to establish attributes for this criterion.

The **environmental** objective is that environmental impact be minimised. However, as the discussion in the conclusions to Section 5 stated, these impacts need to be minimised within the context of where the process is to be placed, both with respect to physical location, and with respect to society. Societal preferences will inform the environmental objective. The criteria used to determine whether the environmental objectives have been met have been established according to the work of Meittinen and Hamalainen (1997). Their figure was included in Section 1 of this thesis and has been reproduced on Figure 6-9 for convenience.

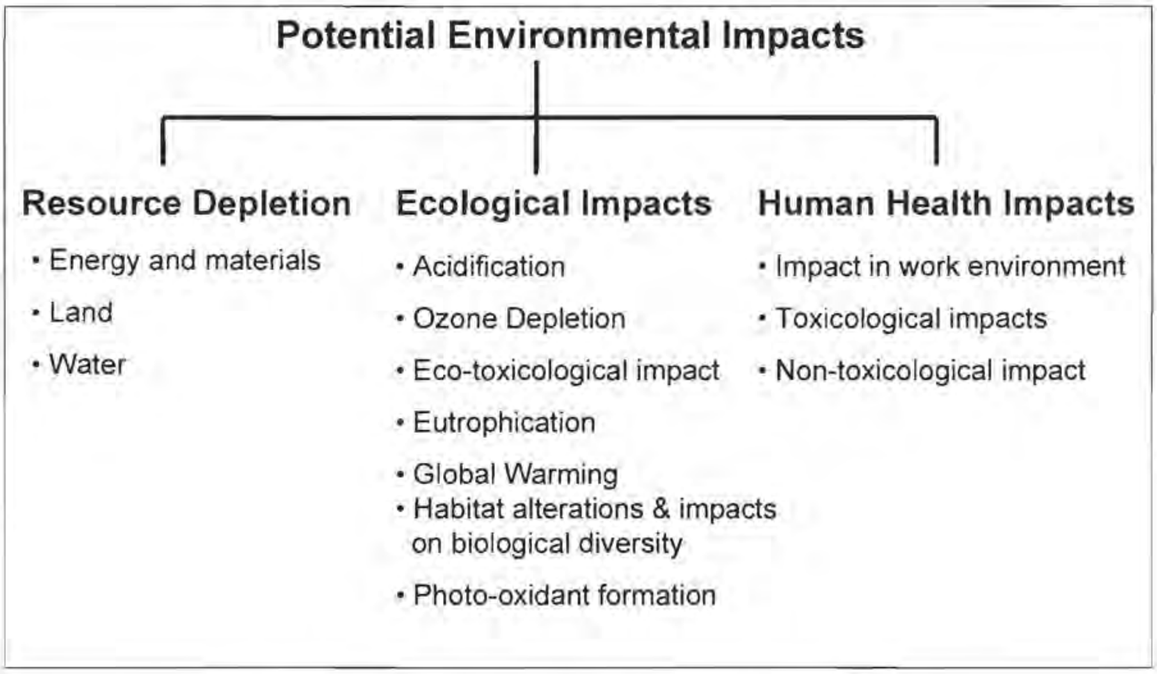


Figure 6-9 *Impact Categories (Meittinen and Hamalainen, 1997)*

From this figure, the criteria to be used are those of resource depletion, ecological impact and human health impacts. LCA is used to quantify the attributes which relates to these criteria - where an attribute is the measurable quantity that is used to determine how well a criterion has been met (see the discussion in Section 4.1.2). The attributes to be included in this study are limited by the information available as well as the applicability of the attribute to the technology suites under investigation. The attributes to be used are included in Table 6-4 below:

Table 6-4 *Criteria and Attributes included in the Case Study*

Criteria	Attributes	Units
Resource Depletion	Landfill Volume	m^3
	Resource Depletion	$year^{-1}$
	Water Consumption	l
Ecological Impacts	Acidification	kg SO_2
	Total Eco-toxicity	m^3
	Greenhouse Emissions	kg CO_2
Human Health Impacts	Human Toxicity	kg/kg
Economic Performance	Cumulative profit	ZAR

On first appearances this suggests that environmental considerations out-weigh economic considerations by three to one as there are three environmental criteria (resource depletion, ecological impacts and human health impacts) and only one economic criterion (economic performance). However this situation can be overcome by using different normalisation regimes. Two different regimes are illustrated in Figure 6-10.

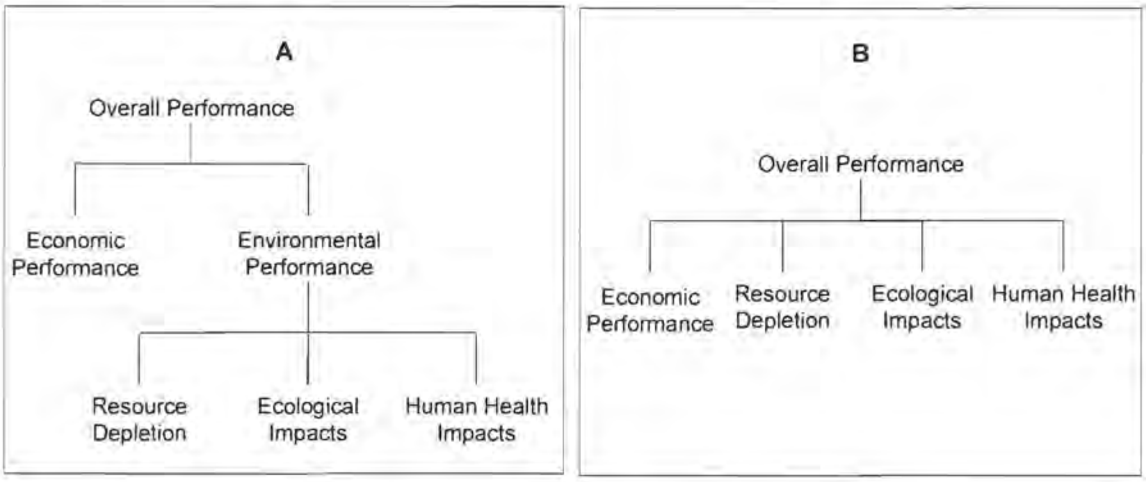


Figure 6-10 *Value Hierachies*

Part A if this figure demonstrates a situation where there is one environmental category and one economic category on the same level. This requires the sub-categories of environmental criteria to be valued relative to each other before they are valued relative to economic performance. Part B of the figure shows a situation where there are three environmental criteria and only one economic criteria. The choice of the correct formulation of this values hierarchy is not a trivial exercise and is linked to the ellicitation of preferences as discussed later in this section. In this case study the criteria have been manipulated as according to the situation illustrated in Part B of Figure 6-10. Further discussion of this topic is beyond the scope of this thesis, reference is made to the work of Basson (1999) for further development of these concepts.

6.3.7.3 Setting the Goals

As was discussed in Section 6.2, goal programming will be used in the initial design stages of the hierarchy. It is thus necessary to determine what goals are to be set for each of the criteria/attributes identified above.

As was also stated in Section 6.2, the legislative framework within which the project will be placed can be used to inform the socio-centric information set at this point in the design. Thus legal limits can be used to establish the goals. The goals set for each of the attributes/criteria using legislation are described in Table 6-5 below.

Table 6-5 *Examples of Goals for the attributes and criteria*

Criteria/Attributes	Goal
Profit	20% return on investment
Minerals depletion	90% of the industrial average
Land use	90% of the industrial average
Water use	90 % of the industrial average
Acidification	90% of the legal limit
Eco-toxicity	90% of the legal limit
Global Warming	90% of the legal limit
Toxicological Impacts	90% of the legal limit

Where the legal limit for an impact category is established using LCA equivalency factors to link legal limits on stream components to legal limits on the impact categories. The industrial average can been evaluated using the models for zinc refining in South Africa as included in Appendix 2-6.

However, there are no legal limits for either water quality or air quality in South Africa at present as the legislation is under review. Legal limits have, to date, been in the form of guidelines as opposed to legislated limits. Appendix 6-2 contains a more detailed review of environmental control legislation in South Africa with respect to water and air quality (DEAT, 1998).

It is for this reason that a different method for setting goals has been determined. It has been decided that, in order to deliver the technology suite that has the "best" possible performance the goals to use are those which represent the minimum possible environmental impact (or maximum return on investment) for the technology suites under examination. Essentially what this requires is to calculate the range of contributions to each environmental impact category, as well as the profit range, possible from the technology permutations represented by Figure 6-8. In order to explain the calculation technique more fully Figure 6-8 has been re-worked to produce Figure 6-11 which highlights the streams splits that can be manipulated in the flowsheet. This flowsheet was then modelled. A complete list of assumptions for this model can be found in Appendix 6-1, Section 6.1.2. This appendix contains a complete reference list.

In order to determine the maximum value of, for example, acidification possible from this technology permutation, the modelled stream splits A and B were allowed to vary and an optimisation was carried out to maximise acidification. This is the value recorded as the maximum for Acidification in Table 6-6. A similar optimisation was conducted to determine the maximum and minimum values for each of the attributes. These ranges are included in Table 6-6 below. An indication of the technology combinations (resulting from the values of stream splits A and B) which result in these values is also included in this table. (Units are as per Table 6-4).

This table includes an indication of how the goals are calculated using the ranges. In the example it is assumed that the "best" performance is defined by that selection of technology which comes closest to achieving a 20% back off from the best possible performance. In this case the best performance is the lower limit of the range (i.e., the aim is to minimise environmental impact and minimise loss). Thus the goal is defined by adding 20% of the range between the upper and lower limits to the lowest value. It is recognised that this is an arbitrary value and is used for illustrative purposes only.

These goals have significant order of magnitude differences. For this reason the attribute values as well as the goals are scaled according to the methodology presented in Section 5 of this thesis. The sensitivity of the preferred solution (the suite of technologies which comes closest to achieving the 80% of best performance for each attribute) to the percentage of best performance chosen was investigated and is discussed in Section 6.3.7.6 below.

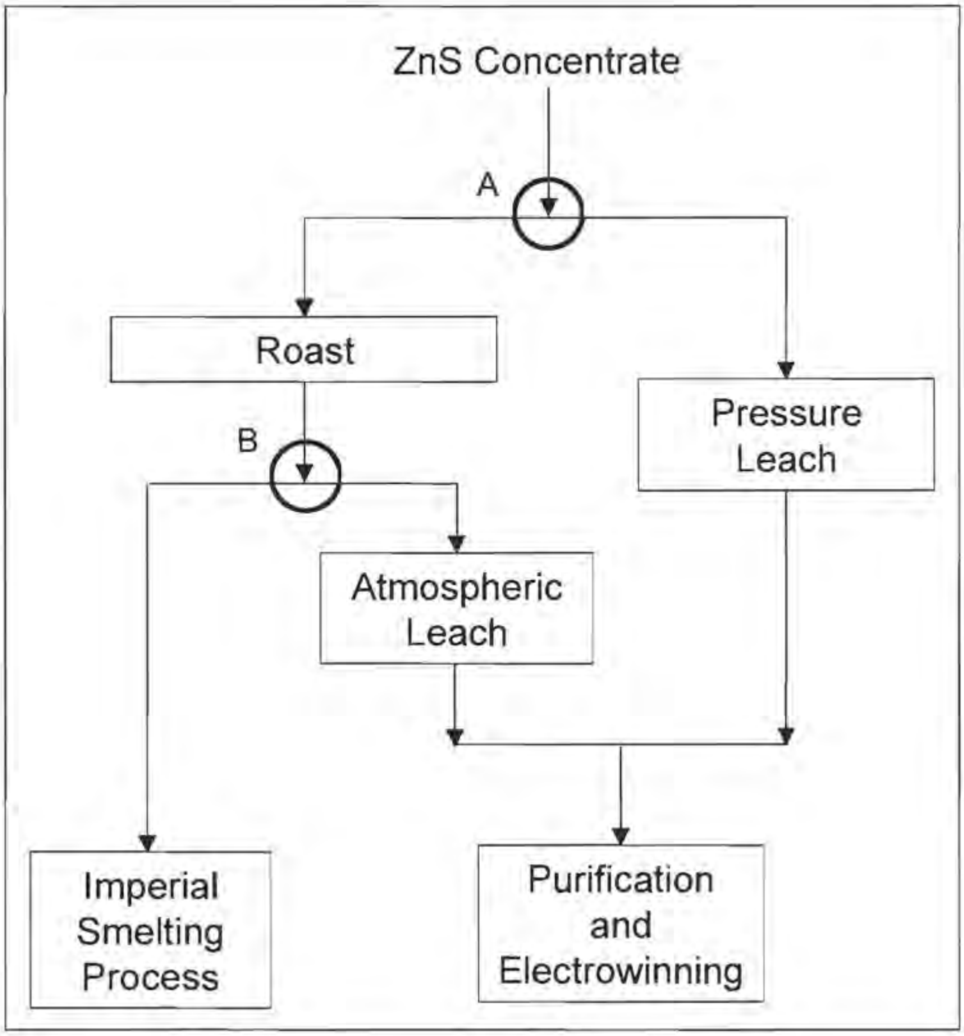


Figure 6-11 *Technology Permutations with Stream Splits highlighted*

Table 6-6 *Range of Values for Attributes - Design Step 2*

Attribute	Maximum /ton Zn produced	Technology Selection	Minimum /ton Zn produced	Technology Selection	Range	80 % of range	Goal
Landfill Volume	5.75	Pressure Leach, Electrowin	5.23	Roast, ISP	0.514	0.412	5.34
Water Consumption	153	Roast, Leach, Electrowin	0.004	Pressure Leach, Electrowin	153	123	30.7
Resource Depletion	0.020	Pressure Leach, Electrowin	0.008	Roast, ISP	0.012	0.009	0.010
Acidification	0.403	Roast, ISP	0.000	Pressure Leach, Electrowin	0.403	0.323	0.081
Total Eco-toxicity	1.40	Roast, Leach Electrowin	0.391	Pressure Leach, Electrowin	1.01	0.806	0.593
Greenhouse	3.41	Roast, ISP	0.000	Pressure Leach, Electrowin	3.41	2.73	0.682
Human Toxicity	0.043	Roast, Leach, Electrowin	0.014	Roast, ISP	0.028	0.022	0.020
Cumulative Profit	462	20% to Roast, Leach; 80% to Pressure Leach, Electrowin	-11800.00	Roast, ISP	-12600.00	9810.00	-22400.00

Table 6-6 also shows that different technology suites give rise to specific impacts categories. This implies that the boundaries to the solution space are defined by single technology suites as opposed to a combination of technologies. In order for the optimal operation point to fall within this solution space the preferred solution will need to be a combination of technologies. Only one of the ranges is defined by a combination of technologies (the maximum cumulative loss), this is due to the high cost of large volume autoclaves and Imperial Smelting Furnaces.

6.3.7.4 Normalising the Goals and Attributes

The objectives of this optimisation are to minimise environmental impact while maximising economic benefit. The best value for environmental performance is the smallest possible value of each attribute, while the best possible value for the economic objective is the largest value of the single attribute used to define this objective.

As was the case with the previous design, there are significant order of magnitude differences between the attribute values. It is necessary to normalise these attribute ranges for goal programming so that the differences calculated between the attribute value and the goal has an equivalent meaning between the attributes (i.e., this difference must not be skewed by the magnitude of the attribute value). Goals were determined with respect to ton of Zinc produced. The range of values for each attribute was then determined. In order to eliminate the order of magnitude differences that still remained the goals were scaled from 0 (representing the best value for the environmental attributes, and the worst value for the economic attribute) to 1. Evaluating the goals on this scale then reduces the chosen value of 80% of best possible performance to a value of 0.2 for the environmental attributes, and 0.8 for the economic attribute.

6.3.7.5 Preferred Solution

The flowsheet as detailed in Figure 6-8 was modelled in *MS Excel®*. Details on the assumptions sets within this model can be found in Appendix 6-1, Section 6.1.2. There are two different stream splits which can be manipulated. These stream splits were changed in order to deliver the preferred solution, i.e., the combination of technologies which came closest to achieving 80% of best performance for the system.

The result of this optimisation is included in Table 6-7 below. This table shows that the preferred solution is a combination of technologies. The information presented in this table is the absolute (as opposed to the scaled) values for each of the attributes. A positive difference from the goal infers that the performance of the technology selection is better than that defined by the goal.

Table 6-7 *Preferred Technology Selection*

Preferred Technology Option	44% of feed to Roaster, 56% of feed to Pressure Leach, Electrowin; 100% of Roaster output to Imperial Smelter		
Sum of Differences (Goal Programming)	2.53		
	Attribute Values (normalised with respect to ton Zn Product)	**Goal**	**Difference from Goal**
Landfill Volume	5.52	5.65	0.124
Water Consumption	2690	123	-2560.27
Resource Depletion	0.583	0.017	-0.566
Acidification	7.11	0.323	-6.79
Eco-toxicity	31.2	1.20	-30.0
Greenhouse	60.1	2.73	-57.4
Human Toxicity	1.18	0.037	-1.14
Cumulative Profit	3900	-1990	5890

Setting the economic goal to be -1990 is discussed in Section 6.3.8.2, Methodological Observations.

For comparison, the performance of discrete technology options has also been included. This illustrates the improvement in performance when technologies are combined. This is a summary of the results included in Appendix 6-1, Section 6.1.3.

Table 6-8 *Preferred Solution, and Comparison with Discrete Technology Suites*

Technology Option	**Sum of Differences** (Goal Programming)
44% of feed to Roaster, 56% of feed to Pressure Leach, Electrowin; 100% of Roaster output to Imperial Smelter	2.53
Roast, Imperial Smelter	5.19
Roast, Leach, Electrowin	5.02
Pressure Leach, Electrowin	4.07

These results bear out the observation made above that separate technology suites define the limits of performance for the attributes. By confining the solution to a single technology suite, worst performance is assured in at least one of the attributes. Within the definition of best performance used, a combination of technologies is far superior than choosing a single process route. Further discussion of these results can be found in Section 6.6.7.7 below.

6.3.7.6 Sensitivity of Solution to Goals Set

The sensitivity of the solution to changing the goals for each attribute was investigated. Table 6-9 contains a summary of these results. A complete set of results can be found in Appendix 6-1, Section 6.1.3. As was stated in Section 5 of this thesis, the decision maker will only select a technology combination which is profitable. For this reason the optimisation was constrained to deliver solutions which delivered a profit over the 40 year life of plant (i.e., profit > 0).

With reference to the stream splits identified in Figure 6-11, this analysis shows that the Roast-Leach-Electrowin flow route becomes part of the preferred combinations of technologies only when the goals are set relatively low, i.e., below 60% of best performance.

Table 6-9 *Change in Preferred Technology for Changing Goals*

Goals	**Preferred Technology Option**			
	Stream Split A		**Stream Split B**	
	Feed to Roaster	Feed to Pressure Leach	From Roaster to ISP	From Roaster to Leach
Best Performance	0.21	0.79	1.0	0.00
80% of Best Performance	0.44	0.56	1.0	0.00
60% of Best Performance	0.46	0.54	1.0	0.00
40% of Best Performance	0.46	0.54	0.81	0.19
20% of Best Performance	0.46	0.54	0.38	0.62
5% of Best Performance	0.46	0.54	0.06	0.94

In addition to this observation and with reference to Table 6-6, the Roast-Leach-Electrowin technology presents the worst values in three of the attributes, and does not present any of the best values for any of the attributes. This implies that, no matter what values are given to the attributes (in this optimisation all the attributes are valued equally), one of the other technology suites would dominate.

Thus, the decision taken at this point in the hierarchy is that:

> *The permutation set will be limited to Pressure Leach-Electrowin in combination with Roast-ISP*

It is interesting to note that the technology suite preferred by the Coega Zinc Plant project proponent was the Roast-Leach-Electrowin process. This demonstrates that including considerations of environmental and social performance in design decisions can change the outcome of the design process.

6.3.7.7 Shortcomings of Goal Programming

As was stated in Section 4.1.3, one of the main failings of Goal Programming is that it allows the value for the attribute to lie on either side of the goal. This means that the attribute value may be better or worse than the desired value (or goal) and this has no effect on the preferred solution. In other words a technology combination which performs better than the goal is not favoured over one which performs worse than the goal by the same extent. A complete listing of the changes in attribute value relative to the goal for that attribute can be found in Appendix 6-1, Section 6.1.3.

The case of changing the goals has been chosen to illustrate this point. It is valid to compare the signs (or the direction of change) of the difference of the attribute value from the goal. The results are included in Figure 6-12. The differences have been evaluated as a percentage of the required goal in order to overcome order of magnitude differences. In this case a positive value indicates that the solution performs better than the chosen goal.

These results illustrate that, while the solution arrived at is the best technology choice for the goals which have been set, this optimum is not determined relative to whether the attribute is less than or greater than the value of the goal. It is possible to find a preferred solution that is greater than the goal in one attribute, when a preferred solution relative to a different goal is less than the goal in the same attribute (or impact category).

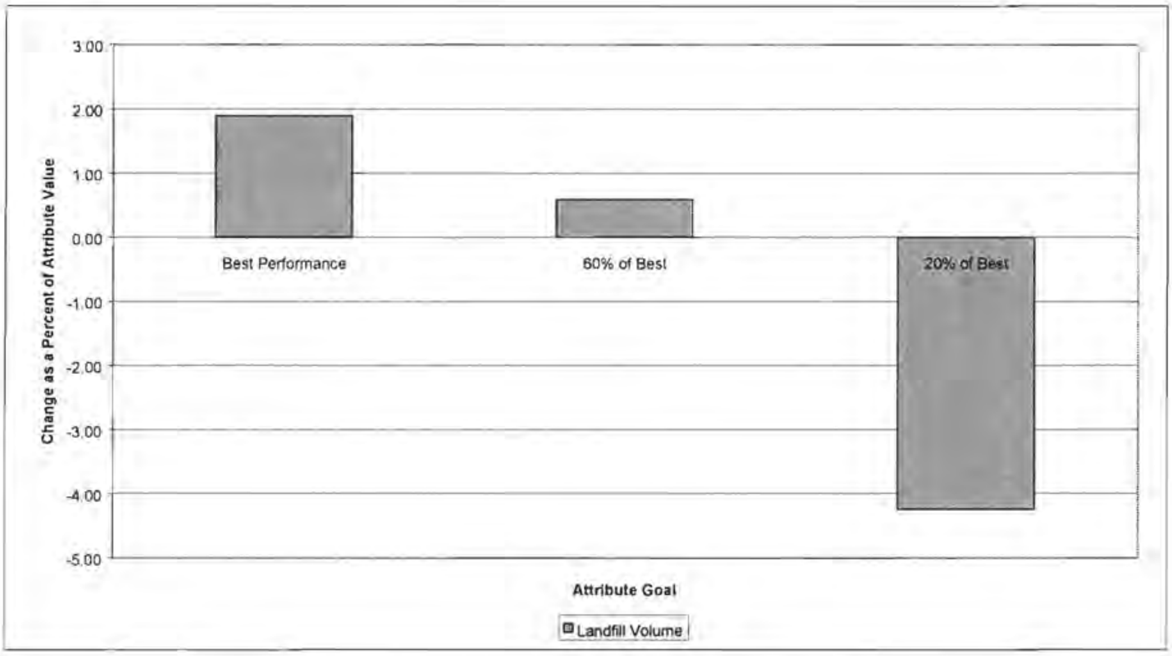


Figure 6-12 *Comparison of Distance of Attribute from Goal*

However, goal programming requires a relatively small amount of information, in undertaking the goal programming no more information was required than was required to develop the mass balance model and the economic performance. Thus, while the shortcomings of Goal Programming are kept in mind, it will be used as the MCDA tool in the next stage of the design hierarchy.

6.3.7.8 Robustness of Solution

As has already been stated, the optimisation of the goal programming equation set was carried out using the "Solver" utility in *MS Excel®*. A complete description of the optimisation algorithm is not available. However, the robustness of the solution was tested to determine whether the solution found by "Solver" was a global optimum for the series of equations, or whether "Solver" was finding a local minimum. This was tested by changing the starting points for the optimisation and determining whether the solution changed for these different initial guesses. It was found that the initial guess did not affect the preferred solution.

The solution space for the equation set is relatively constrained in that:

- It is constrained to ensure mass balance closure
- The stream splits are constrained to fall between 0 and 1

These constraints together define the solution space explicitly. No attempt has been made to determine the shape of the solution space. The solution appears unique and there are no local minima.

6.3.8 Level 3 - Recycle Structure leading to the Environmental Impact Assessment

The decision taken in the previous stage reduces the number of technology options to be included at this point in the hierarchy. The technology permutations to be evaluated at this stage of the hierarchy are illustrated in Figure 6-13.

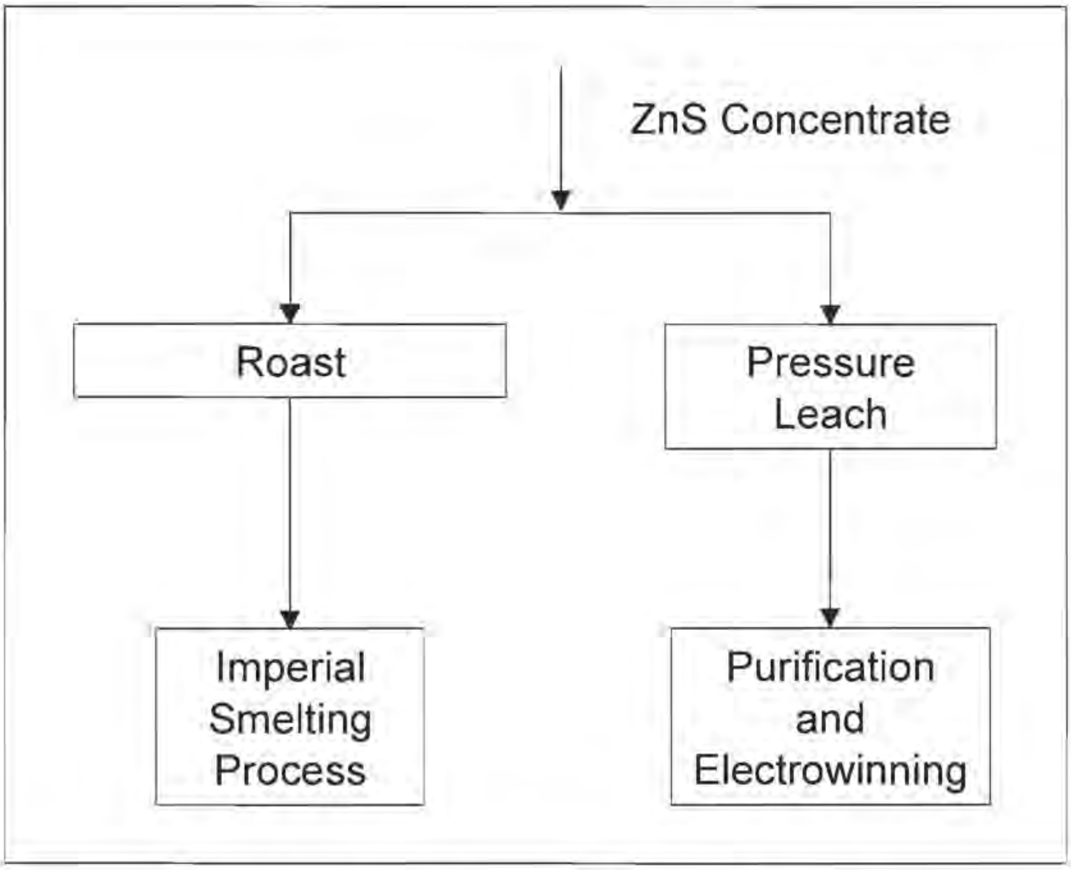


Figure 6-13 *Technology Permutations for Step 3 of the Hierarchy*

It is at this point that the recycle structures need to be determined. Waste management technologies must also be considered according to the proposed design hierarchy, in that they fall within the potential recycle structure. Technology groups for waste management at the zinc plant are listed below

Waste Management Technologies

Sulphur Scrubbing and Sulphuric Acid Manufacture: These technologies are included to manage the gaseous waste stream from the Roast unit process

Waelz Kiln and other Thermal treatments: These processes are included after the leaching circuits to render the solid waste from the leach circuits less hazardous in nature; they do not necessarily render the solid wastes inert. This case study has been simplified by modelling only the Waelz kiln. The inclusion of alternative thermal treatment processes (such as Ausmelt and CSIROSmelt technologies) is possible. However, in the intention of this case study is to demonstrate the application of the design hierarchy developed, not to provide a definitive flowsheet for Zinc Refining. A more detailed study would include these alternative thermal treatment technologies.

Impoundment and disposal to landfill: These are alternative solutions to the management of solid wastes from the leach circuits

Sewage treatment plants: These are present in a number of technology permutations and are included for the management of aqueous wastes from the processes. In this work they are defined to fall under utilities management and are included in the final step in the hierarchy.

The integration of the potential recycle structures into the technology permutations is illustrated in Figure 6-14. This structure forms the basis of the model developed for stage three of the hierarchy. For completeness, the recycle permutations of the Roast-Leach-Electrowin process route are included in Appendix 6-1, Section 6.1.4. These recycle permutations are far more complex than those included in Figure 6-14.

As was discussed in Section 4 of this thesis, the recycle of water streams from an effluent treatment plant is not included in this stage of the design hierarchy. This recycle is seen as the management of a utility and is included in the last step of the decision hierarchy. For this reason the recycling of water from the effluent treatment plant has not been included in Figure 6-14.

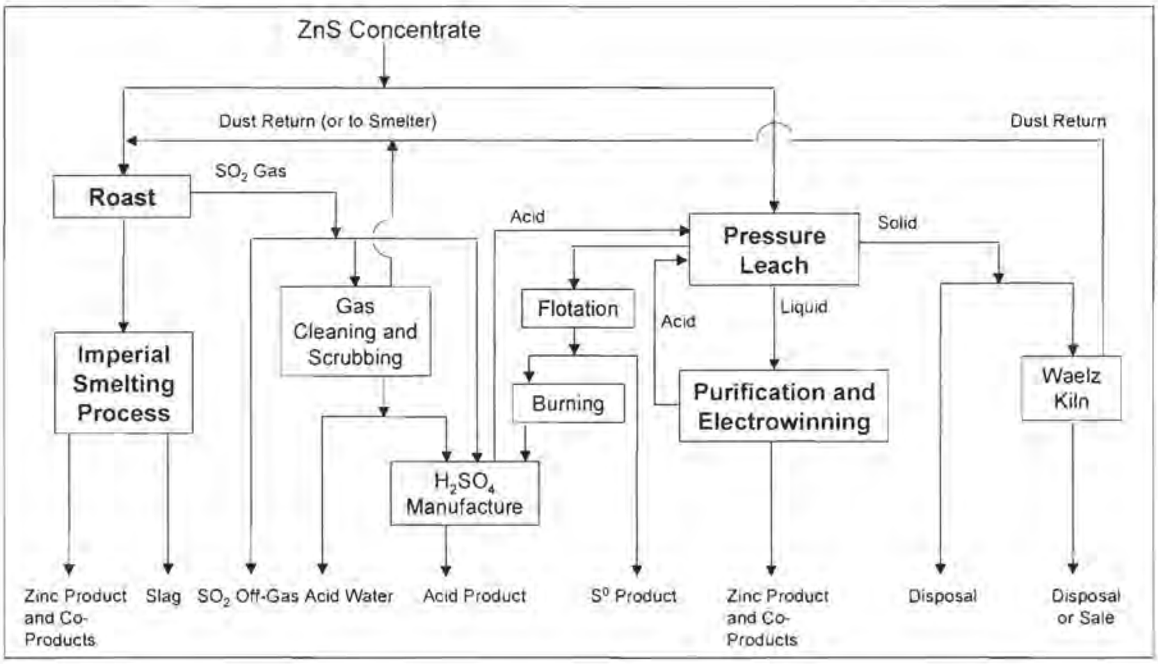


Figure 6-14 *Recycle Permutations*

It was decided to evaluate the Waelz Kiln thermal treatment only as this is the technology which is most common in the industry. While it is acknowledged that there are significant advances in the thermal treatment of zinc process wastes at present, for example:

- the Mintek DC-arc furnace developed in South Africa
- the Ausmelt technology developed by the CSIRO in Australia

there is not sufficient information available on these processes as yet. A discussion on the thermal treatment of wastes and their significance within processing as well as waste management in the minerals industry is included in Section 7 of this thesis.

The recycle of dust from the Waelz Kiln and the Imperial Smelter has not been modelled as the mass flow of the stream is insignificant and the inclusion of this recycle does not affect the outcome of the model. This was evaluated using the model developed for the South African Zinc industry as discussed in Section 2 of this thesis and included in Appendix 2-6. The recycle of sulphur present in the roaster off-gases from the roaster to the autoclave in the form of an acid product from the acid plant is also relatively small. It was not necessary to include this recycle in the model for the same reason.

The recycle of acid from the electrowinning process back into the autoclave can be viewed as an internal recycle to the system. This implies that none of the attributes will change if this recycle were to be included. There are a number of reasons for making this statement:

- The cost of the autoclave is defined to be a function of the feed to the system (in this case the portion of the stream which does not report to the roaster) as this is the only information which was available. Thus the recycle has already been accounted for in the cost calculation.
- There is no purge from the recycle stream. In actual plants there is a purge stream from within this recycle to prevent the build up of manganese within the system. This purge would then cross the process boundary and report to the effluent treatment plant. The nature and quantity of the purge stream would be dependent on the amount of manganese in the feed stream. It would be necessary to calculate the recycle stream to evaluate the nature of the purge stream. However, as a simplifying assumption, manganese was not included in the stream components as it constitutes less than 0.1% of the feed stream, thus it is not possible to calculate this purge stream.
- None of the elements in the impact matrices described in Section 4 of this thesis are a function of the mass flow rate through the autoclave in this specific case.

As this case study serves to demonstrate the methodology being developed - as opposed to developing a complete and detailed process design - calculating the recycle in detail is not necessary as it will not effect the results obtained. Thus a calculation of the acid recycle was not necessary. The calculation of recycle streams did form a part of the information evaluated for the South African minerals industry as described in Section 2 of this thesis. In these cases the recycles were calculated by iteration until mass balance closure was achieved.

While it is acknowledged that it is necessary to have a mercury removal step between the roaster and the production of sulphuric acid, the processes available for this purification step are proprietry. Thus it is not possible to gather any information on the costing of the equipment. For this reason the mercury removal step has not been costed. Similarly, as it has not been possible to gather information for costing the sulphur burner, this unit operation has also not been costed.

6.3.8.1 Equivalency Factors

The equivalency factors in LCA do not make sufficient provision for minerals and metals with different bio-availabilities, as was noted in Section 3 of this thesis. The metals in the solid waste from the pressure leach process are potentially more mobile than those in the product from the Waelz Kiln due to their thermodynamic state. The energy added to the Waelz Kiln is provided with the express intention of rendering the metals immobile. This discussion forms part of the recommendations section of this thesis (Section 7). Suffice it to say at this point, that, as the LCA equivalency factors do not make provision for this differentiation, it was decided to set the equivalency factors for metals in the output from the Walelz Kiln to zero. This is equivalent to making the assumption that the Waelz Kiln renders the metals immobile. While this is not strictly true (AES, 1996), is it the best assumption to make at this point. The same assumption is made for metals in the slag from the ISP. It is assumed that the solid wastes from both the Waelz Kiln and the ISP are disposed of to landfill.

6.3.8.2 Setting the Goals

As was the case with the previous design step, it was necessary to determine the potential range of values for each of the attributes. Table 6-10 contains the ranges for each of the attributes as determined by either maximising or minimising the attributes in isolation.

Table 6-10 *Range of Attribute Values for Design Step 3*

Attribute	**Maximum** /ton Zn produced	**Technology Selection**	**Minimum** /ton Zn produced	**Technology Selection**
Landfill Volume	5.47	Pressure Leach; Sulphur to product; Solid waste to Waelz Kiln; Gas from Waelz kiln to acid Plant	5.06	ISP; Solid Waste to Landfill; Off-gas to Atmosphere
Water Consumption	4230	ISP; Solid waste to Landfill; Roaster off-gas to Gas Scrubber; 50% of Scrubber water to Acid Plant	0.000	ISP; Solid Waste to Landfill; Off-gas to Atmosphere
Resource Depletion	0.068	Pressure Leach; Solid waste to Landfill; Sulphur to product	0.060	ISP; Solid Waste to Landfill; Off-gas to Atmosphere
Acidification	0.436	ISP; Solid waste to Landfill; Roaster off-gas to Atmosphere	0.124	ISP; Solid Waste to Landfill; Off-gas to Acid Plant
Eco-toxicity	0.247	ISP; Solid waste to Landfill; Roaster off-gas to Acid Plant	0.159	ISP; Solid Waste to Landfill; Off-gas to Atmosphere
Greenhouse	3.41	ISP; Solid waste to Landfill; Roaster off-gas to Atmosphere	0.287	Pressure Leach; Solid waste to Waelz Kiln; Off-gas to Atmosphere
Human Toxicity	0.042	Pressure Leach; Solid waste to Landfill; Sulphur to product	0.009	ISP; Solid waste to Landfill; Off-gas to Atmosphere
Cumulative Profit	250	34% of Feed to ISP, 66% to Pressure Leach; Solid waste from Pressure Leach to Waelz Kiln; Off-gas to atmosphere	-11700	14% of feed to ISP, 86% to Pressure Leach; Solid waste to Waelz Kiln; 8% of off-gas to Gas Scrubber, 92% of gas to atmosphere; Water from gas scrubber to Acid Plant; Sulphur to Sulphur burning and Acid Plant

As was the case with the previous design step, the best and worst possible performances with respect to individual criteria (with the exception of the economic criterion) are defined by a single technology suite. This suggests that the technology combination which represents the point of least trade-off across all attributes will be a combination of the discrete technology options.

The goals were set as for the previous step of the hierarchy, i.e., they were set to represent 80% of best possible performance for the available technologies. However, it is at this stage of the design hierarchy that the technology to be taken forward to the EIA will be determined. For this reason it is necessary to ensure that the economic performance of the preferred solution is adequate. As has been stated, the decision maker in this case will only allow the project to go ahead if it is profitable. Within this context it was decided to evaluate the difference between articulating the economic objective in different ways. Three different approaches to establishing the goal for the economic attribute were evaluated:

- Setting the goal to be 80% of best performance which is consistent with the goals set for the other attributes.
- Setting the goal to represent a return on investment equal to the required hurdle rate of 20%, this is equivalent to setting a goal of 97% of best possible performance
- Constraining the solution of the optimisation to deliver a minimum of 20% return on investment (in this case the economic goal is removed and replaced by a constraint on the optimisation)

A complete set of results from this investigation is included in Appendix 6-1, Section 6.1.5. A summary of the results, showing only the points of difference in technology combinations for each of the cases identified above is included in Table 6-11 below. This table demonstrates that changing the goal for the economic attribute does affect the outcome of the optimisation.

Table 6-11 *Comparison of Technology Combinations for changing Economic Goals*

Preferred Solution	**Split of Feed**		**Split of Off-gases**			**Split of Sulphur**	
	Roaster	Press. Leach	Atmosphere	Scrubbing	Acid Plant	Product	Acid Plant
Constrained to Hurdle Rate of 20%	0.46	0.54	0.71	0.28	0.01	0.33	0.67
Economic Goal = 20% Hurdle Rate	0.46	0.54	0.71	0.28	0.01	0.33	0.67
Economic Goal is 80% of Best Performance*	0.64	0.36	0.54	0.19	0.27	0.53	0.47

The solution for the case where the economic goal was set at 80% of best performance represents a profitability of 0.7% for the forty year life of plant. This will not be acceptable to the decision maker. The economic performance of the other two preferred solutions would be considered adequate.

Setting a goal for an attribute is different from constraining the solution. If the hurdle rate is set as a goal, the solution is allowed to be either bigger or smaller than the goal, while constraining the solution requires that the solution be bigger than the constrained value. Within the context of goal programming such a constraint would serve to limit the potential to trade-off between the various attributes as any constraint removes a section of the solution space. This was investigated for the attribute values obtained for the first two sets of solutions listed in Table 6-11 by evaluating the sum of the absolute value of the differences from the goal for each of these cases. The findings are summarised in Table 6-12. These results demonstrate that there were larger trade-offs made in the case of the constrained solution.

Table 6-12 *Sum of Differences in Attribute Values*

Constrained Solution	Goal = 20% Hurdle Rate
6.79	6.48

In conclusion, it is recognised that the decision maker will not accept a solution that represents an unprofitable combination of technologies. It has been demonstrated that constraining the solution for one of the attributes leads to greater trade-offs being made in the other attributes. In order to include both of these emphases it was decided that the goal for the economic attribute would be set at a 20% hurdle rate (or 97% of the potential range of values) and constrained to be above the minimum return on investment required by the decision maker. It was decided that this minimum return on investment would be set at 10%. This implies that, while the decision maker would prefer a 20% return on investment from the project, they are willing to decrease this to 10% in order to meet the environmental requirements for the project - be these requirements legislative or otherwise.

6.3.8.3 Results of the Optimisation

The technology combination which resulted in the smallest sum of differences relative to the set of goals already described is illustrated in Figure 6-15. A complete information set for this solution can be found in Appendix 6-1, Section 6.1.5.

This is an interesting result for a number of reasons:

- The combination of roaster and pressure leach is very similar to that achieved in the previous design step; 46% of the feed reports to the roaster in this solution as opposed to the 44% of the feed reporting to the roaster in the previous design step
- Acid production is not driven by the SO_2 off-gases produced but rather by the burning of the sulphur product from the pressure leach. This is a manifestation of limiting the performance of the system to being economically viable.
- The bulk of the off-gases report to the atmosphere which is unlikely to be acceptable to society. For this reason the sensitivity of the solution to changing the preference (or weight) placed on this attribute is investigated in Section 6.3.8.5 below.

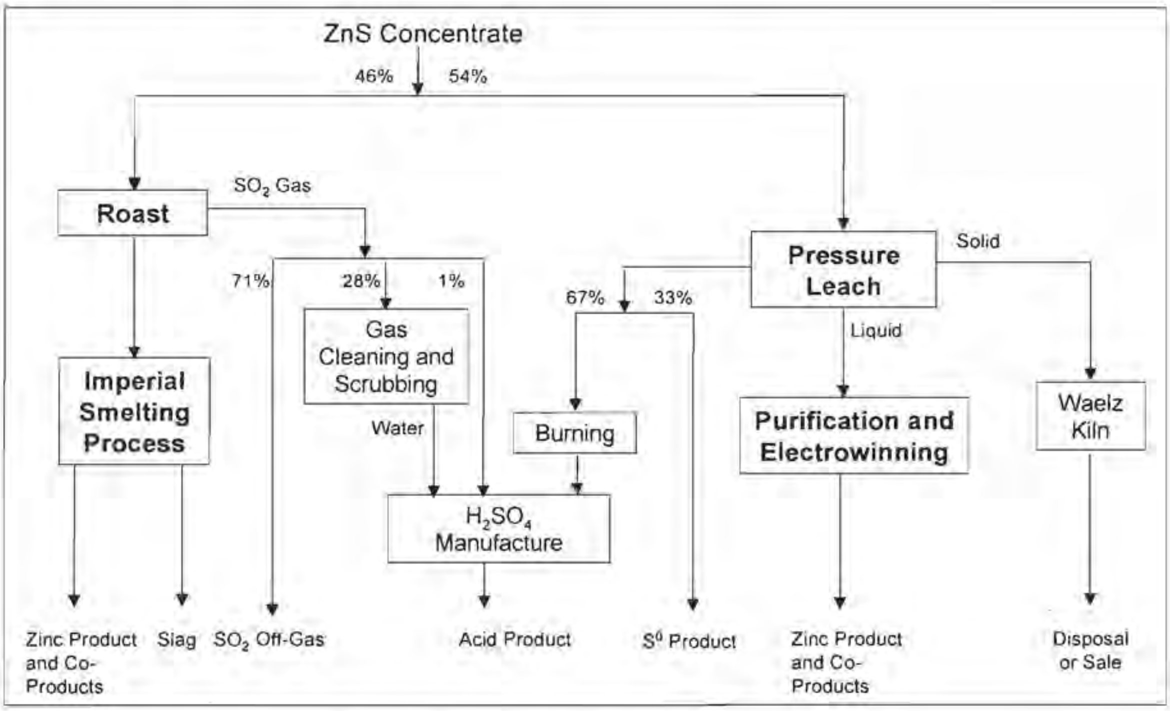


Figure 6-15 *Preferred Technology Combination*

6.3.8.4 Robustness of Result

The complexity added to the model by including a significantly larger number of variables (relative to the number of potential different stream splits), introduced local minima to the solution space. This was apparent in that the "Solver" in *MS Excel®* found more than one solution for the equation set. The different solutions were a function of the initial estimate for the system. For this reason it was necessary to search the solution space defined by the best and worst possible results for each attribute. A trial and error approach was used. The results included in this section were found to be the global minima for the solution space.

6.3.8.5 Sensitivity of solution to including weights in Goal Programming

The goal programming executed to this point has not included weighting of the criteria in any manner. This implies that trade-offs made between the criteria are viewed equally. However, the result achieved has a significant amount of SO_2 being vented to the atmosphere. It is unlikely that this would be acceptable to stakeholders. As the purpose of this step in the hierarchy is to both deliver a suite of technologies for the EIA and to incorporate the findings of the EIA it is necessary at this point to determine the sensitivities of the proposed solution to changes in environmental preferences.

To facilitate this, weights were introduced into the goal programming algorithm. A number of investigations were carried out:

- Evaluate the sensitivity of the solution to changing the value placed on each attribute in isolation
- Evaluate the sensitivity of the solution when higher value is placed on grouped impacts relative to their domain of influence, i.e., global, regional and local. In this case the attributes are grouped into these three categories and then the sensitivity of the solution to changes in weightings applied to each of these groups is evaluated. These groupings (as opposed to the groupings detailed in Table 6-4) were used as they give an indication of the spatial effect of the proposed solution. As this step in the hierarchy is the precursor to the EIA it is necessary to include an indication of spatial effects in the analysis.
- Identify the preferred solution when the optimisation is on environmental impacts only and to determine the best economic solution

- Identify the change in the solution when the environmental attributes together are equivalent in value to the economic attribute (i.e., the environmental attributes were given a weighting of 1/7 each)

The aim of this investigation is to determine the sensitivity of the solution to different values being placed on the environment, as well as to guide the specialist studies within the EIA. Abbreviated results are presented here. An indication of how these results are used to inform the EIA is also given. A complete set of results for these analyses can be found in Appendix 6-1, Section 6.1.6.

The first observation to be made is that the split of the solid waste between the Waelz kiln and to landfill overwhelmingly favours treating the solid waste in a Waelz kiln. Thus the option of landfilling solid waste can be removed from the flowsheet. The second observation is that any water produced in the scrubbing of SO_2 containing off-gases is routed to the acid plant (if one exists). Thus the option of sending this water stream to disposal can also be removed from the flowsheet. This serves to support the decisions already taken and illustrated in Figure 6-15.

In order to illustrate the effect that changing preferences has on the preferred solution, a number of figures have been developed. These figures reflect the fact that stream splits (used to determine the technology combinations) are most sensitive to changing preferences on different attributes. This describes where the process is most sensitive to changing preferences in society. In addition, an indication of the effect of the weighted preferences on the economic performance of the process is given. This shows the sensitivity of the economic success of the project to different preferences. In each figure the heavy black line is an indication of the value for the stream split for the case where all attributes are valued equally.

Figure 6-16 shows that the split between the Roaster and the Pressure Leach is most sensitive to changes in preferences related to landfill volume and Human Toxicity. The only attributes which favour using the Roaster over the Pressure Leach are the contribution to Greenhouse gases and the economic performance.

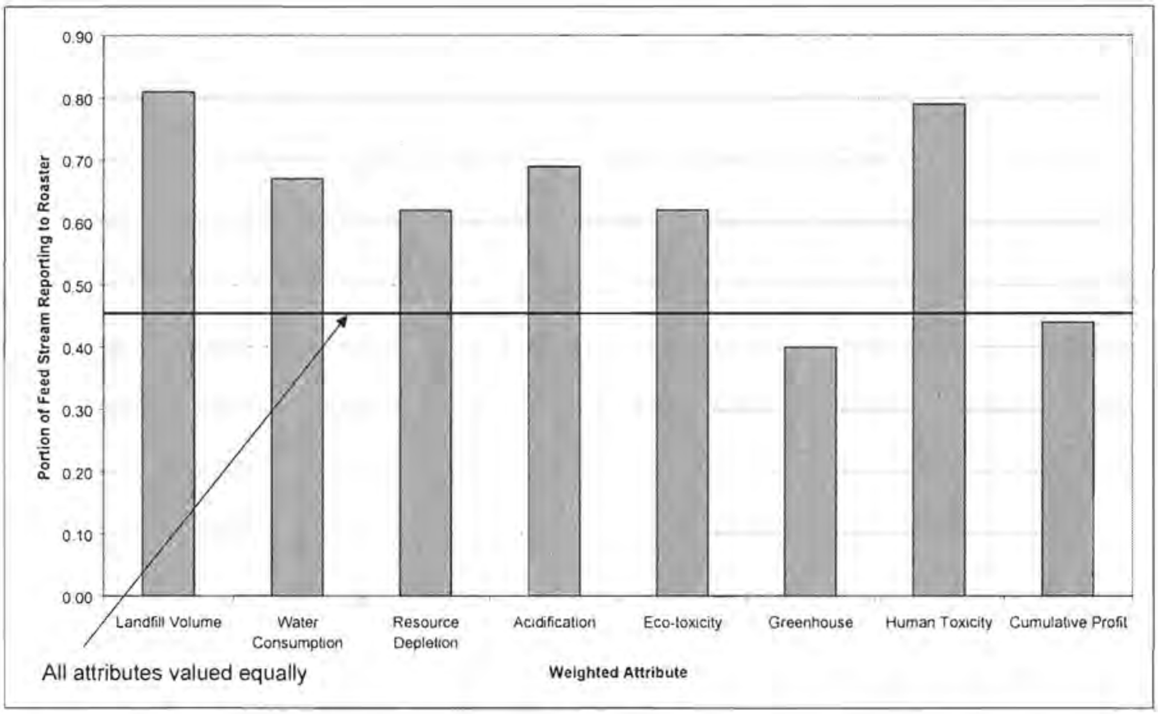


Figure 6-16 *Change in Portion of Feed Stream reporting to Roaster for different attribute weightings*

Figure 6-17 demonstrates the sensitivity of the split of the off-gas stream to different preference weightings. There are three potential routes for the gas to follow, *viz*:

- To the acid plant
- To the gas scrubber
- Direct to the atmosphere

This figure shows that, if greater concern is expressed about (or more value is placed on) landfill volume, acidification effects and human toxicity, off-gas treatment swings towards an acid plant. The portion of the gas reporting to the scrubber lies in a relatively limited range. Thus it is not particularly sensitive to weightings on any of the attributes.

The fact that the stream splits calculated when all attributes were weighted equally are outside the ranges of the results for the weighted attributes is a further indication of the fact that goal programming allows infinite trade-offs to be made between attributes.

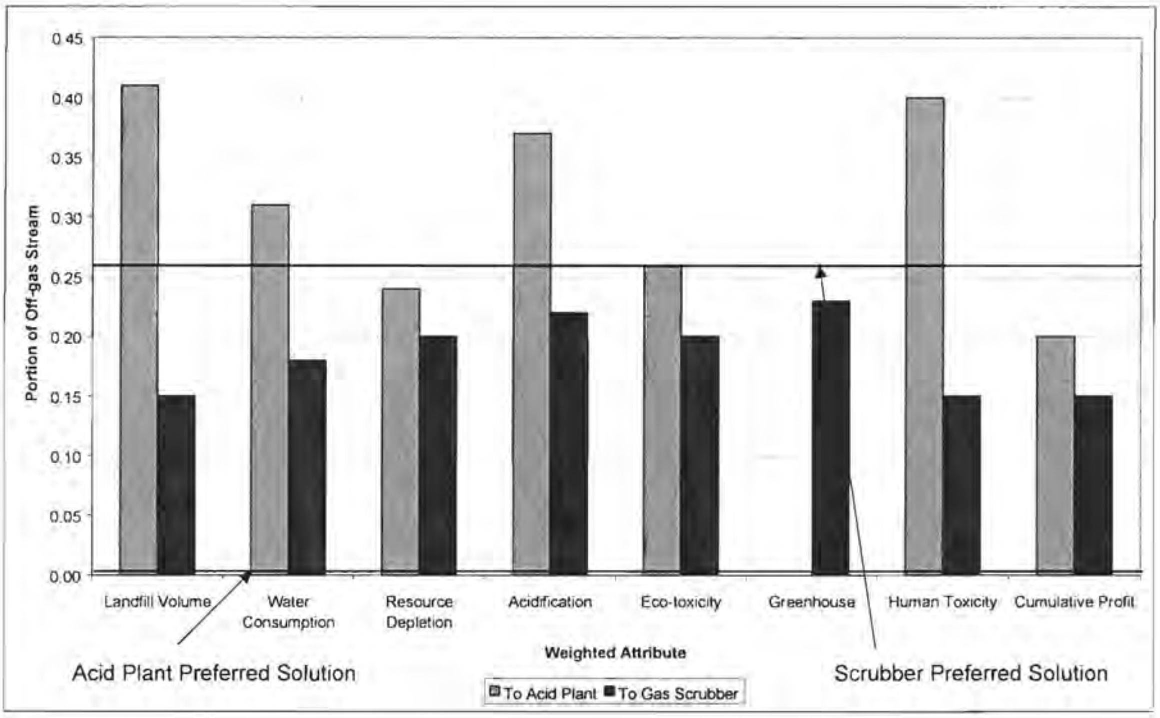


Figure 6-17 *Change in Portion of Feed Stream reporting to Acid Plant and Gas Scrubbing for different attribute weightings*

Figure 6-18 shows that the amount sulphur product produced from the Pressure Leach is most sensitive to concerns about landfill volume and human toxicity. If these are of greatest concern then more sulphur should be produced and less sulphuric acid. The only attribute which favours the production of sulphuric acid is a consideration of contributions to greenhouse gases.

Figure 6-19 gives an indication of the preferences which, in isolation, have the most profound effect on the economic performance of the process. In this figure the black line is an indication of the 10% cut-off rate discussed in Section 6.3.8.2. This demonstrates that the preferences which are most likely to threaten the economic viability of the project are concerns about landfill volume, human toxicity and acidification. It is interesting to note that, in spite of the significant energy requirements of the electrowinning process, the process is least susceptible to changes in preference around greenhouse gas concerns (input impacts associated with electricity being the major source of greenhouse effects for the project). The main reason for this is that greenhouse effects are an input impact to the process and thus form part of the background system as identified in Section 2 of this these. The only way that it is possible to address these impacts within the model is by decreasing the amount of energy drawn. However, as was highlighted in Section 3, there are significant energy requirements in minerals processing, this is associated with

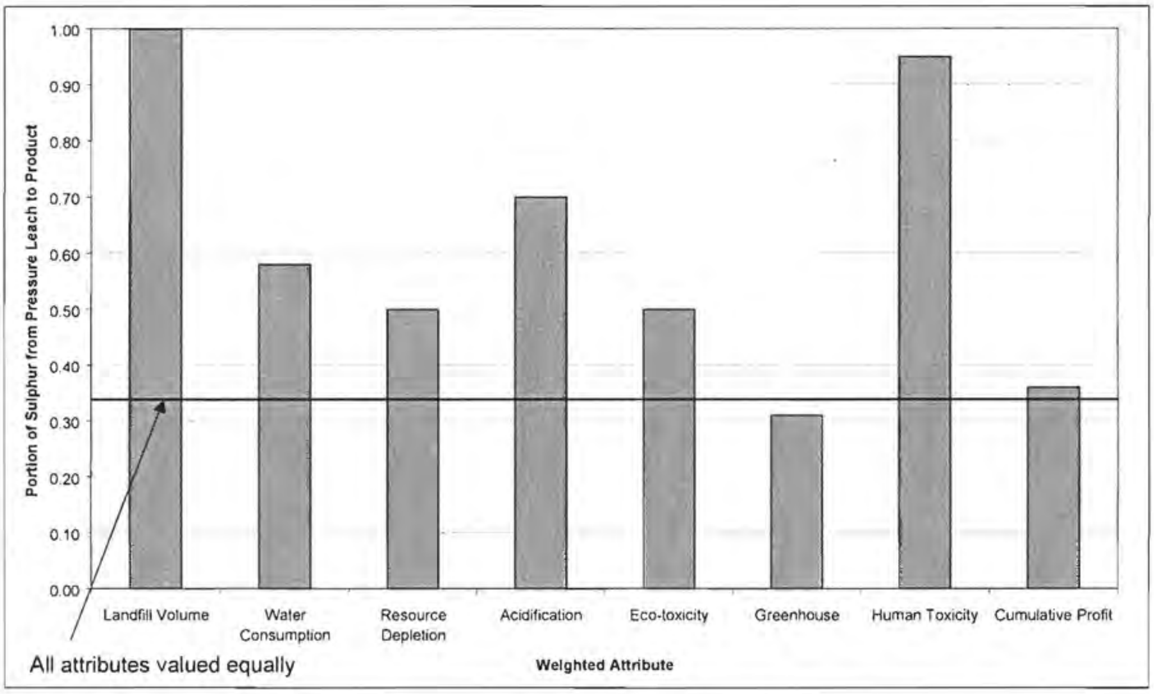


Figure 6-18 *Change in Portion of Sulphur from the Pressure Leach reporting to a Sulphur Product for different attribute weightings*

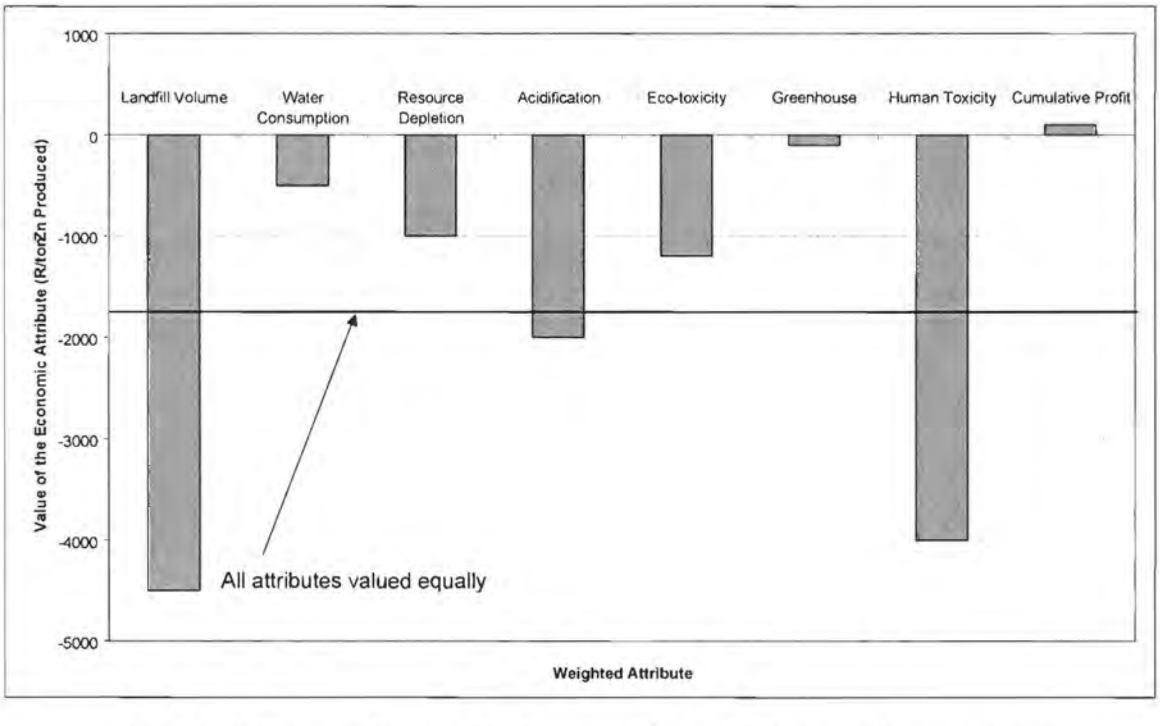


Figure 6-19 *Change in Economic Performance relative to different attribute weightings*

the energy required to overcome the entropy inherent in the dilute ores which form feed materials to minerals processes. Thus there is a thermodynamic limit below which it is not possible to reduce energy requirements.

The sensitivity analyses presented in Figure 6-16 to Figure 6-19 highlight the preferences which affect technology choice most profoundly. Thus it is necessary to ensure that these impact categories are addressed specifically within the EIA. It is also necessary to ensure that the information used to model the unit operations within the flow sheet which give rise to these impact categories is as accurate as possible. The impact categories are:

- Landfill Volume
- Acidification
- Human Toxicity

The sensitivity of the economic performance to acidification effects is used to eliminate the option of venting off-gases to the atmosphere from the flow diagram. As the decision has already been taken that all the water from the gas scrubber would report to the acid plant, and there is no reason for the plant to have both a gas scrubber and an acid plant, the decision is also taken to remove the gas scrubber from the process flowsheet.

The next sensitivity analysis evaluated the change in the preferred solution relative to emphasis being placed on local, regional and global issues. To this end the impact categories were grouped as indicated in Table 6-13. The results of the sensitivity analyses included in Appendix 6-1 contain results for:

- Optimising with respect to the grouped impacts only
- Optimising when the grouped impacts are twice as important as the other impacts
- Optimising when the grouped impacts are five time as important as the other impacts

The results of this analysis are as expected from the previous result, that the solution is most sensitive to emphasis being place on local issues, followed by regional issues and finally by global issues.

Table 6-13 *Grouping Impact Categories*

Spatial Effect	Impact Category
Local	Landfill Volume Total Eco-toxicity Human Toxicity
Regional	Acidification Water Consumption
Global	Greenhouse Resource Depletion

The main reason for conducting this analysis was to determine which grouping of impacts had the greatest effect on the economic performance of the process. To this end Figure 6-20 has been included. This figure gives an indication of the effect on the economic attribute of placing an emphasis on the grouped impacts. This figure shows that the economic viability of the process is most susceptible to increased concern relating to local issues. This is a significant finding, and two conclusions can be drawn from this result:

- That minerals processing plants have local impacts which are so significant that they outweigh global and regional impacts. This suggests that the minerals industry might concentrate rather on the mitigation of local impacts as opposed to focussing on such issues as greenhouse gas emissions
- The information used to determine the impacts are LCA equivalency factors. These impacts represent a potential to impact on the environment on a global scale. It may be possible to determine equivalency factors for global impacts to some degree of certainty. However, the uncertainty inherent in evaluating local impacts within the context of LCIA will be far greater as an attempt is made to quantify what are essentially site-specific impacts in an aggregated and globally representative manner. Thus the results included in Figure 6-20 may be skewed by the level of aggregation and uncertainty inherent in the manner in which a "life cycle" based impact assessment chooses to articulate local impacts. Site-specific information from the EIA will address this issue explicitly.

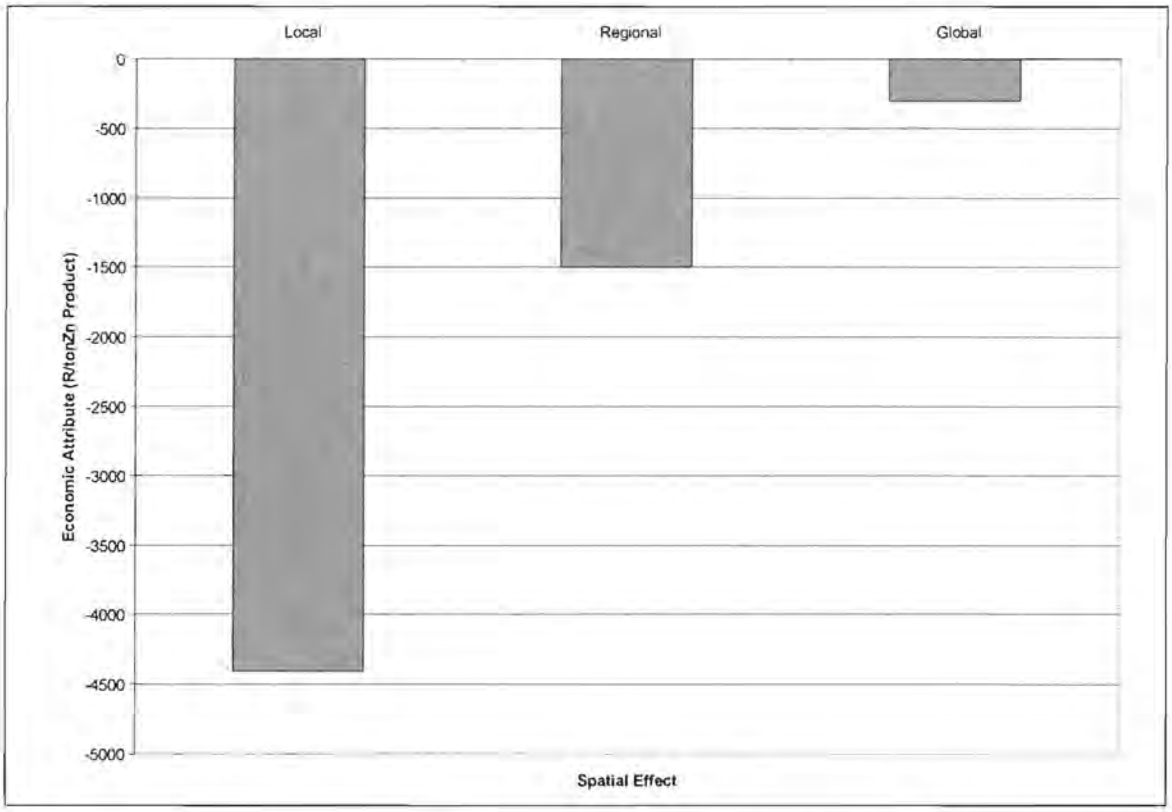


Figure 6-20 *Change in Economic Performance relative to Emphasis on Different Impact Groups*

There are two ways in which this information can be used, both of which relate to site selection for the project. The one way to use the information is to select a site that is most likely to be able to assimilate the local effects of the proposed project. In this case this would mean that the site should have sufficient landfill space available, not have an ecology that is likely to be easily damaged, and not be too close to significant human settlements. The other way that this information can be used is selecting the site relative to the demographics of the people in the area and an understanding of their potential concerns about the project. If the main concerns of the society in the area are on greenhouse gas effects then their preferences are least likely to undermine the economic viability of the project. These preferences would depend on the stakeholders in each project.

The final sensitivity analysis was used to determine the technology combination which delivered the best environmental performance, and the best economic performance. As the goals for the optimisation were defined to fall between the best and worst values the solution was restricted to being a combination of technologies. It was found that, for best economic performance, the pressure leach process was preferred to the roaster process, whilst the opposite held for optimal environmental performance. For this reason the technology suites to be carried forward to the EIA will be:

- Roast, ISP with treatment of off-gas by scrubbing or an acid plant, all water from the scrubber to be routed to an acid plant if that is the preferred option (Option A)
- Pressure Leach, Waelz kiln with all Sulphur being sold as a product (Option B)
- A combination of Roast-ISP and Pressure leach limited by the decisions already taken (Option C)

Flow diagrams for these three options are included in Figure 6-21. (Note: detail on internal recycles, such as the recycle of H_2SO_4 on the pressure leach process, has not been included for the reasons offered in Section 2.3.3 which shows that process streams not crossing the system boundary can be discounted from the model. A small amount of the product H_2SO_4 would be returned to the pressure leach as a make-up stream, this has been accounted for in the model.) The range of stream splits to be used in the combination of technologies is included in the figure. The mass balance for the processes detailed in this figure can be evaluated using the model and changing the stream split to reflect the process option under consideration. These then would be the mass balances used to direct the specialist studies in the EIA. This is discussed in Section 6.3.8.7.

In conclusion, the three sensitivity analyses carried out can be used in different ways:

- The sensitivity of the solution to changing the values placed on different attributes can be used to eliminate technologies from the flowsheet as well as give an indication of the sensitivity of the proposed project to changing societal preferences
- The sensitivity of the solution to spatially grouped impacts can be used to guide site selection
- The sensitivity of the solution to shifting emphasis from environmental attributes to economic attributes can be used in the decision as to which technology suites should be taken forward to the EIA.

Thus, the decision taken at this point in the hierarchy is that:

> *Three potential flowsheets have been identified to be carried forward to the EIA process*
>
> *Decisions relating to site selection and the EIA process have also been taken outside the hierarchy*

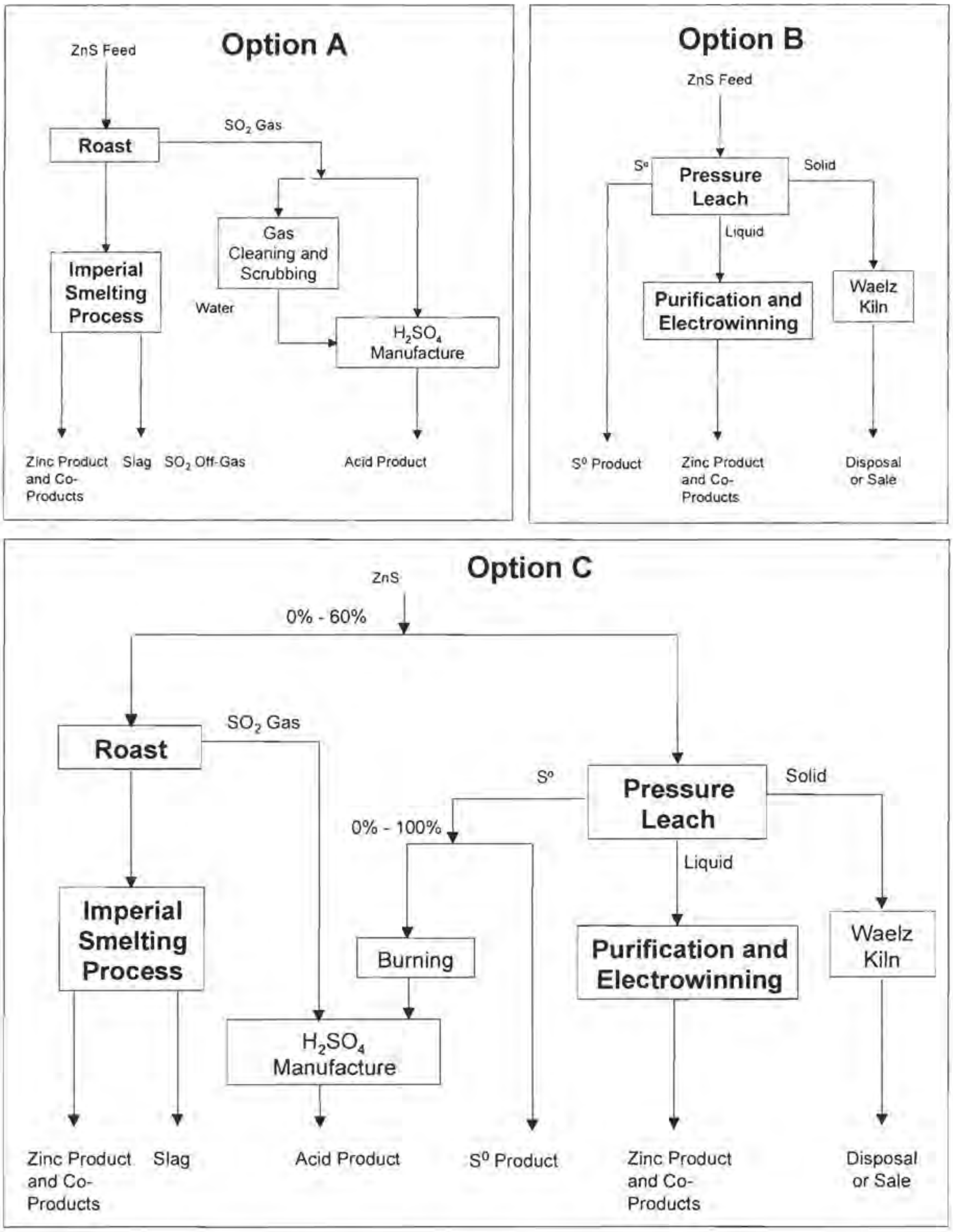


Figure 6-21 *Technology Options to be included in the EIA*

6.3.8.6 Methodological Observations

Three distinctly different observations can be made from analysing the results included in Appendix 6-1. The first of these is that including valuation (or weightings) in the goal programming algorithm has a distinct effect on the preferred solution This is evident in the summarised results included in Figure 6-16 to Figure 6-18. However, the absolute value of this weighting is not necessarily significant. Multiplying a single attribute by two and multiplying it by five does not have a significant effect on the preferred solution. This suggests that, once the solution has been biased towards a single attribute in goal programming, the emphasis that is placed on this bias does not affect the outcome.

One of the reasons for using MCDA tools detailed in the introduction to this section is that they allow for an inter-dependence to exist between weights. This means that the solution should be sensitive to changing the weights, as opposed to what was observed when multi-objective optimisation was used in the case study included in Section 5 of this thesis where the solution was found not to be sensitive to changing the magnitude of the weights. The solution is affected by changing the weights. However, the solution is not affected by the magnitude of this change. Thus an MCDA algorithm which uses relative (as opposed to discrete) attribute weighting values is required in order to minimise the trade-off in weighted value as opposed to minimising an absolute number. This observation supports the decision to use a value function approach which utilises pair-wise comparisons between the attributes in establishing the weights to be applied to the attributes.

A further observation relates to the fact that goal programming uses the absolute value of the difference from a desired goal. It gives no preference to solutions in which the attributes are all performing better than the required goal in comparison to a solution where some of the attributes may be performing worse than their required goals. Thus it is possible to have a solution which is optimised on environental performance delivering worse performance with respect to a single attribute than one which focuses on less rigorous environmental performances. For this reason an MCDA methodology which restricts the attribute values to being below a desired value would be preferable. It is possible to constrain goal programming to conform to this approach. However, the resulting equation set is so constrained that it is difficult to solve.

The final observation is that, by setting the goals to lie inside the solution space (as defined by the best and worst possible outcomes for each attribute), the potential for a technology solution which defines one of these solution space boundaries to be the preferred solution is limited. In attempting to minimise the trade-offs between different attributes by defining the goal to be 80% of best performance, a technology that makes no contribution to one of the attributes may result in a significant difference for that attribute. It is thus necessary to evaluate the effect of a zero attribute value.

6.3.8.7 Information supplied to the EIA process

Figure 6-21 contains flowsheets of the process which are to be taken to the EIA process. As was stated, the model as developed can be used to evaluate the mass balance and energy requirement for each of these scenarios. These mass balances supply the information as required by the specialists within the EIA process. However, as there is a range of values (as opposed to a single technology option), the specialists would be required to give an indication of the environmental impact of the range of options as opposed to a single assessment as is the case at present.

To illustrate this further, consider a potential air pollution specialist study for the proposed plant. The air pollution specialist would receive the following information:

- The off-gas stream from Option A
- A number of off-gas streams for various combinations in Option C.

The combinations in Option C must, as a minimum, include the maximum and minimum value for the stream split as detailed on Figure 6-21. Additional combinations can also be included. The number included would be determined by the potential to interpolate the results of the air pollution result over the required range of the output gases (and this relates to the linearity of the models used by the air pollution specialist).

The specialist would then deliver a report which contains an indication of the impacts associated with the off-gases from the Roaster-ISP process (Option A) as well as the combination of technologies in option C. These results will then be used to update the equivalency values used in the model with respect to:

- Accuracy
- Site Specificity

- Time Dependence

The impact categories to which the preferred solution is most sensitive will require the most accuracy in the specialist result. In addition, the unit operations which give rise to these impacts must also be modelled in sufficient detail and with as accurate information as possible. In this case the specialist reports which are most significant are those relating to the local impacts (landfill, human toxicity and eco-toxicity). The unit operations giving rise to these impacts can be determined from the audit trail structure established in the model. The sensitivity analyses highlight this audit trail. Taking human toxicity as an example and reviewing the sensitivity of the preferred solution to weighting this attribute more heavily leads to the following conclusions:

- More feed is routed to the roaster and thus the pressure leach process can be seen as a greater source of human toxicity than the roaster
- More of the off-gases are routed to the Acid plant and thus the gas scrubber is a higher source of human toxicity
- Sulphur from the pressure leach is routed to product as opposed to the acid plant

Thus, in order to address human toxicity issues the pressure leach, the gas scrubber and the acid plant must be investigated.

In conclusion, the results from this section of stage three can be used to inform the EIA process as well as the next stage of design.

6.3.9 Level 3 - Recycle Structure incorporating the findings of the Environmental Impact Assessment

This stage of the design hierarchy, and all subsequent stages, are interactive in that it is necessary to take onboard the preferences of society and demonstrate that their concerns are being addressed, both with respect to site selection and with respect to technology choice. However, the bulk of the EIA studies, namely the social scoping exercise as well as the specialist impact assessment reports, need to be completed before a selection can be made between the technology options available.

6.3.9.1 Information delivered by the EIA process

As detailed in Section 6.1.1, the EIA process has well-developed social scoping from which the values that society places on different environmental criteria or attributes can be determined. While this is usually carried out in a qualitative manner, as was stated in the discussion on EIA, it is possible to articulate these qualitative value sets as quantitative values. This may necessitate a shift in focus for the social scoping exercise. The social scoping process may be the same as used at the moment but with different deliverables. The results of the social scoping would now include a quantification of the values of the interested and affected parties. These values would need to be stated in such a manner as to be available to the multi-criteria decision analysis algorithm used in the evaluation of alternatives during this stage of the design hierarchy.

While all effort should have been expended in step C of the hierarchy (detailed in Section 6.3.7) to ensure that all important environmental categories were included when the environmental objectives were defined, it is possible that one or more significant attributes could have been excluded from the analysis. For this reason it must be recognised that the social scoping study as well as the specialist studies have the potential to highlight environmental attributes that have not been considered this far. If this is the case, it will be necessary to re-visit the decisions taken in all stages of the hierarchy prior to the EIA and to evaluate the options analysed in each stage in terms of their performance relative to these new attributes. This will ensure that the options selected are optimal in terms of the new set of attributes. An example of another attribute which may be of significant concern to the I&APs is noise, this has not been included in the analysis of the case to this point. If noise pollution is of significant concern then it will need to be included in the decisions already taken.

A further outcome from the EIA would be to make the impacts associated with the proposed technology options site specific. This information would then be interpreted in terms of the equivalency factors used in the decision framework model. The equivalency factors used in the model would be re-written to include the temporal and spatial effects of the project. While it is not common practise to formulating equivalency factors in this manner, work is underway at present on how to address this deficiency in the LCA methodology (Hansen *et al*, 1998). This is discussed in Section 7 of this thesis.

In summary, there are three necessary outputs from the EIA process:

- Any new attributes which need to be included in the analysis
- A set of social values
- "Equivalency factors" which are site specific and reflect the temporal and spatial effects of the proposed project.

In the context of the case study [the Environmental Impact Report that was drafted for the proposed development of a Zinc Plant at Coega in the Eastern Cape, South Africa (AES, 1996)] it is difficult to infer any of the above listed requirements from the documentation available. The following conclusions were drawn:

- The main focus of social concern was the size of the waste dump associated with the project. Landfill volume has been included as one of the attributes in the model, thus the attribute set used was deemed to be sufficient.
- The requirements of society were described in a qualitative manner only; no indication of society's value set was made. This highlights the fact that, while the social scoping exercise may not change significantly, the outcomes required are different from those delivered at present. For this reason a mock valuation exercise was conducted in this thesis. This is outlined in Section 6.3.9.2 below. The outcome of this exercise is a set of values that can be used in a value function analysis.
- It is possible to interpret the specialist reports and develop a new set of equivalency factors for the process. This is not accepted practise and is discussed in more detail in the recommendations of this thesis, Section 7. As this case study is purely illustrative, this has not been pursued as it does not add significant value to the demonstration of the methodology.

6.3.9.2 Determining weights from Pair-wise trade-off Values

The MCDA algorithm to be used in this stage of the design hierarchy is a Value Function approach. This requires weights to be allocated to each attribute. In order for the preferred solution to represent a position of least trade-offs, it is necessary for these weights to reflect the trade-off that society is willing to accept.

For this reason a questionnaire was developed that required people to state the value they placed on a single attribute relative to one other attribute. The reason for taking this approach is that the

EIA social scoping process includes this type of approach. While social scoping is qualitative at present, sufficient work has been conducted on preference elicitation to enable the quantitative evaluation of these preferences (Beinat, 1997). Weights used to inform MCDA models are an interpretation of a **value function**. Value functions have a specific shape over the attribute range. This shape is related to the amount of performance in one attribute that society is willing to sacrifice for a gain in another attribute. Determining the shape of these value functions is not a trivial exercise (Stewart, 1992).

There are different ways to generate weighting information from value functions (Beinat, 1997). In this case study it was decided that weights would be determined on a pair-wise basis. It was also decided that the value functions would be linear, it is recognised that more complex shapes would exist in practise. These two assumptions mean that it is possible to articulate preferences as ratios of the preference of one attribute when compared with another attribute. These assumptions also mean that the weights are dependent on the attribute range, the definition used means that the weights are not an explicit function of the attribute range.

To this end a questionnaire was developed which required respondents to value one attribute with respect to another. An example of this questionnaire is included in Figure 6-22. The ratio of the values gleaned from this questionnaire represents the weighting respondents placed on one attribute relative to the other, or how much people are willing to sacrifice in one attribute for a gain in the other attribute. As such these values give an indication of the acceptable trade-off between the two attributes. These ratios were normalised so that the sum of each pair of weights is one. All possible pairs of attributes were constructed and the relative weightings for each pair established.

The weights were calculated according to the following equations:

The average of the values elicited using the questionnaire included in Figure 6-22 are allocated the variable name $av_{i,k}$. From these values the following matrix of attribute values, $\underline{AV}$, can be established:

There are a number of couples included below, please give them each a value where this value is an indication of how much more important the first of the couple is than the second. Example, I am four time more concerned about acidification effects than I am about landfill effects so I would answer.

Couple: Landfill - Acidification Landfill = 1 Acidification = 4

Couple	First	Value	Second	Value
Landfill Volume - Water Consumption	Landfill Volume		Water Consumption	
Landfill Volume - Resource Consumption	Landfill Volume		Resource Consumption	
Landfill Volume - Acidification	Landfill Volume		Acidification	
Landfill Volume - Eco-toxicity	Landfill Volume		Eco-toxicity	
Landfill Volume - Greenhouse Effects	Landfill Volume		Greenhouse Effects	
Landfill Volume - Human Toxicity	Landfill Volume		Human Toxicity	
Landfill Volume - Cumulative Profit	Landfill Volume		Cumulative Profit	
Water Consumption - Resource Consumption	Water Consumption		Resource Consumption	
Water Consumption - Acidification	Water Consumption		Acidification	
Water Consumption - Eco-toxicity	Water Consumption		Eco-toxicity	
Water Consumption - Greenhouse Effects	Water Consumption		Greenhouse Effects	
Water Consumption - Human Toxicity	Water Consumption		Human Toxicity	
Water Consumption - Cumulative Profit	Water Consumption		Cumulative Profit	
Resource Consumption - Acidification	Resource Consumption		Acidification	
Resource Consumption - Eco-toxicity	Resource Consumption		Eco-toxicity	
Resource Consumption - Greenhouse Effects	Resource Consumption		Greenhouse Effects	
Resource Consumption - Human Toxicity	Resource Consumption		Human Toxicity	
Resource Consumption - Cumulative Profit	Resource Consumption		Cumulative Profit	
Acidification - Eco-toxicity	Acidification		Eco-toxicity	
Acidification - Greenhouse Effects	Acidification		Greenhouse Effects	
Acidification - Human Toxicity	Acidification		Human Toxicity	
Acidification - Cumulative Profit	Acidification		Cumulative Profit	
Eco-toxicity - Greenhouse Effects	Eco-toxicity		Greenhouse Effects	
Eco-toxicity - Human Toxicity	Eco-toxicity		Human Toxicity	
Eco-toxicity - Cumulative Profit	Eco-toxicity		Cumulative Profit	
Greenhouse Effects - Human Toxicity	Greenhouse Effects		Human Toxicity	
Greenhouse Effects - Cumulative Profit	Greenhouse Effects		Cumulative Profit	
Human Toxicity - Cumulative Profit	Human Toxicity		Cumulative Profit	

Figure 6-22 *Example of Questionnaire*

$$\underline{\underline{AV}} = \begin{bmatrix} 0 & av_{2,1} & \cdots & av_{k,1} & \cdots & av_{y,1} \\ av_{1,2} & 0 & & av_{k,2} & & av_{y,2} \\ \cdots & \cdots & & \cdots & & \cdots \\ av_{1,k} & av_{2,k} & & 0 & & av_{y,k} \\ \cdots & \cdots & & \cdots & & \cdots \\ av_{1,y} & av_{2,y} & & av_{k,y} & & 0 \end{bmatrix}$$

Equation 6-1

where $av_{i,k}$ is the value given to attribute i in the pair attribute i - attribute k

y is the total number of impact categories

$av_{k,k}$ will always equal 0 as an attribute cannot be valued relative to itself

In order to eliminate order of magnitude differences in this matrix and to ensure that the weights calculated represent trade-offs between the pairs of values, ratios between the values included in Equation 6-1 are calculated and then normalised to fall between 0 and 1:

$$aw_{i,k} = \frac{\left(\frac{av_{i,k}}{av_{k,i}}\right)}{av_{i,k} + av_{k,i}}$$ **Equation 6-2**

where $aw_{i,k}$ is the normalised weight applied to attribute i in the pair attribute i - attribute k

It can be shown that:

$$aw_{k,i} = \frac{\left(\frac{av_{k,i}}{av_{i,k}}\right)}{av_{i,k} + av_{k,i}} = 1 - aw_{i,k}$$ **Equation 6-3**

From this it is possible to construct a matrix $\underline{\underline{AW}}$:

$$\underline{\underline{AW}} = \begin{bmatrix} 0 & aw_{2,1} & \dots & aw_{k,1} & \dots & aw_{y,1} \\ aw_{1,2} & 0 & & aw_{k,2} & & aw_{y,2} \\ \dots & \dots & & \dots & & \dots \\ aw_{1,k} & aw_{2,k} & & 0 & & aw_{y,k} \\ \dots & \dots & & \dots & & \dots \\ aw_{1,y} & aw_{2,y} & & aw_{k,y} & & 0 \end{bmatrix}$$ **Equation 6-4**

From this matrix it is possible to calculate the weight to be applied to impact category k, wf_k from:

$$wf_k = \sum_{r=1}^{y} aw_{k,r}$$ **Equation 6-5**

A worked example is used to demonstrate this system of equations. A response to a questionnaire delivers the information included in Table 6-14.

Table 6-14 *Sample Values from a Preference Elicitation Exercise*

Couple	First	Value	Second	Value
Respondent 1				
Landfill Volume - Water Consumption	Landfill Volume	1	Water Consumption	4
Landfill Volume - Resource Consumption	Landfill Volume	1	Resource Consumption	2
Landfill Volume - Acidification	Landfill Volume	1	Acidification	5
Water Consumption - Resource Consumption	Water Consumption	3	Resource Consumption	1
Water Consumption - Acidification	Water Consumption	1	Acidification	2
Resource Consumption - Acidification	Resource Consumption	1	Acidification	5
Respondent 2				
Landfill Volume - Water Consumption	Landfill Volume	1	Water Consumption	6
Landfill Volume - Resource Consumption	Landfill Volume	1	Resource Consumption	2
Landfill Volume - Acidification	Landfill Volume	1	Acidification	10
Water Consumption - Resource Consumption	Water Consumption	5	Resource Consumption	2
Water Consumption - Acidification	Water Consumption	2	Acidification	3
Resource Consumption - Acidification	Resource Consumption	1	Acidification	2
Respondent 3				
Landfill Volume - Water Consumption	Landfill Volume	1	Water Consumption	7
Landfill Volume - Resource Consumption	Landfill Volume	2	Resource Consumption	1
Landfill Volume - Acidification	Landfill Volume	1	Acidification	4
Water Consumption - Resource Consumption	Water Consumption	5	Resource Consumption	1
Water Consumption - Acidification	Water Consumption	4	Acidification	1
Resource Consumption - Acidification	Resource Consumption	1	Acidification	4
Averages				
Landfill Volume - Water Consumption	Landfill Volume	1.0	Water Consumption	5.7
Landfill Volume - Resource Consumption	Landfill Volume	1.3	Resource Consumption	1.7
Landfill Volume - Acidification	Landfill Volume	1.0	Acidification	6.3
Water Consumption - Resource Consumption	Water Consumption	4.3	Resource Consumption	1.3
Water Consumption - Acidification	Water Consumption	2.3	Acidification	2.0
Resource Consumption - Acidification	Resource Consumption	1.0	Acidification	3.7

Reviewing the values given by respondent 1, these number mean that they are four times as concerned about water consumption than they are about landfill volume. It is possible to say that, on a scale of 0 to 1 they would weight water consumption as 0.8 and landfill volume as 0.2.

Matrix <u>AV</u> is then established using the average of the values included in this table.

Table 6-15 *Worked Example of Matrix <u>AV</u>*

	Landfill Volume	Water Consumption	Resource Consumption	Acidification
Landfill Volume	0	1.0	1.3	1.0
Water Consumption	5.7	0	4.3	2.3
Resource Consumption	1.7	1.3	0	1.0
Acidification	6.3	2.0	3.7	0

The attribute weight for Landfill Volume relative to Water Consumption is calculated from:

$$\mathrm{aw}_{\mathrm{landfill,water}} = \frac{\left(\frac{1.0}{5.7}\right)}{1.0 + 5.7} = 0.03$$

Thus matrix AW is constructed.

Table 6-16 *Worked Example of Matrix AW*

	Landfill Volume	Water Consumption	Resource Consumption	Acidification
Landfill Volume	0	0.03	0.27	0.02
Water Consumption	0.97	0	0.57	0.27
Resource Consumption	0.73	0.43	0	0.06
Acidification	0.98	0.73	0.94	0

The weight to be applied to each attribute in the value function is then the sum of rows in this matrix:

Table 6-17 *Worked Example of Weighting factors, wf*

	Weight
Landfill Volume	0.31
Water Consumption	1.82
Resource Consumption	1.22
Acidification	2.65

In order to evaluate the weighting factors, wf, to be used in the model, ten random post-graduate students were asked to complete the questionnaire included in Figure 6-22. The results can be found on the CD which accompanies this thesis. The weighting set which resulted from this exercise is included in Table 6-18. This weighting set was used to inform the value function.

Table 6-18 *Weightings used in the Case Study*

Attribute	**Weight**	**Normalised Weight**
Landfill Volume	2.64	0.10
Water Consumption	4.07	0.15
Resource Depletion	3.65	0.13
Acidification	3.83	0.14
Total Eco-toxicity	4.07	0.15
Greenhouse	4.06	0.15
Human Toxicity	3.47	0.13
Cumulative Profit	1.79	0.06

Note, the objective is to minimise the total score in the value function so the higher the weight applied to the attribute, the more significant it can be deemed to be. This is not the conventional approach adopted in MCDA but has been chosen to ensure that the directional trends of both the weights and the attribute values are correct.

6.3.9.3 Preferred Technology Options

The three technology options detailed in Figure 6-21 were analysed with respect to these values. Option B is a single technology option while Options A and C have a number of possible permutations. Thus, to determine the preferred solutions for each of these options a value function algorithm was included in the model. The maximum and minimum values for each attribute were recalculated and the attribute scores normalised relative to these different attribute ranges. Stream splits between the unit operations were allowed to change until the technology option which gave the lowest score for the value function was found.

This technology combination represents the technology combination within that option which comes closest to minimising the trade-offs made between the attributes. The three technology options arrived at are included in Table 6-19 and illustrated in Figure 6-23. A complete set of results for each of these options is included in Appendix 6-1, Section 6.1.6.

Table 6-19 *Preferred Technology Combinations post-EIA*

Option	Preferred Technology Combination	Score
A	Roast, Imperial Smelter, all off-gas to acid plant	13.89
B	Pressure Leach, Electrowin, all S^o to product, solid waste to Waelz kiln	13.59
C	43% of feed to Roast, ISP; 57% of feed to Pressure Leach, Electrowin; all solid waste to Waelz Kiln; all gases to acid plant; all So to acid manufacture	11.83

The decision taken at this point in the hierarchy is that:

> *The technology to carry through to the next step of the hierarchy is a combination of 30% of feed reporting to Roast/ISP; 70% of feed reporting to Pressure Leach/Electrowin; all solids are treated in a Waelz Kiln; all off-gases and all S^o product report to an Acid Plant*

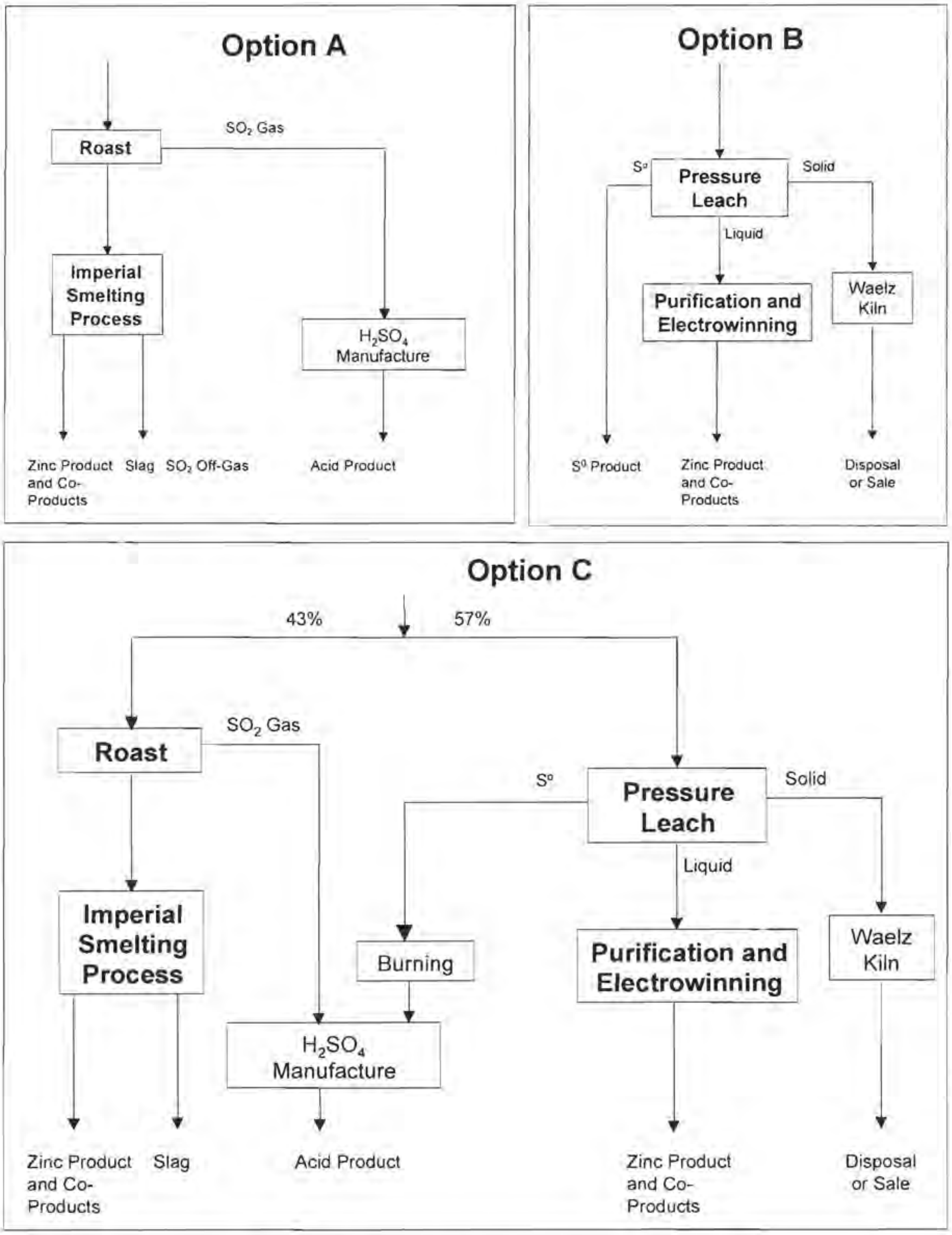


Figure 6-23 *Preferred Technology Options Post-EIA*

6.3.9.4 Methodological Observations

The preferred solution delivered is that technology set which comes closest to meeting the trade-offs defined by the social scoping exercise by minimising the sum of weighted attribute values where the weights applied are a combination of the trade-offs defined by society. To analyse this information Figure 6-24 has been developed. This figure shows the performance of Options B and C (the two best options) with respect to the possible range of values for each attribute. To overcome order of magnitude differences the possible ranges of values have been scaled to fall between 0 and 1. Best possible performance is zero.

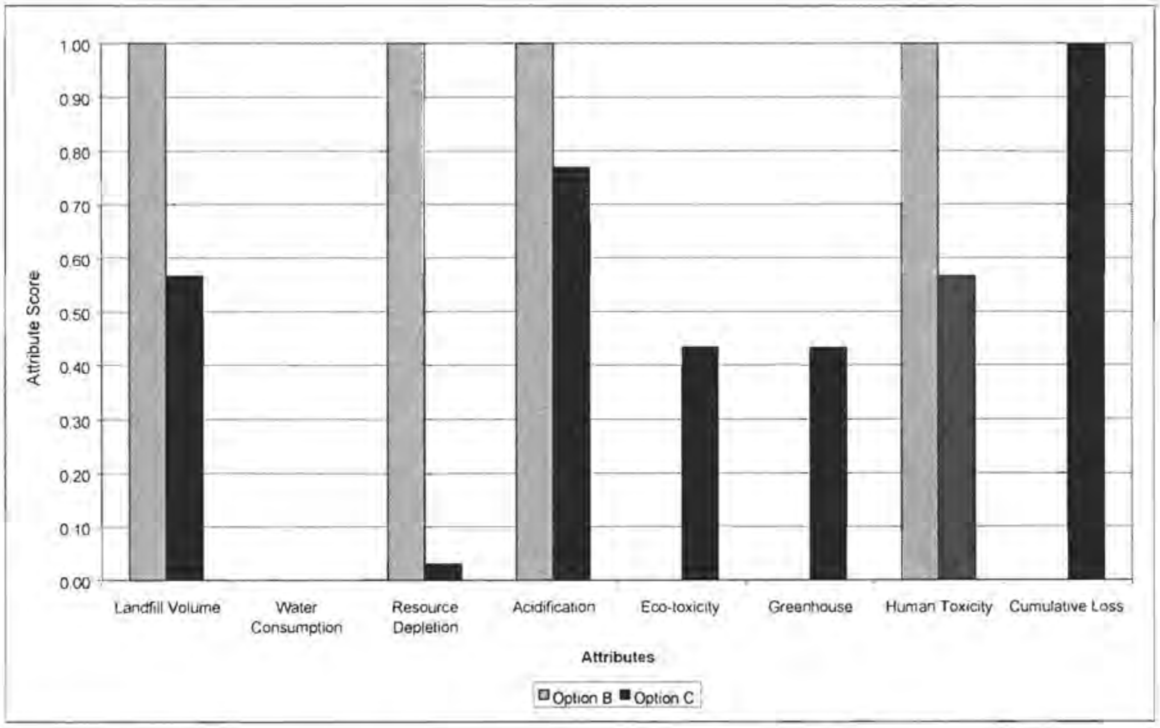


Figure 6-24 *Comparison of the Performance of Options B and C*

This figure demonstrates two aspects:

- The attribute scores for the option which represents a discrete technology choice (Option B) lie on the extremes of the range. This supports the observation that the best and worst possible performance for the flowsheets under scrutiny were defined by discrete technology options
- How the different options use the range of values available to them. This range of possible values is also called the utility of the function. Option C, the preferred solution, performs

worse than Option B in a number of attributes. However, the weightings given to these attributes was obviously not significant enough to swing the result away from Option C.

As an observation, the objective function has been optimised within the range of technologically possible and economically viable values for each attribute. As such, the best possible technology combination within the possible solution space, and with respect to a stated value set, has been established. It is possible to demonstrate to stakeholders that their concerns have been addressed in deciding on this technology option. This is not to underestimate the difficulties which would arise from interpreting this information and conveying it to the broader public.

This solution does not incorporate veto positions at all, a veto position being a limit on an attribute beyond which the attribute value cannot go. While it is easy to include such a position in the model (by introducing constraints on the model), if the limit for a specific attribute falls outside the solution space for this suite of technology options it will not be possible to meet this requirement. In order to address a concern such as this it will be necessary to re-evaluate the decisions taken at previous stages of the hierarchy to determine whether it is possible to meet such a requirement with the technology that is available at present. Care should be taken to include an indication of such veto positions when and if they arise and the relevant constraints introduced into the model as soon as these limits become known.

Figure 6-25 has been included to demonstrate the sensitivity of the solution to changing weights placed on the various attributes. A complete information set for this figure can be found in Appendix 6-1, Section 6.1.6.Thus shows that the solution is most sensitive to concerns relating to greenhouse gas issues and least sensitive to water consumption issues. This can be interpreted in two ways:

- Changing societal pressure concerning greenhouse gas issues will have the most profound affect on technology selection. This is at odds with the conclusions drawn in the previous step of the design hierarchy where greenhouse issues were highlighted because they did not affect the outcome. This is an indication that the decisions taken at this stage have constrained the solution more. At this advanced level of information detail decisions have already been taken to address the significant impacts and thus impacts of lesser concern come to the fore.
- Even if society expresses concerns about water consumption issues it will not be possible to address them as the preferred solution is not sensitive to changes in the weighting applied to water consumption. This would be problematic in an area where water is scarce and concern

about water consumption were high. It is this type of problem that becomes a "mess" and would require approaches such as conflict resolution (see discussion in Section 6.1).

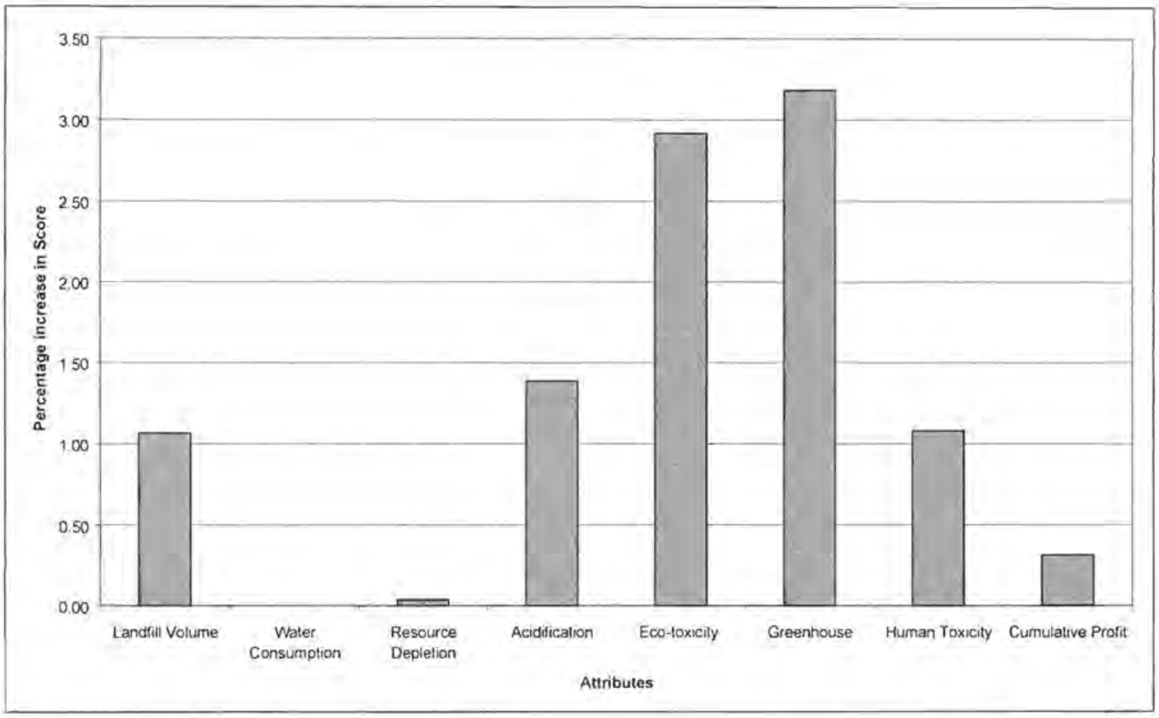


Figure 6-25 *Change in Flowsheet score for a 10% increase in attribute weighting*

6.3.10 Level 4 - Separation Systems

At this point of the design hierarchy the technology to be used has been established. This technology combination is illustrated in Figure 6-23. The separation technologies chosen will not change the nature of the waste, but they will determine the quantity of the waste. While this has the potential to change the value function, changes that accompany the design of a separation system will be relatively limited, really only "tweaking" the margins, as opposed to causing a significant change in the attribute value. For this reason the decisions taken will be driven by the efficiency of the separation and the economic costs associated with increasing efficiency.

In addition, all decisions taken at this stage should be informed by the value set elicited from society. This will ensure that the separation technologies selected do not prejudice the result obtained in the previous decision step.

In order to inform the selection and prioritisation of the separation systems assessed and selected, a sensitivity analysis can be carried out. Figure 6-26, demonstrates the sensitivity of the preferred solution to equivalent changes in the values for each attribute. A complete set of information can be found in Appendix 6-1, Section 6.1.6.

This sensitivity analysis shows that the solution is most sensitive to eco-toxicity issues and landfill volume. This is a further manifestation of how decisions taken at one level absorb constraints inherent in the permutations available and thus shift the focus of concerns as the design process proceed from step to step in the hierarchy.

It is not strictly possible to address eco-toxicity issues within the design of separation systems as this attribute or impact category is not affected by the operation of the separation system. However, it is possible to address landfill volume within the optimisation of separation systems. As the preferred solution is most sensitive to changes in this attribute then separator technology options that minimise landfill volume should be evaluated first. From the sensitivities included on Figure 6-26 the following hierarchy of separator properties can be established:

1. Landfill Volume
2. Resource Consumption
3. Cumulative Profit (or equipment cost)
4. Acidification
5. Greenhouse gas issues

In this hierarchy, landfill volume is the most important criterion when choosing the separation system, followed by resource consumption, etc. This decreases the number of criteria included in the analysis of the separation systems and simplifies the decision making process by ensuring that only the equipment which does not undermine the viability of the technology combination is included in the analysis.

Using a sensitivity analysis in this manner means that a significant number of separation system options can be pre-screened and only those options that will not jeopardise the preferred solution and its ability to address the concerns of society need be included in the model.

As this case study is purely illustrative the design of separation systems has not been included.

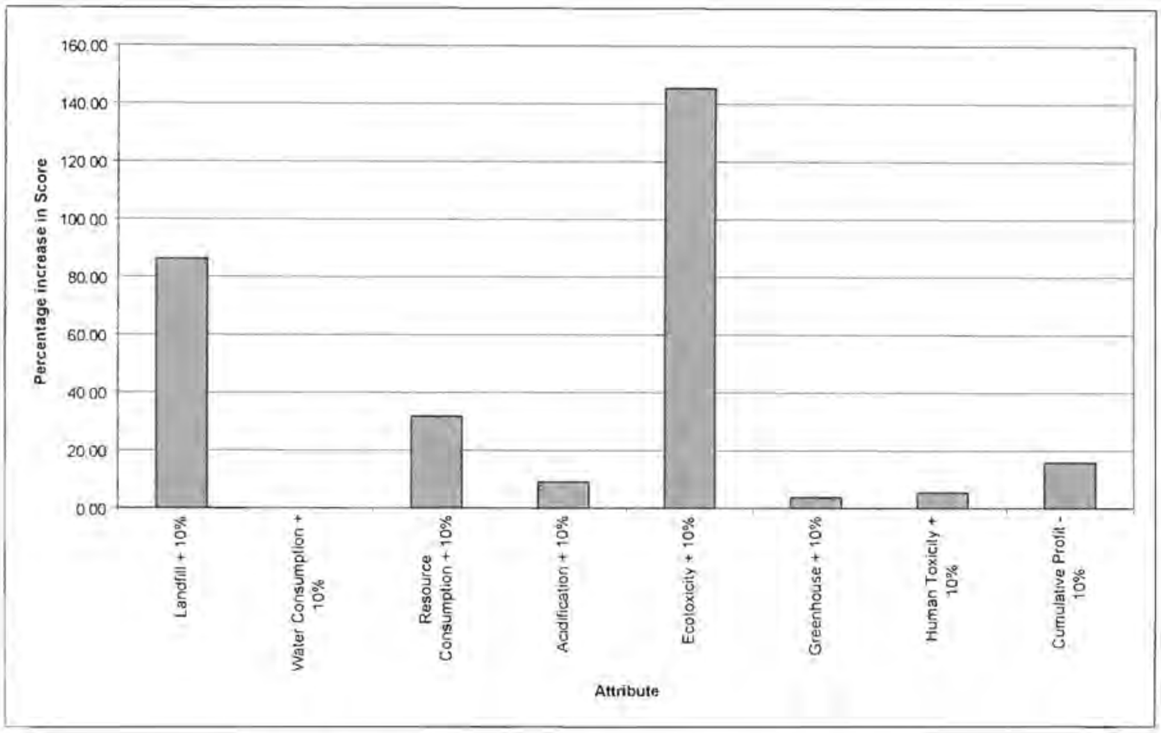


Figure 6-26 *Increase in Score for a 10% increase in Attribute Value*

6.3.11 Level 5 - Energy Minimisation and Utilities Management

The sensitivity analysis included in Figure 6-26 shows that the preferred solution is surprisingly insensitive to water consumption and greenhouse gas emissions. Greenhouse gas emissions are directly linked to the provision of energy (either as an input impact associated with electricity, or as a direct emission from the burning of coal) so it can be said that the preferred solution is not sensitive to changes in the amount of energy consumed. However, the solution is sensitive to the weighting placed on greenhouse gas emissions (Figure 6-25). Thus the minimisation of energy usage is of importance in the process.

There are a number of aqueous waste streams from the process. While it is common practice to combine these waste streams and treat them in a central effluent treatment process, a more effective waste management regime would be to keep these streams separate if possible and recover the metal value from them for re-processing either on-site or in other plants. Tools such as pinch analysis applied to heat and mass exchange network (as discussed in Section 3 of this thesis) are applicable to this step in the hierarchy.

6.3.12 The Final Decision

The final decision taken is to determine whether to proposed project will go ahead. The project proposer will be able to demonstrate how the concerns of society have been addressed in the decisions that they have taken relative to technology and site selection. As such, the project is unlikely to be vetoed. The preferred technology selection is a combination of Imperial Smelting Process and Pressure Leach. While flexibility has not been included as one of the criteria, this combination of technologies should be able to process a range of feed materials. The main constraint on flexibility of the pressure leach process being to ensure that there is sufficient iron in the feed material (Baldwin and Demopoulos, 1995). The ISP has an iron-rich slag which can be used to meet the iron requirements of the pressure leach. Concentrates that have a significant quantity of volatile metals can be routed to the pressure leach to minimise their toxic effect while concentrates with a high silver and lead content can be routed to the ISP which recovers these metals effectively to product.

The technology permutations arrived at using the design decision support framework developed in this thesis are different from the Roast-Leach-Electrowin process proposed for the Coega Zinc plant.

6.4 Conclusions

The design hierarchy presented in Section 5 of this thesis has been extended to a three-stage design process. The information gathered during an EIA process was shown to have been of value within the context of the extended design hierarchy, for his reason EIA and process design have been integrated. The point in the design hierarchy that it is possible to start an EIA was found to be design step 3 - the point at which recycle options are assessed. The three-stage design hierarchy has distinct decision structures for each stage. These have been developed. The nature of the decisions taken at these various levels can be analysed within the context of Table 2-14 of this thesis. Table 6-20 has been included to demonstrate the different levels at which the decisions taken during process design can be placed.

Table 6-20 *Decision Contexts and Decisions taken during Process Design*

Level of Decision	Interactions	Decision Process/ Cycle (UN 1999)	Decision in Extended Design Hierarchy	Element in Project Life Cycle
Strategic Level		5. Strategic planning	B - Project Selection	Project Selection
Tactical Level		3. Design and development	C - Reactor-Separator Combinations 1 - Batch vs Continuous 2 - Input-output Structure 3 - Recycle Structure	Initial Design
Operational Level		1. Operational management	4 - Separation of solids from liquids 5 - Energy Minimisation	Detailed Design

A case study on design of a zinc refinery is included to illustrate the three-stage design process. This case study demonstrates that it is possible to determine the combination of technologies (and optimal process conditions) that minimises that trade-offs made between environmental categories as well as economic performance. The results of this case study are interesting in that they identify a combination of old and new technologies as the preferred technology suite.

A number of observations can be made on the tools that can be used to inform the information structure included in Table 6-21. These tools relate to process modelling, the evaluation of the environmental objective or the MCDA element of the framework. Table 6-21 below has been developed to show where these tools are used in the extended design hierarchy.

Placing the decision structure within the context of the project life cycle as presented in Section 3 of this thesis, it is possible to delineate initial design and detailed design. This is done according to the level of detail in the information set and where these levels are placed relative to the selection of a specific site. In the project life cycle illustrated on Figure 3-2 there are four planning stages:

- Identification of Project
- Choice of Technology and Initial Design
- Site Selection
- Detailed Design

Table 6-21 *Impact Assessment, MCDA and Design Optimisation tools for specific steps within the Design Hierarchy*

Design Hierarchy Step	Decision Context	Information Structure Element			
		Process Modelling	Environmental Burden	Social Preferences	MCDA
Project Selection	Strategic	Heuristic	Macro-scale LCA	Limited, generalised information	Comparison of discrete options; heuristic or AHP
Reactor-Separator Combinations	Tactical	Process Synthesis tools; limited information available	Macro-scale LCA	Limited but less generalised	Comparison of discrete and continuous options; pre-screening; Goal Programming
Batch versus Continuous	Tactical	Process Synthesis tools; limited information available	Macro-scale LCA	Limited but less generalised	Comparison of discrete and continuous options; pre-screening; Goal Programming
Input-Output Structures	Tactical to Operational	Process Synthesis and Optimisation tools	Macro-scale LCA moving to specialists' studies from EIA	Limited but less generalised to Social Scoping results from EIA	Comparison of discrete and continuous options; pre-screening; Goal Programming to Value Functions
Separation Systems	Operational	Process Optimisation tools	Specialists' studies from EIA	Social Preferences from EIA	Optimisation of discrete options; Value Functions
Utilities Management	Operational	Heat Exchange and Mass Exchange Networks	Specialists' studies from EIA	Social Preferences from EIA	Optimisation of discrete options; Value Functions

Figure 6-27 below shows where the levels in the design hierarchy are placed relative to these stages. In this figure "Consultants" are defined to be any group of experts that supply information to the design engineers. This figure also illustrates the iterative nature of the design process and demonstrates that there is the potential for information to be found during the data collection of a level that would require the decisions taken at the previous level to be revisited. It must be recognised that decisions taken at one level of the hierarchy are predicated on the decisions taken at the previous level.

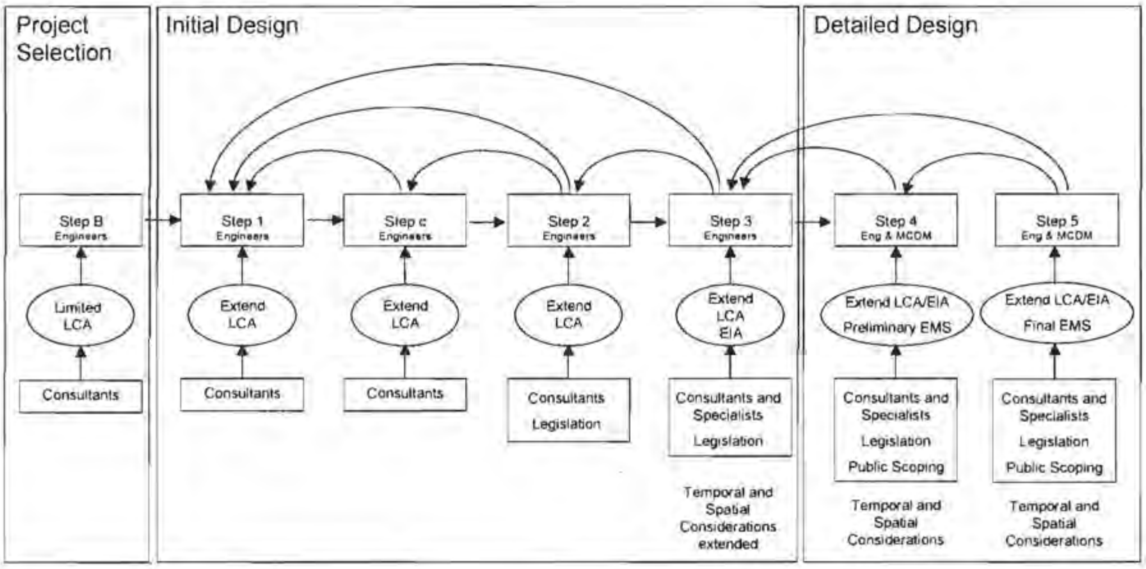


Figure 6-27 *Decision Hierarchy, Project Life Cycle and Information Sources*

Figure 6-27 also illustrates the potential sources of information for each level in the hierarchy. It indicates that the LCA/EIA process together could form the basis for the environmental management system that will be installed for the process during its operating life as well as post-closure. The flow of information to support decisions within this management structure can be within the same "shape" of information flow as within the decision support structure employed during design. This information structure is illustrated in Figure 4-8.

7 Conclusions and Recommendations

In this thesis the potential for Life Cycle Assessment (LCA) to inform environmental decision making practices for minerals processing and the design of minerals processes in South Africa has been investigated. An integrated design hierarchy for process design in the minerals industry has been developed and demonstrated within the context of a number of case studies. As such the objective of this thesis, to guide design for the environment in minerals processing, has been met.

7.1 Conclusions

There are a number of conclusions which can be drawn from the intellectual development of the decision support structure developed in this thesis. Table 1-1, included in Section 1 of thesis, highlights the main themes of this thesis:

- Minerals Processing
- Process Design
- Life Cycle Assessment
- Decision Making

Conclusions will be discussed in the context of these themes.

7.1.1 Minerals Processing

Minerals Processing was used as the context within which to develop environmental decision making and design structures for two reasons:

- The significance of the industry to the South African economy
- The lack of guidance available to the industry at present on how best to meet their stated environmental policies and goals, this with specific reference to the long term environmental impacts associated with the industry

Section 2 developed an information structure that can be used to guide environmental decision making in the industry. This information structure is based on a flowsheet approach to developing input-output models for the industry. A methodology for developing these flowsheets was developed. This methodology includes a definition of information requirements and generic set of "rules" for drawing unit operation boundaries. The potential of the information structure to guide different decisions with different decision contexts was illustrated for the case of the South African minerals industry by way of a number of case studies. In order to conduct these case studies input-output models for the South African minerals industry as a whole were developed. This inventory is unique in its coverage and comprehensiveness. The inventory has been verified by the industry in South Africa. The information structure developed can be used to support environmental decision making in the minerals industry.

In Section 3 the sensitivity of the overall environmental performance of a process to decisions taken during design was highlighted. As a result of this sensitivity it was decided that process design would form the focus of the remainder of the thesis. Process design methodologies were reviewed and were found to be lacking with respect to their ability to address considerations specific to the minerals processing industry, such as the number of contaminants in the feed stream to a minerals processing plant, and the significant energy requirements of minerals processing. A review of approaches used in design and optimisation for best environmental performance was also included. These methodologies were found to be deficient in that:

- Environmental objective functions were aggregated to the point that addressing the temporal and spatial effects of impacts associated with wastes from the minerals industry would not be possible
- The boundary definitions used in these design and optimisation methodologies very limited (usually to a process boundary) which eliminates a number of significant impacts associated with the provision of inputs to the process (such as energy) from the analysis

Section 4 presented a review of decision making and the tools of MCDA. It was proposed that these tools be used to overcome the deficiencies associated with this over aggregation of environmental objectives.

An extended design hierarchy was presented in Section 5. This hierarchy is based on that of Douglas (1988), but has been extended to include considerations specific to the minerals industry, as well as environmental considerations. The extended hierarchy was demonstrated in the context of the design of a gold plant. This demonstration showed that the hierarchy can be used to guide process design decisions for the minerals industry.

7.1.2 Process Design

The intention of this thesis is to incorporate environmental considerations into process design. Quantifying the potential environmental impact of a process and incorporating information into design decisions is not sufficient. It is also necessary to determine how these impacts are valued by society in order that decisions made during process decision address society's concerns.

The rules used to develop flowsheets and information sets for the information structure developed in Section 2 were discussed in the context of design and design variables. As a result the information structure can be used to synthesise models developed for process design. Section 3 of this thesis illustrated the importance of design decisions to the overall environmental performance of a process. Section 3 also contains a review of different process design approaches. It was decided that a knowledge-based approach to process design would form the basis of the design methodology developed in this thesis. The Douglas design hierarchy (1988) was chosen as a point of departure for two reasons:

- It is based on a flowsheeting approach to process design and thus can be informed by the information structure developed in Section 2
- It reflects a hierarchy of decisions and decision making is another theme in this thesis

Process synthesis for improved environmental performance was also reviewed in Section 3 as the decisions taken during design are based on models of the proposed process at each point in the hierarchy. It was found that, while the synthesis methodologies are rigorous, the manner in which environmental objectives are aggregated (bar the work of Azapagic (1996)) excludes the potential for incorporating social values into the design process. In Section 4 the structures of LCA were used to formulate environmental objectives functions, based on process models which were developed using the information structure included in Section 2. These environmental objective functions retain sufficient information detail to facilitate:

- The inclusion of social values into process synthesis
- Considerations of the long-terms environmental impacts associated with minerals processes

Section 5 extends the Douglas Design hierarchy (1988) to include considerations specific to minerals processing. These extensions relate to the nature of minerals processes which are usually made up of a chain of reactors and separators for all phases (solids, liquids and gases). The design hierarchy is extended further to include environmental considerations. The questions of whether the proposed project is the most effective use of that raw material in the context of a specific set of social values, is addressed here. This extended design hierarchy was then demonstrated to be effective in the context of the design of a gold process which is a combination of small and large scale plants.

At this stage the design hierarchy is still deficient in its ability to incorporate, proactively, the requirements of society into the decisions taken. The main reason for this deficiency is that adequate information is not available at this point in the project life cycle. EIA is highlighted as a process which gathers information on social values as well as on the site-specific impacts associated with proposed projects. However, it is not possible for an EIA to be conducted before process design has started. For this reason the EIA process and process design are integrated. The point in the decision hierarchy at which sufficient information is available to enable an EIA to be conducted is identified. This is the point at which the recycle structure is chosen. This is the first time that streams crossing the process boundary are calculated.

The final stages of the design hierarchy are informed by the EIA process. Technology is chosen and optimised in the context of the set of values expressed through the EIA. The tools of MCDA are used in this optimisation exercise. In this context a three-stage design hierarchy was developed and demonstrated in the context of the design of a Zinc Refinery.

7.1.3 Life Cycle Assessment and Life Cycle thinking

LCA was chosen as the metric whereby the potential environmental impacts associated with a process can be evaluated. In addition, Life Cycle thinking, within the cradle-to-grave boundary was applied to all developments in this thesis.

In Section 2 an information structure was developed to evaluate LCIs of minerals processes. A set of "rules" for defining boundaries was established. The aim of these rules is to allow as much aggregation within the flowsheet as possible while still retaining sufficient information detail to facilitate the Improvement Assessment stage of LCA. To this end the audit trail structure of LCA was developed fully in Section 4. This audit trail forges the link between unit operation and environmental impact, directing Improvement Assessment.

The application of LCA to decision making is explored in Section 4 and demonstrated in the case studies included in Sections 5 and 6. LCA is used to formulate environmental objective functions for proposed flowsheets structures. This enables design engineers to incorporate environmental criteria in process synthesis and optimisation. This was demonstrated in the context of the case studies in Section 5 and 6.

Life Cycle thinking informed the discussion included in Section 3 where design decisions were analysed in the context of the entire project life cycle. Life Cycle thinking also prompted the inclusion of the first two steps in the extended design hierarchy developed in Section 5. Using LCA information to guide EIA specialist studies was demonstrated in Section 6.

7.1.4 Decision Making

Process design can be viewed as a series of inter-related decisions. In order to include environmental considerations in process design in a meaningful manner it is necessary to use the tools of MCDA. For MCDA tools to be applicable the decisions must be correctly structured and the decision context defined.

Section 2 demonstrated the ability of the information structure to support environmental decisions in different decision contexts. Section 3 demonstrated that decisions taken at different points in the project life have different effects on the overall performance of the project.

Decision making was reviewed in Section 4 of this thesis. Decision contexts and decision structuring were discussed. This Section also presented the tools of MCDA and illustrated the manner in which these tools are used in decision making. The use of LCIA to inform the selection of criteria within an MCDA algorithm was demonstrated in Section 5. This Section also demonstrated the decisions taken during design for the environment using the case of a gold plant to illustrate these decisions. In Section 6 the three-stage integrated design hierarchy of decisions was presented. Decision cycles and decision structures were developed for each stage in the design hierarchy.

7.2 Recommendations for Future Work

The conclusions presented above address a number of the considerations included in Table 1-1. However, deficiencies in a number of areas have been noted throughout this thesis. These deficiencies form the basis for the recommendations included here. These recommendations give an indication of how each deficiency could be addressed. Recommendations are grouped according to the considerations presented in Table 1-1.

7.2.1 Information structures

The information structure developed in this thesis is sufficient to inform LCA and to support environment decision making for the process industries. However, the modelling methodologies applied to the structure could be more rigorous. The matrices developed are sparse. The application of sparse matrix algebra to the optimisation regime would be beneficial. The fact that local minima were found in the solution spaces of the case studies in Section 6 suggests that not only should more rigorous optimsation tools (as opposed to *Microsoft Excel®*) be used, but that optimisation algorithms which give efficient solution time should be explored.

In addition, the extended design hierarchy includes design considerations specific to minerals processing and to design for best environmental performance. However, there is no consideration of design for controllability and operability. These aspects play a significant role in the environmental performance of a process (Romangoli, 1999). It is suggested that these considerations be factored in from step 3 of the hierarchy (recycle structure) but would become more significant in the final two steps of the hierarchy where process optimisation takes place. This field requires more study.

7.2.2 Life Cycle Inventories

The information structure developed includes a consideration of where unit operation boundaries should be drawn around unit operations. This choice is driven by considerations of the potential impact associated with each process. These unit operation boundaries are drawn to aid the audit trail to ensure that it is possible to trace the source of an environmental impact within the process.

However, it is possible for the boundaries to be drawn in such a manner as to obscure the source of an impact. This can occur in two instances:

- When there is insufficient information available to specify unit operations to the level of detailed required to support the audit trail
- When the unit operation boundary is drawn to include a recycle stream

To illustrate these two points, refer to the flowsheet modelled for the zinc refining industry and included as Figure 6-8 in Section 6. In this figure, solution purification has been grouped into a single unit operation due to lack of information on the various unit processes; and leaching has been drawn so that the unit operation boundaries lie outside the recycle loops. Figure A6-1 included in Appendix 6-1 shows more detail of the structure of this recycle scheme. It should be possible to allocate impacts to unit operations in the more detailed flowsheet without having to add this increased detail to the flowsheet being analysed.

In order to address this it will be necessary to develop an approach for allocating impacts to unit operations. An approach to this allocation method would be to determine the sensitivity of the impacts to changing operating variables within the unit process. This could be executed as a marginal analysis allowing a marginal change in contribution to impact categories to be allocated to an operating variable and thus a single section of an aggregated unit operation in a similar manner to that adopted by Azapagic (1996).

7.2.3 Environmental Impact Assessment

The integrated design hierarchy requires that the output from the EIA process be altered. While it is possible for the EIA process to deliver the information in the format required by the design decision structure, this has yet to be tested. The two focuses of this work should be:

- The ability of specialist studies to be conducted and presented for a combination of technology permutations
- The ability of the Social Scoping exercise to deliver values as required by the MCDA methodology selected

The first of these should be possible. There will however be an associated increase in cost as a result of information being required on a larger number of permutations.

To address the second, it should be recognised up-front that there is a school of thought that argues that this should never be done. However, MCDA specialists have invested a great deal of time in determining methodologies suitable for interpreting social requirements mathematically so that they can be incorporated into mathematical models. These approaches range from determining non-linear trade-off schemes (Voronin, 1997) to fitting scales to ratio comparisons (Wolvaardt, 1997). Suffice it to say that these approaches are usually specific to their areas of application and decision context. However, they are sufficiently well-developed to be applicable in the context of decisions taken during the EIA process. More important than the development of these methodologies are the following reservations:

- Whether the EIA community is prepared to use these tools
- Whether the groups included in the social scoping exercise are able to understand the methodologies and accept them as meaningful and un-biased

Addressing these reservations would require a significant amount of capacity building both amongst the EIA specialists and in the various stakeholder groups involved.

7.2.4 Impact Assessment

The specialists' studies included in EIA are usually "snapshot" views associated with a proposed project being located at a specific site. These specialist studies often use complex modelling tools to derive their interpretations. However, the temporal and spatial effects of a proposed project are often poorly resolved in this type of analysis. In order to include these effects it would be necessary to evaluate the performance of the proposed project/site combination at a number of time intervals during the proposed life of the plant. For example, if the proposed life of plant is 40 years, then the specialist study should determine the potential impact for every 5 yearly interval over those 40 years. While some of these impacts would not change, impacts on, for example, groundwater, would change with the seasons as well as with time as pollutants accumulated in soils.

There are two fields of study required to determine whether this issue can be addressed:

- Is it possible for EIA specialists to deliver time and space dependent information?
- Can the information structure be adapted to include temporal and spatial effects?

If the EIA specialists were able to present their information as a function of time and space over the life of the project (for example, a moving boundary of pollutant concentration in the groundwater system), it should be possible to factor this into the information structure. Economic information is calculated for each year and then summed to give an indication of the total economic performance. In the same way it should be possible to develop an environmental profile for the process for each year (or some other time step) and thus determine the temporal and spatial effects of decisions taken. It must be recognised that these impact assessments will still be predicted, potential impacts.

7.2.5 Decision Contexts and Decision Structures

The decision contexts and decision structures developed in this thesis are particular to process design. There is potential to apply the decision support structure developed in different contexts such and Strategic Environmental Assessments and Environmental Management Systems.

A further recommendation is in regard to the economic objective formulated in this thesis. With reference to Figure 3-5 where economics is included in two information sets:

- As micro-scale economics in the techno-centric information set
- As macro-scale economics in the socio-centric information set

This economic objective formulated in this work includes considerations of micro-scale effects only. No indication of the economic effect at a macro-scale is made. This was mentioned in the case study on the gold plant where the different economic effects of small-scale plants as opposed to large-scale plants could not be accounted for. It is necessary to develop the formulation of the economic objective function further to include these considerations.

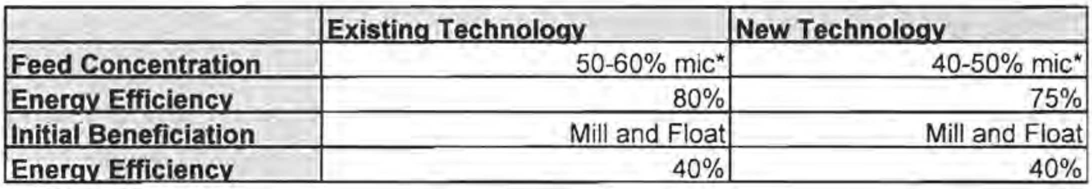
7.2.6 Thermodynamics

An argument has been presented that thermodynamic limitations will set the limits for the environmental performance of a process. It is proposed that the best manner in which to ensure that the technology combination selected during process design approaches this limit as closely as possible is by conducting a thermodynamic analysis of processes being considered in the design. This will not be a trivial matter.

As has been stated throughout this document, energy is a significant input to the minerals processing industry. Energy is required to change the physical (for example milling) and/or the chemical (for example leaching) state of the minerals in the ore. The reason for this energy input being so high is related to considerations of entropy - metals occur in ores as dispersed, usually inert, minerals. Energy is invested in the process to make the metals available to concentration and refining technologies, and then to increase the purity of the product.

It should thus be possible to plot the path which uses the least amount of energy in delivering the required product. As was observed in Section 3 of this thesis, there is a thermodynamic limit within which the process must operate. In order to drive process performance as close as possible to this thermodynamic limit a closer examination of energy inputs is required. To illustrate this, Table 7-1 has been developed. This table lists details of two potential processes; one that can refine material from a less concentrated feed material, the second requires a higher concentration in the feed to the refinery. The refining processes have a higher energy efficiency than the beneficiation process (where efficiency is defined relative to the amount of energy required to deliver a set amount of metal to the product from that process). While the new technology may have a reduced energy efficiency relative to the existing technology, the amount of energy invested in initial beneficiation, which has a significant energy requirement, is reduced as the material fed to the new technology is of lower concentration.

Table 7-1 *Comparison of Energy Inputs to Technology Combinations*



	Existing Technology	**New Technology**
Feed Concentration	50-60% mic*	40-50% mic*
Energy Efficiency	80%	75%
Initial Beneficiation	Mill and Float	Mill and Float
Energy Efficiency	40%	40%

* mic = metal-in-concentrate

Assuming that it takes two-thirds the amount of energy to beneficiate the feed to the new technology than it takes to beneficiate the feed to the existing technology then it is possible to calculate that the new process required 80% of the input of the existing technology if beneficiation and purification are considered together.

While this is a qualitative indication of the type of analysis that could be conducted it is argued that such an analysis has significant value for the minerals industry.

A further element should be added to the analysis. This is the consideration of the thermodynamic stability of wastes leaving the process. Equivalency factors in LCA are inadequate in their ability to interpret the potential of metals to impact on the environment. One potential method would be through a thermodynamic analysis of the wastes where the bio-availability (as a function of their thermodynamic stability) of metals is determined. The more stable a waste, the less available it is and thus the lower its potential to pollute. These considerations of stability are directly linked to the energy input to the process, and whether the energy was added to the process to change the physical or the chemical state of the mineral.

This is not a trivial exercise. Complications arise in trying to determine the basis for the system, and whether entropy or exergy should be analysed. Much fruitful work could be conducted in this respect.

7.2.7 Uncertainty

Information uncertainties have not been addressed specifically in this thesis. There is the potential for uncertainty to arise in a number of places in the information structure. There is also the potential for this uncertainty to be translated through the information structure, rendering the final result questionable. The study of this translation of uncertainty is a significant one and beyond the scope of this thesis. The main sources of information uncertainty are:

- Choice of system boundary
- Too high a degree of aggregation within the unit operations as discussed above
- Assumption sets governing unit operations performance
- Stream splits directing stream flow between unit operations
- Insufficient and inaccurate equivalency factors in LCA
- Assumptions governing economic performance, such as assumptions made about interest rates
- Translation of societal preferences into a set of weightings

As a final statement, the process design decision support structure developed in this thesis is not merely an academic extension and combination of existing tools. It is applicable to the minerals industry in its current form and can guide continuous improvement through innovative design. In applying this approach to environmental decision making the minerals industry will be better placed to meet their stated environmental objectives as part of their commitment to sustainability.

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