Towards sustainable metal cycles:

the case of copper

Damien Giurco

Thesis presented for the degree of
DOCTOR OF PHILOSOPHY
in the Department of Chemical Engineering
UNIVERSITY OF SYDNEY

March 2005

Cover illustration: Stall roasting of copper matte

From *De Re Metallica* by Georgius Agricola, 1556

Per
Giorgio Giurco
and
Francis Crowe

DECLARATION

I declare that all work in this thesis is my own original work, unless stated otherwise.

This thesis is submitted for the degree:
Doctor of Philosophy, at the University of Sydney.
Material in this thesis has not been submitted for any other degree.

____
Damien Giurco

ABSTRACT

Developing an approach that delivers improved environmental performance for metal cycles is the aim of this thesis. Integral to the sustainable use of metals is the need to reduce environmental impacts associated with the mining, refining and recycling activities that supply metal to the economy. Currently, the links between the location and duration of these activities, their resultant impacts and the responsible parties are poorly characterised. Consequently, the changes to technology infrastructure and material flow patterns that are required to achieve sustainable metal cycles remain unclear to both industry and government actors. To address this problem, a holistic two-part methodology is developed.

Firstly, a reference schema is developed to address the complexity of structuring analyses of the material chain at different geographical and time scales. The schema identifies actors and system variables at each scale of analysis and guides the level of information detail and performance indicators to be used in material chain characterisation. Material chain characterisation involves modelling material and energy flows for current activities as a series of connected nodes and linking these flows to resultant environmental impacts. The approach identifies the material chain activity responsible for each environmental impact and makes trade-offs between impacts explicit. Sensitivity analysis of the models identifies the key variables that enhance performance. The influence of actors over these variables is assessed to target areas for improvement.

This first part of the methodology is illustrated using case studies that assess the current performance of copper material chain configurations at different geographical scales within the reference schema.

The analysis of global material and energy flows indicates that the majority of environmental burden in the copper material chain is attributable to primary refining of metal from ore. Modelling of the dominant primary refining technologies using region-specific information for ore grade, technology mix and energy mix reveals that the total environmental impact differs by factors of 2–10 between world regions. The study of refined copper imports to Europe from various regions outside of Europe reveals that lower global warming impacts are achieved at the expense of increased local impacts from the producing regions. Overall, only limited improvements are possible without investing in new technology infrastructure.

Evaluation of an innovative copper refining technology finds that collaboration with clean energy suppliers reduces global warming impacts more than changing process design parameters. To better assess the local impacts that are directly controllable by the technology operator, a new indicator incorporating the stability of solid waste is developed.

In the second part of the methodology, the link established between actors, their control over key system variables and resultant impacts is used to design preferred future configurations for the material chain. Dynamic models are developed to evaluate transition paths towards preferred futures for individual and collaborative action by industry in the context of externally changing variables (for example, increasing demand for copper and declining available ore grades).

Both new copper technology infrastructure and new material flow patterns are assessed in transitions toward preferred futures for a case study of the United States. The improvements resulting from the introduction of new primary refining technology by individual actors are negated by increasing impacts from declining copper ore grades over time. Achieving a combined reduction in local and global environmental impacts requires collaboration between industry actors to immediately increase the recycling of secondary scrap.

Significantly, this methodology links actor decisions with their impacts across scales to prompt accountability for current performance and guide useful collaborations between actors. The methodology then delivers a comprehensive assessment of the scale and timing of required interventions to achieve more sustainable metal cycles.

ACKNOWLEDGMENTS

Many people have supported me on the journey toward submitting this thesis, for which I am very grateful.

I wish to sincerely thank my supervisor Prof. Jim Petrie, for his support and his encouragement to strive for excellence in academic scholarship.

Financial assistance from the F. H. Loxton Postgraduate Studentship, the Department of Chemical Engineering and Prof. Jim Petrie are gratefully acknowledged.

Thank you to staff at BHP Billiton and Intec Copper for fruitful collaborations, especially to Heather Thompson for help with process modelling.

Special thanks to Peter Holt, Mary Stewart, Mary Tomsic, Brett Alexander, Matthew Warnken and Martin Treitz for generously giving their time to support my work and to Flavio Giurco for invaluable proofreading. Thank you also to the University of Sydney library staff for their willing assistance with obtaining reference material.

Thank you to Prof. Jannie van Deventer (University of Melbourne) for first suggesting that postgraduate study at The University of Sydney would be a worthwhile pursuit, and to all my friends and colleagues who have contributed to making this time in my life so enjoyable.

Thank you to my family for their steadfast support in everything I do.

Lucy, thank you for your patience and love which I treasure.

CONTENTS

FIGURES

TABLES

ACRONYMS & TERMS

Acronym or Term	Description
Acidification	decreasing pH of natural systems through mechanisms such as acid rain
Actors	industry and government decision makers that can influence change to flows and infrastructure configuration of material chains
Ecotoxicity	toxicity to local aquatic systems
Flash smelting	the dominant pyrometallurgical process for copper smelting
Gangue	waste from mining processes
GHG	Green House Gases
GWP	Global Warming Potential
Hydrometallurgy	use of liquid reagents to purify metal, for example heap leach solvent extraction electrowinning (SX/EW)
LCA	Life Cycle Assessment, a tool for evaluating the environmental performance of products and processes comprising four main phases: goal definition and scope, inventory analysis, impact assessment, interpretation
LCIA	Life Cycle Impact Assessment, the third stage in LCA
Long-life scrap	scrap derived from goods which have a useful lifetime of 20–60 years
Low grade scrap	scrap with a copper content of 10%–70%, average 30%
Material chain	collective term for the processes of mining, refining, manufacture, use, disposal and recycling through which metal cycles in the economy
MC	material chain (also called value chain or material value chain)
Metal cycle	the representation of metal cycling through the material chain
MFA	Materials Flux Analysis, also called Material Flow Accounting
MIPS	Material Intensity Per unit Service
No. 1 scrap	scrap with a copper content of 99%
No. 2 scrap	scrap with a copper content of 95%
Pyrometallurgy	use of thermal processes to purify metal, for example, flash smelting and reverberatory smelting
Reverberatory smelting	a pyrometallurgical process for copper smelting which is being phased out due to its emissions of sulfur dioxide which contribute to acid rain
Short-life scrap	scrap derived from goods which have a useful lifetime of 0–10 years
Spatial domain	geographic system boundary of interest
SX/EW	solvent extraction electrowinning a hydrometallurgical process for copper refining

CHAPTER ONE

Introduction

1.1 BACKGROUND

Metals are essential to our everyday lives. Since before the Bronze Age in 3000 BC, metals were recognised as useful for civilisation and have continued to perform unique roles in supporting basic human needs. Today, metals are used in machinery that harvests and eventually transports food to our homes; in pumps and pipes that supply our water; and in electrical wires that power our lighting and telecommunications infrastructure. We rely on metals to sustain our lives.

The scale of metal usage worldwide has increased dramatically since the Industrial Revolution. The increasing use of metals has led to adverse environmental impacts, ranging in scale from global warming to toxic discharges affecting local land and waterways. Our current patterns of metal production, use and disposal render the magnitude of these impacts unsustainable in the long term. As a result of thesis impact, the current health and wellbeing of human and other life on Earth today is also diminished.

The mining, refining and recycling industries, which make metals available for use in our society, are under increasing pressure to improve their environmental performance. Improving this environmental performance is part of a wider initiative to change the operation of the minerals industry towards being more sustainable. A sustainable system will seek to reduce emissions associated with the metals cycle and 'close the loop' of metal flows through increased recoveries and recycling of metals from secondary sources. It will also help balance the social and economic impacts of the industry.

1.2 MOTIVATION AND AIM

Designing strategies to improve the sustainability of metal cycles is a complex task. Attempts thus far have largely failed to show how preferred futures can be identified and transitions toward them evaluated. The task has proved difficult for several reasons.

First, quantifying baseline performance is subject to uncertainties regarding where, when and to what extent the impacts from generated pollution will be manifested.

Second, the mining, refining and recycling activities, which deliver metals to society, are inter-related and must be considered collectively to fully appreciate the problem and create solutions; to date this has not been the case.

Third, this 'materials chain' of activities (also called 'value chain') operates at different geographical locations across the globe and is controlled by government and industry actors with varying abilities to facilitate improvement to one or more material chain activity. Actors need clearer signals regarding what changes are required to bring about more sustainable operation of the material chain.

To systematically improve performance in the material chain requires a thorough understanding of the interaction between:

- ♦ flows of materials and energy through the material chain
- ♦ the ability of actors to influence changes to infrastructure and the configuration of flows in the material chain
- ♦ their resultant impacts associated with material chain configurations.

A structured approach is required to characterise the current operation and environmental performance of the value chain across geographical and time scales.

To guide industry decision making, it must also establish a clear connection between required actions by industry, the scale of the actions, their timing and their resultant impacts in order to evaluate different transition paths toward more sustainable futures.

This thesis aims to develop such an approach.

1.3 STRUCTURE OF THESIS

This thesis is presented in two main sections. The first develops the new methodology in generic terms, while the second demonstrates how the methodology is applied via a series of case studies (Figure 1-1). The dotted lines in Figure 1-1 indicate the links between methodological developments and the case studies in which they are applied.

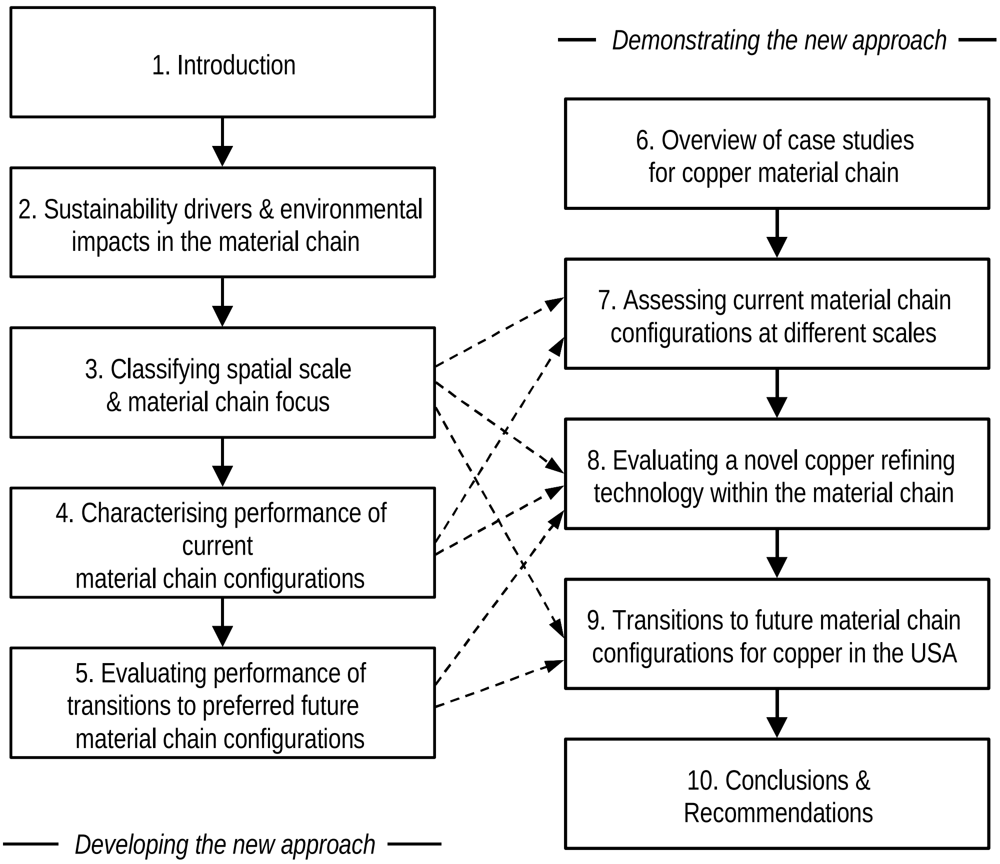


Figure 1-1: Overview of thesis structure

1.3.1 *Developing the new approach*

Chapter 2 explores in detail the drivers of sustainable development and their effect on improving the environmental performance of the minerals industry. In particular, it asks why current approaches to date have been too narrow in focus (across a range of spatial scales and along the value chain) to effect significant progress toward improved environmental performance. It then outlines the key hypotheses for the thesis.

Chapter 3 develops a 'reference schema' to classify decision problems according to their spatial scale and material chain focus, from local to global and from constituent parts of single material chains to multiple material chains. This reference schema establishes a consistent framework for assessments at different scales, including appropriate models, indicators and information details at each scale.

Chapter 4 develops an approach to characterise the current materials chain configuration at different spatial scales. The aim of characterisation is to link potential actions (decisions) taken by industry and government actors to change material chain configurations to their resultant impact. It involves:

- developing models of material and energy flows
- using these models to assess environmental impact
- identifying model variables to which impact is sensitive and
  the actors who control these sensitive variables.

The characterisation of current material chain configurations, serves as a baseline against which future improvements can be compared.

Chapter 5 develops a new approach to challenge the status quo by envisioning more sustainable future material chain configurations and developing models to evaluate different transition paths towards these preferred futures. The use of dynamic modelling, over an extended time horizon, allows for the influence of actor-controlled and external variables on performance to be assessed.

1.3.2 *Demonstrating the new approach*

Chapter 6 summarises the new approach and highlights how the key aspects of the methodology will be demonstrated through case studies presented in Chapters 7, 8 and 9 that relate to the copper material chain.

The case studies in Chapter 7 assess performance of the status quo at an aggregated global level, and then based on the results of the global analysis, look in more detail at the mining and refining elements of the value chain by including region-specific geological and technological detail. They then explore the improvements to environmental performance that can be made within the current network of material chain infrastructure for the region of Europe, and associated trade-offs between different environmental impacts.

Given that only limited improvement can be made by altering flows through existing infrastructure, Chapter 8 shows how to assess an innovative copper refining technology using plant-specific detail, as an example of a potential new infrastructure which could be introduced to the material chain. It also demonstrates the ability to characterise material and energy flows and impacts at a range of scales within the reference schema. Life Cycle Impact Assessment (LCIA) is used as a basis for characterising environmental performance and Chapter 8 extends impact characterisation techniques to reduce uncertainty regarding potential environmental impacts inherent with the LCIA approach.

Chapter 9 develops specific alternate futures where more ambitious changes to infrastructure (via the introduction of new technologies) and changes to flows (for example, the ratio of primary to secondary resource utilisation) take place. Dynamic modelling is used to show how different paths toward preferred futures can be evaluated for the least environmental burden over a 50 year time horizon. Based on the system variables requiring change to effect these preferred futures, a discussion of the required actions to follow these roadmaps toward preferred futures is given. The modelling is undertaken in the context of a predicted decline in primary resource quality and changing residence times of copper products in use, which affects secondary resource quality and availability.

Chapter 10 presents the final conclusions and recommendations concerning the generic methodology development and its copper-specific implementation.

CHAPTER TWO

Metal cycles & their environmental impact

Metals are used extensively in society to perform a variety of useful functions, as highlighted in Chapter 1. However, the processes of mining, refining and using metals also generate adverse environmental impacts, which are ultimately unsustainable. Within the broader context of sustainability, the focus of this thesis is on reducing the environmental burden associated with making metals available for use in the economy, and on understanding how this might be achieved by manipulation of the metal production chain. This narrows the scope of this work in two ways; first, to a focus on environmental performance; second, to a focus on metal production rather than use.[1] The environmental impacts occur at a range of spatial scales from global, including such issues as climate change, to local and regional scales, covering pollution of air, land and water. The current magnitude of these impacts and the lack of accountability for their generation makes the current situation unsustainable (OECD, 2001; Azapagic et al., 2004). At present, the effect of initiatives that target improved environmental outcomes in metal production are not clearly articulated in terms of their impact on the material chain as a whole, nor in terms of describing their impacts at different geographic scales. This hampers effective intervention by industry and government because each has different interests and influence over activities from mining and refining to production, use and re-use, and co-ordinated planning efforts directed to improve performance of the material chain as a whole are lacking. This thesis proposes that connections between material and energy flows in the material chain, the ability of actors to influence the material chain configuration and the impact of these actions, must be better characterised in order to identify preferred material chain configurations that cycle metal in society with less environmental impact.

This chapter provides an overview of the minerals industry's operation and performance (Section 2.1). Sustainability concepts and interpretations are explored to establish goals for improved environmental performance. The limited ways that the minerals and metals industry has used sustainability concepts to drive improved environmental performance are then explored (Section 2.2) together with a future vision for sustainable metal cycles and the contribution of this work toward this aim. Finally, Section 2.3 proposes an analytical framework and specific hypotheses for improving the future environmental performance of industry, based on a materials chain approach that is applied across spatial scales from considering the global industry to local operations.

2.1 BACKGROUND TO METAL CYCLES

Refining metal generates significant environmental impacts (Dudka and Adriano, 1997; Norgate and Rankin, 2000) and the metals industry accounts for more than a quarter of global toxic emissions (Jackson, 1996). Before examining strategies for reducing the impact of making metals available to society, an understanding of the ways in which metals are currently sourced and circulated in our economy is required. This section provides an overview of the metals industry, the concept of a materials chain, the impacts derived from the operation of the materials chain, the actors involved in the materials chain and the geographic activity of the industry.

2.1.1 *The economic dimension of bringing metals into the economy*

Few metals occur naturally in forms which are readily usable (Henstock, 1996). Consequently, considerable effort is expended in the mining, beneficiation and refining of metals to prepare them for service in the economy. The individual steps in this process are further discussed in Section 2.1.2.

To provide a context for this research, consider the extent to which metals are used in society. Table 2-1 shows the production of the top four metals produced globally (plus

---

[1] Consideration is given to the types of uses to which metals are put, as this affects the quality and quantity of potential secondary scrap resources, but impacts resulting from the use phase of metal-containing goods are not considered in detail in this work.

gold for comparison), which amounts to millions of tonnes annually. The total value of these mineral commodities is a significant driver behind many of the world's economies. The three countries with the largest minerals sectors by economic value are the USA, South Africa and Australia. For the USA, minerals only represent 0.5% of GDP; however, in Australia, the minerals sector represents 45% of merchandise exports and 9% of GDP (MMSD, 2002). In less developed countries – such as Zambia, Niger and Guinea – the minerals sector accounts for up to 70% of merchandise exports (MMSD, 2002). This illustrates the importance of metal products to many national economies.

Table 2-1: Production of selected metals of importance in 2000 (MMSD, 2002)

Metal	Annual Production (thousand tonnes)	Approximate Price ($US per tonne)	Total Annual Value (US$ million)
Steel	760 000	300	228 000
Aluminium	24 000	1 500	36 000
Copper	15 000	1 800	27 000
Zinc	9 000	1 200	10 800
Gold	2.6	8 600 000	22 360

Copper, which is the focus for case studies in this thesis, is an important world commodity as shown in Table 2-1. It is widely used in electrical and electronic wiring and equipment (both domestically and industrially) and in the transport and telecommunications sectors. Copper is also used in piping and roofing and as an alloy in brass and bronze.

Technological advances in mining and refining have reduced the real cost of many metals over the last century (Ayres et al., 2001; Batterham, 2003). This fall has occurred despite the fact that companies are currently mining ores of much lower grades,[2] which require additional processing that increases the cost of production. For example, while the average ore grade for copper in 1900 in the USA was approximately 3%, in 2000 it was 0.5% (Ayres et al., 2001). Technological advances have enabled the mining of lower grade ores by overcoming technical and economic barriers, but at the expense of increasing environmental impacts.

From an environmental perspective, there are significantly increased impacts associated with refining metals from lower grade ores, compared with higher grade ores.

[2] Grade is defined as the percentage of the desired metal contained in the ore. For example, a copper ore with a grade of 1% would contain 10 kg of copper for each 1000 kg (tonne) of ore.

Norgate and Rankin (2000) show that for both copper and nickel, the global warming impact associated with metal production doubles when refining ores with 0.5% metal content as opposed to those with 1% metal content and the impact doubles again with an ore grade reduction from 0.5% to 0.25%. These environmental costs of processing lower grade ores have largely been externalised (as evidenced by declining costs through time for metals, despite lower ore grades). In effect, the extraction and refining activities of metals are priced too cheaply for the amount of environmental impact associated with them. This is illustrated in Figure 2-1 which shows that 'resource extraction' and then 'processing & refining' have the highest environmental impacts respectively, but are costed in a way that has them contribute too little in economic value, reflected by the steep slope of the impact/value relation.

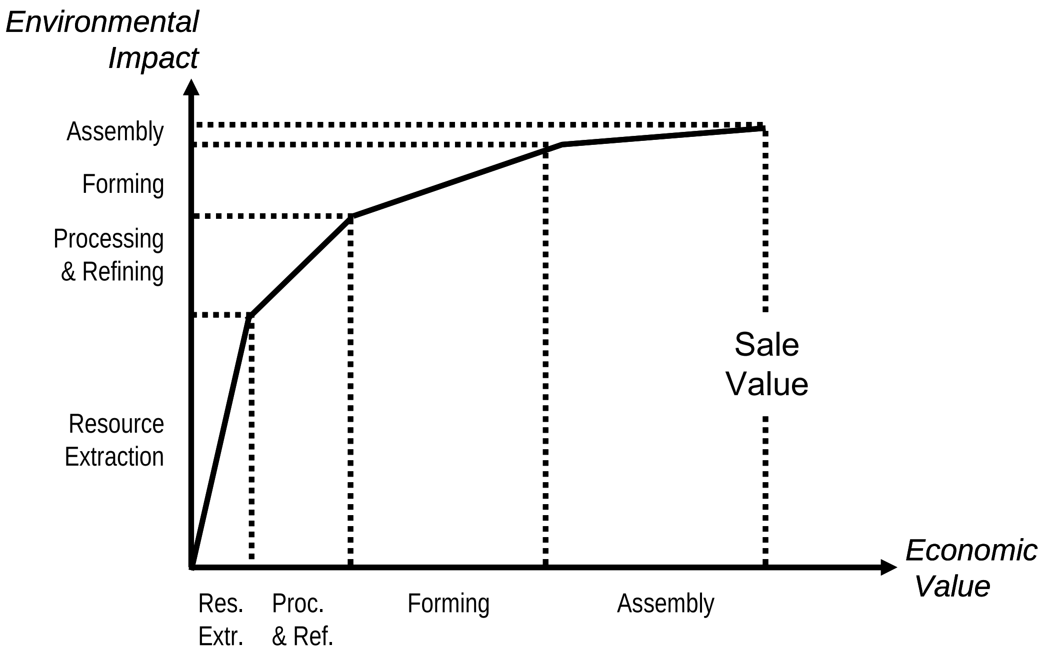


Figure 2-1: Relationship between added economic value and environmental impact at resource processing stages (after Clift and Wright, 2000)

By contrast, 'forming' and 'assembly' have less environmental impact, whilst generating the majority of the economic value. The example in Figure 2-1 relates to the manufacture of a mobile telephone, however, the authors expect the convex nature of the impact/value curve to apply more generally to other supply chains. This suggests that resource extraction and processing companies may have leverage to improve the environmental performance of the material chain overall by improving the highly impacting stages within their control. However, if this increases the price of metal commodities they sell, then until assemblers are judged on both the cost and cumulative impact of the finished products they sell, there will be little motivation to preferentially source metal from cleaner resource extraction and processing companies. To address this problem, the merits of changing the way costs are calculated to include externalities, or, supplementing cost indicators with separate environmental indicators to aid decision making are explored in the remainder of this section (Section 2.1.1).

An 'externality' or externalised cost, is a cost that is (either partially or mostly) borne by parties other than those controlling the externality-producing activity (Jaffe et al., 2005). This contrasts internalised costs to the firm such as labour and raw materials, for which it pays. An example of an externality would be site-contamination or river pollution whose clean-up cost is borne by the community rather than the pollution generator. In this example, the full extent of environmental damage may only manifest after the factory generating the pollution has closed and government authorities could be left to take responsibility for the problem. Continued growth in economies which fail to include externalities is not optimal, nor sustainable (Hepburn, 2002) as unsustainable practices are only further perpetuated.

Environmental policies seek to address the externality problem in either of two ways (Jaffe et al., 2005)

- imposing limits on pollution through regulation
- internalising environmental costs.

Using state-based regulations to specify pollution limits within industrialised countries occurred in the 1960s and 1970s, where local and regional air pollution were first to be addressed and regulations now covers water, solid waste and toxics (Bridge, 2004). Critics argue that 'command and control' regulatory policies are inefficient, blunt instruments and that more flexible approaches to internalising environmental costs are preferred.

To internalise the externality requires that the cost of the pollution's effects be included in the production cost (which then may also be passed on to the consumer). Environmental economics seeks to put a dollar value on the environment including people's 'willingness to pay' for a clean environment. It assumes that natural capital and manufactured capital may be substituted (Rennings and Wiggering, 1997). This means that the marginal benefit of a cleaner environment can be compared to the marginal cost of reducing pollution (Jaffe et al., 2005). The authors explain that the implications of this approach are that very harmful pollutants become restricted due to their high cost to the environment, while on the other hand, pollutants which are very costly to eliminate are tolerated due to the high cost of reducing them.

Placing an economic valuation on the environment in this way is controversial, with opponents arguing that to use a single (economic) indicator as the basis for comparison of the worth of a project oversimplifies the situation and leads to poor outcomes (Vatn and Bromley, 1994; O'Connor, 2000). Externalities are difficult to account for, especially when impacts manifest at different spatial and time scales. O'Connor (2000) elaborates these two key difficulties of placing a monetary value on environmental assets, good and services where economic valuation methodologies were not devised to:

1. extend spatially to the non-produced, non-commodified natural environment
2. extend temporally to cover long term ecological change and sustainability concerns.

The concept of the 'Monetization Frontier' (O'Connor, 2000) is presented in Figure 2-2 to conceptually delineate where economic 'monetised' valuations are useful and where they are of low usefulness due to the uncertainty of the values they are given and also because the concepts to which they are being applied may not be sensibly measured in monetary terms.

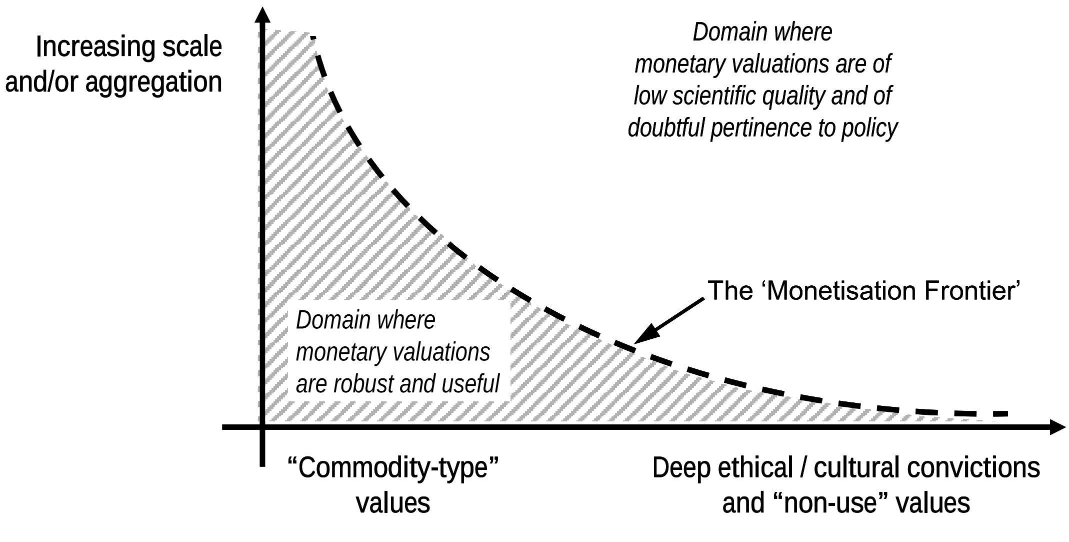


Figure 2-2: Conceptual diagram of the 'Monetisation Frontier' (O'Connor, 2000)

It illustrates that at increasing scale (referring to both space and time along the vertical axis), monetary valuations become less useful because of the uncertainties associated with the monetary values assigned. Furthermore, O'Connor (2000) highlights that for all scales, monetary values are an unhelpful measure of utility when applied to fundamental ethical choices which are present in sustainability choices, for example, relating to the current and future distribution of resources worldwide.

Consequently, additional ecological indicators are required to report on impacts which are externalised or not usefully reported using monetary indicators (Rennings and Wiggering, 1997). Currently, few corporations adequately cost externalities in their decision making. In fact, the structure of a corporation has even been likened to 'an externalising machine' (Bakan, 2004) whose aim is to increase short-term profits as a result of getting away with externalising costs which may be picked up by society in the longer term. Particularly in developing countries, one can argue that the mining industry was traditionally 'structured to externalize environmental costs' in order to maximise profits by appropriating resources cheaply and passing on to others the environmental costs of doing so, rather than making profits via process innovation and efficiency (Auty and Warhurst, 1993). To address this problem, the ecological impacts of uncosted externalities must first be identified and quantified, so that efforts can then be directed toward solutions. In short, the actions of corporate decision makers must clearly be linked to their environmental consequences and this understanding must be used to guide them to more sustainable choices. More detail regarding the environmental consequences of minerals processing activities are discussed in Section 2.1.2.

2.1.2 *Environmental impacts of the minerals and metals industry*

To provide an overview of the environmental impacts in the minerals and metals industry, discussion will focus on:

- how environmental impacts are classified
- which activities generate impacts, with reference to life cycle *stages* and life cycle *phases* and responsible parties
- specific impacts of concern and the need for a new approach to address them.

The range of environmental impacts arising from minerals processing includes air, water and land pollution, leading to adverse effects on plants, people and other animal species which may occur at locations remote from where the pollutant was generated. These adverse effects manifest at a range of geographic scales: locally, regionally and globally. Impacts also span a range of time scales from short-term (acute) to long-term (chronic). A summary of the way in which impacts are commonly classified based on what, where and when they manifest is presented in Table 2-2.

Table 2-2: Taxonomy of impact classification

Primary Classifier	Example Classification Categories		
Affected medium	Land	Air	Water
Affected life	Plants	Animals	People
Geographic Scale	Local	Regional	Global
Time scale	Short-term	Mid-term	Long-term

These classifications are included to illustrate the range of classifiers which should be – but are not always – stated explicitly when using a particular primary classifier. For example, if considering environmental impacts to water, one must further seek to specify whether the impacts of concern affect plants, animals and/or people, whether they are primarily local or regional impacts and whether they manifest in the short or long-term.

To plan initiatives that can mitigate impacts, it is necessary to understand which activities generate the adverse environmental impacts. It was shown earlier in Figure 2-1 that overall environmental impacts are greater for resource extraction (mining), processing and refining, than for forming and assembly of final metal-containing products. A different split between land-air-water impacts occurs at each processing stage as summarised in a general sense in Table 2-3. Actual impacts will vary for each metal and country in which processing operations occur (Villas Bôas and Barreto, 1996). Table 2-3 shows that the most severe impacts to land and water occur in the extraction and processing production steps. Air impacts are also significant at these phases as well as during fabrication.

Table 2-3: Comparison of impacts at each production step (Villas Bôas and Barreto, 1996)

Production Step	Land Impacts	Water Impacts	Air Impacts
Extraction	Severe	Severe	Moderate
Processing	Moderate→Severe	Moderate→Severe	Severe
Fabrication	Low	Low	Severe
Manufacturing	Low	Low	Low

Impacts of concern for selected metals industries are given in Table 2-4 to show how specific concerns vary between industries.

Table 2-4: Major impacts for selected metal industries (after Villas Bôas and Barreto, 1996)

Metal	Impact
Aluminium	Red mud slurry from alumina processing, HF emissions from smelting, CO_2 emissions from the high electricity requirements for smelting, tar pitch volatiles from anode manufacture, spent pot linings
Copper	SO_2 emissions from smelters, metal fumes, heavy metal effluents
Zinc	Iron oxide, SO_2, Cd, other heavy metal effluents

The production steps referred to in Table 2-3 refer to life cycle *stages*. Additional stages not represented in Table 2-3 would include product use, product disposal or recycling. Distinguishing life cycle stages along the material chain is important because different parties control the impact-generating activities at each stage and measures to improve performance must take account of the position of the activity within the material chain. The material chain is discussed in more detail in Section 2.1.3. and a conceptual illustration of the difference between life cycle phases and stages is presented in Figure 2-3.

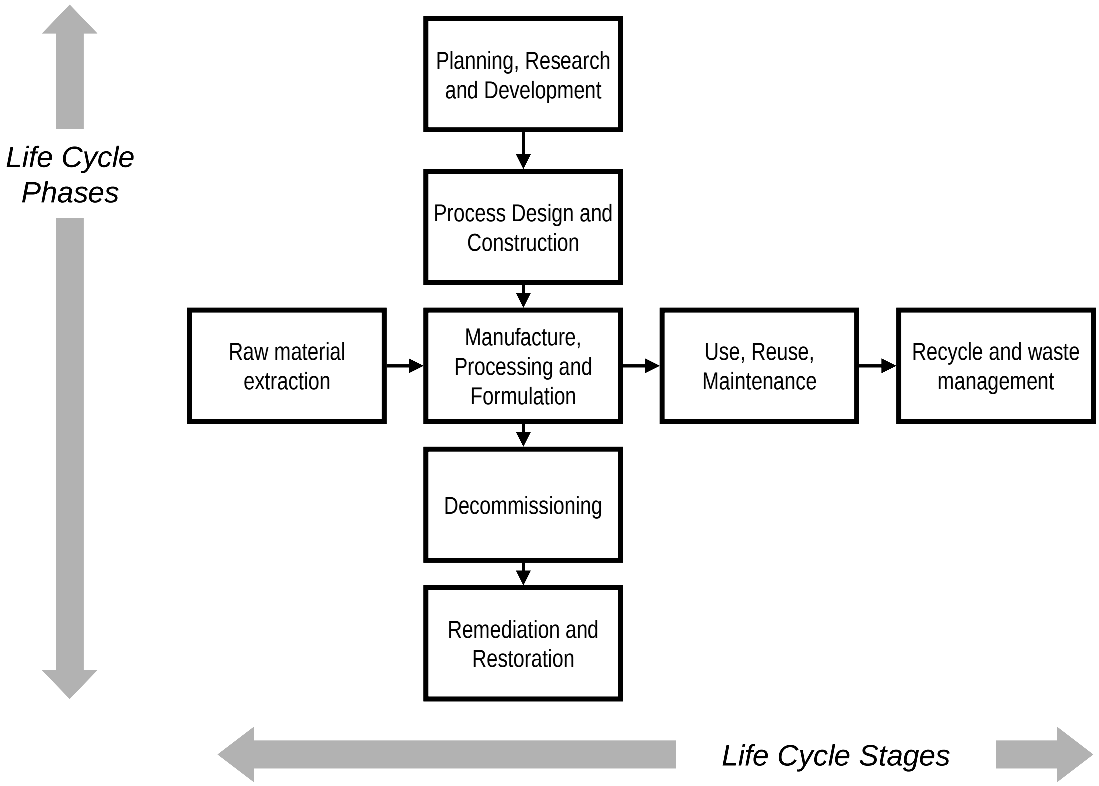


Figure 2-3: Conceptual diagram of life cycle phases and life cycle stages (after Allen et al., 1997)

At each life cycle stage, there are general project *phases* consisting of planning, construction, operation and then closure. For example, in mining, there will be exploration, mine planning, construction and operation of the mine, and then mine closure and rehabilitation. Each of these phases can give rise to specific environmental impacts (Frost and Mensik, 1991; Cragg et al., 1995; Farrell and Kratzing, 1996) with a summary shown in Figure 2-4.

POSSIBLE TYPES OF ENVIRONMENTAL DAMAGE	PHASES OF MINING PROCESS					
	Geological Exploration	Establish Pilot Mine Site	Establish Mine	Operate Mine	Close Mine	Post-Closure
Surface degradation and contamination	●	●	●	●	●	●
Flora and Fauna (e.g. Die back)	●	●	●	●	●	●
Damage to historical or sacred sites	●	●	●	●	●	—
Contamination of streams and rivers	●	●	●	●	●	●
Contamination of dams	—	—	●	●	●	●
Underground Water	—	●	●	●	●	●
Change in water table	—	—	—	●	●	●
Soil Erosion	—	—	●	●	●	—
Local air pollution	—	—	—	●	●	●
Regional air pollution (e.g. acid rain)	—	—	—	—	—	—

Figure 2-4: Possible environmental impacts at phases of mining process where black dots indicate possible impacts at that phase, adapted from Frost and Mensik (1991)

The columns in Figure 2-4 show defined phases and that environmental impacts can continue beyond mine closure to the post-closure stage. For example, as in Queenstown, Tasmania, where tailings from a copper concentrator were discharged into the river and continue to impact the surrounding environment decades after closure (Farrell and Kratzing, 1996). Consequently, it is now recognised that planning for closure and land rehabilitation at the beginning of a project will minimise impact (Bell, 1996). This reflects the recognition by companies of the need to take responsibility for their actions across *phases* of a project that will extend into the future. Similarly in refining, the earlier in the process design phase in which potential environmental impacts are considered, the greater the potential improvement in environmental performance over the life of the minerals processing operation (Stewart, 1999). Whilst better planning and integration throughout process phases in mining can deliver improved environmental impacts, such an approach does not question the balance between *stages* such as the mining and recycling activities that provide metal to society. Young (1992, cited in Bridge 2004) argues that 'metal use' must be decoupled from 'mineral extraction' as a means to overcome the standard policy of industrial nations which promoted using virgin materials to meet demand, rather than conserving mineral stocks that are already circulating in the economy. The demand rate for metals themselves must also be questioned (Graedel and Klee, 2002) to examine sustainable patterns of consumption.

Returning to specific industry problems, locally, impacts arise from the large volumes of tailings generated from mining operations. For an ore at 0.5% copper, 200 tonnes of ore must be extracted to offer one tonne of copper, only 60–80% of which will find its way into a copper product due to processing losses. With approximately 10 million tonnes of copper produced from ores annually, the tailings burden is enormous. Tailings dumps pollute surrounding waters through the generation of an acidic leachate by oxidation of sulfur compounds (e.g. pyrite: FeS_2) present in the original ore and discarded in the tailings (McQuade and Riley, 1996). This phenomenon is commonly referred to as Acid Mine Drainage or Acid Rock Drainage. Toxic leachates are also generated from landfills, where used goods containing metals are buried rather than being recycled. Small scale mining operations which use crude and inefficient techniques are also significant contributors to local environmental impacts (Higueras et al., 2004; Hilson, 2000a). For example, in northern Chile where centuries of copper-gold-mercury mining has polluted the local environment and nearby agriculture from runoff and downstream dispersion (Higueras et al., 2004). Whilst specific local impacts are site-dependent, it highlights the need to consider local impacts from the mining stage of the material chain.

Local and regional pollution (although not necessarily at the mine site) arises from the electricity generation required to crush and grind the ore. Pollution is also created from the on-site solid, liquid and gaseous wastes produced when smelting and refining the ore.

Global impacts are largely derived from gaseous emissions that contribute to global warming. Global warming's ultimate impact on regions and local communities will differ according to their location. Significant sources of these emissions occur from direct mineral smelting operations (such as CO_2 in cement production or perfluorocarbons from aluminium smelting which have a global warming potential almost 7,850 times greater than CO_2) or as a result of electricity generation (especially from coal-based power) used in minerals processing.[3]

[3] While the focus of later case studies in this thesis is on copper, the general approach developed is applicable to any metal; hence, the impacts associated with other metals' production are also noted here.

There are several reasons behind why environmental impacts associated with mining and refining are increasingly unsustainable. Taking the example of copper, mine production has increased to meet growing demand from larger populations using more copper per person as living standards rise as shown in Figure 2-5(a). As production has risen, the ore grades for copper have declined as higher quality ore-bodies become fully exploited (see Figure 2-5(b)). Processing lower grade ores drastically increases the energy required for processing as shown in Figure 2-5(c) because a greater throughput of ore must be crushed to contain an equivalent mass of metal and the ore must be crushed finer to liberate metal particles from more complex ores.

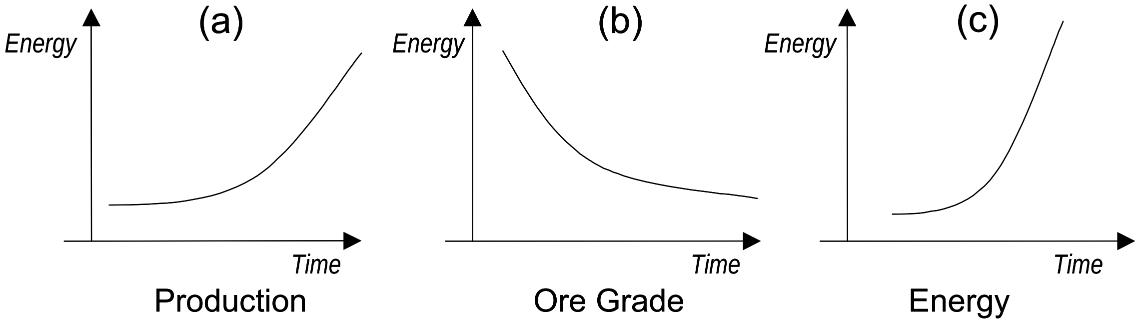


Figure 2-5: Illustration of rise in energy associated with processing as a result of increased production from declining ore grades (adapted from Ayres et al., 2001 and van Deventer and Lukey, 2003)

The resultant environmental impacts from increased production and from processing lower grade ores are problematic both on-site, with a greater need for tailings management, and off-site, with emissions from increased electricity generation requirements for crushing a greater quantity of ore.

The continuing instances of tailings dam failures reflects inadequate performance and projects a poor image of minerals processing operations. Van Deventer and Lukey (2003) note that such failures have often occurred at a site remote from the location of the mining company's head office, which may be located in a different country. The personnel in head offices of multinational companies often fail to appreciate and act on local plant conditions in their environmental decision making, which leads to poor local outcomes (Petrie and Raimondo, 1997). The 'out of sight, out of mind' reality, highlights the need to look beyond the office boundary, and indeed beyond the plant boundary to quantify all effects associated with producing metals – not only geographic boundaries, but also boundaries between material chain stages. Like externalities, this is another example of a disconnect between the focus of interest for companies, the domain of impact of their activities and where the required intervention or corrective influence by the company or an external actor must be directed to bring about change.

A further motivation for considering the links between material chain stages relates to future resource availability. Ore reserves are dwindling and given a continuation of current demand, may suffice for less than fifty years in the case of lead, zinc, copper and nickel based on production from primary ore alone (Norgate and Rankin, 2002; Zeltner et al., 1999). In this time, industry will face the inability to supply several metals required by society from ore (Lee, 1998). This necessitates that industry look beyond the mining and refining of lower grade ores (with increasing environmental burdens), to the entire life cycle of metal use for potential future resources. Consequently, secondary resources (e.g. metal in discarded scrap) must be considered when evaluating how best to source and process metal for our use in society. Indeed, significant research efforts are now being directed to improve secondary resource recovery (see Dalmijn et al., 2003) and to identify secondary stocks (Spatari et al., 2002). Unlike fossil fuels, metallic resources are not generally depleted when extracted from the Earth's crust, but the way they are subsequently used determines the required effort and impact associated with their recovery (Stewart and Weidema, 2004). The available stock of secondary resources is depleted when metals are used dissipatively – such as in pesticides sprayed on crops – from which it is impractical to recover the metal. Recovery of secondary resources from discarded scrap is complicated where metals are used in alloys or, for example, in electronic equipment where recovery yields a mixed waste with impurities that are difficult to remove; hence secondary materials could not fully supply the total demand for metals due to current technical constraints (Verhoef et al., 2004).

Making metal available within the economy with reduced environmental impacts requires an approach that assesses both primary and secondary processing routes. A 'material chain' approach that considers both local and global geographical scales is proposed. There are additional reasons for choosing a material chain methodology, which are discussed after first describing the material chain concept in more detail in Section 2.1.3.

2.1.3 *Structure of the materials chain*

A generic representation of a material chain (also called 'value chain' or 'material-product chain') as a network of connected nodes with material flows between each node is given in Figure 2-6. Using copper as an example, Figure 2-6 includes qualitative descriptions for each node which may represent either resource stocks (○) or processing activities (▭). It illustrates that the concept of a material chain extends beyond mining and refining to include use and recycling. This contrasts the historical competencies and self-perceptions of the 'minerals industry' which was centred on ore-extraction (Cowell et al., 1999). Consequently, it challenges the industry to adopt a new, expanded focus on which to pursue performance improvements both within and between nodes – this also comes with requirements for new tools to map performance and assess the impacts of such interventions. The material chain representation in Figure 2-6 is a highly aggregated representation to simplify explanation of the concept. More detailed material chain representations are used in later case studies.

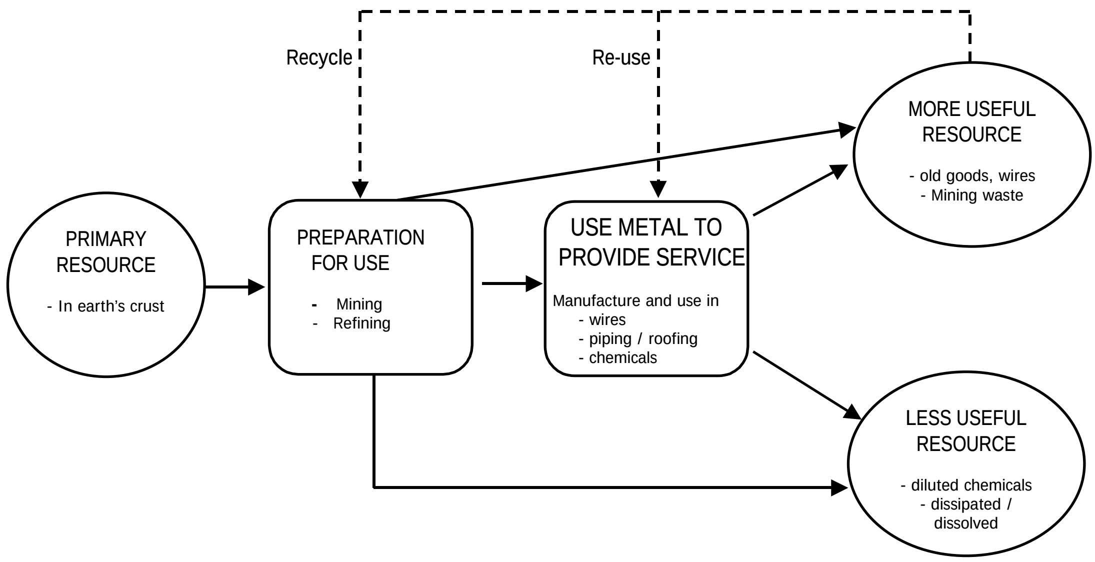


Figure 2-6: Aggregated generic representation of a materials value chain as a network of five aggregated nodes (with examples for copper)

'Primary resources' currently exploited for copper are generally contained in the Earth's crust, although significant resources are also available in oceans, but are not exploited (Edelstein, 2001).[4] Primary metal resources in the Earth's crust generally occur in an impure form as complex ores. Metals in ores must be 'prepared for use' by mining and refining to a deliver metal product as represented in Figure 2-6. Mining may either be underground or open cut, depending on the metal and type of ore deposit. A variety of technologies are then used to concentrate and refine the metal to a pure product. Further

[4] Ocean resources are not considered further in this thesis as they are currently impractical to recover for copper and do not contribute to the supply of copper metal to the economy.

technical details of processes regarding 'preparation for use' are considered in case studies for copper in Chapters 7, 8 and 9.

Using copper as an example, the pure metal product is sold to manufacturers to produce, inter alia, copper wire, copper pipe and electronic circuitry. These products are then used to provide desirable services to industry and consumers. The use of metal in manufacturing and its continued use in finished goods defines the node 'Use metal to provide service' shown in Figure 2-6. The focus in this work is on how to supply metal to markets with less environmental impact. For this thesis, the key driver of material flows within the value chain is taken to be society's need for metal; to provide useful services via metal-containing products, rather than a need for metal itself. Whilst beyond the scope of this work, it suggests there is a need for additional research that questions the link between desirable services and which metal is best placed to deliver those services (e.g. copper or aluminium for carrying electricity). Furthermore, to move toward a material chain that is part of a sustainable society, the total demand for metals must also be questioned. In particular, what is an acceptable demand for metals and how might it be reduced? What is the nature of the rebound effect regarding technological progress in the minerals industry?[5] The switch from selling products to services has been occurring in several sectors (e.g. Interface Carpets, Xerox photocopiers, chemicals) as a means of reducing product sales without reducing profits (Reskin et al., 2000) – but not for minerals and metals. What changes to enterprises, regulations and prices would be required to transform the industry from 'make and sell' to a 'service' industry that rents metal to users and returns them at the end of their use as proposed by Ayres an colleagues (2001).

The industry has recognised the need for longer term thinking and new institutional arrangements to 'bridge the discrepancy between the multigenerational time frame of indigenous peoples and the short time frame of mining' (MMSD, 2002), for example thorough planning for closure at a mine and developing capacity for a continuing economy beyond mine closure. However, this is longer term thinking is within a single stage of the material chain only – for example, at a mine site – and must be extended to examining approaches that benefit the entire material chain across all stages For example, to consider not only what infrastructure is appropriate for meeting current demand with today's resources, but also what technology combinations are suited to

[5] The rebound effect refers to the situation where technological progress may make production costs and impacts to produce a product lower, but due to lower costs, the total usage of the product may increase giving a reduced net benefit, or even a negative benefit (see Binswanger, 2001).

processing ore grades and secondary scrap resources of the future which will be of different compositions as patterns of consumption and use change. The approach proposed in this thesis is to first characterise the impacts of material and energy flows at stages along the material chain to provide an expanded focus from which the abovementioned questions can be further explored. In particular, it provides information for stakeholders in the material chain to understand their direct and indirect impacts and to identify areas requiring change to improve overall performance.

As noted earlier, making metal available for use in the economy depends not only on sourcing metal from ore, but also from secondary 'More Useful Resources' as shown in Figure 2-6. In turn, the availability of 'More Useful Resources' is dependant on four factors:

- the rate of metal consumption in society
- the split of discarded metal between 'More Useful Resources 'and 'Less Useful Resources'
- the useful lifetimes of metal-containing products
- the purity (and associated impurities) of metal products in society.

After the metal is no longer in useful service its value decreases and it proceeds to a stock of potentially recyclable goods labelled 'More Useful Resources', namely, those with the potential to re-enter the material chain. Alternatively, if the metal is not potentially recoverable, it is labelled a 'Less Useful Resource' such as the dissipative use of copper in pesticides. Some potentially recyclable goods may undergo a 'disposal treatment', but still remain as resources. For example, landfills are considered 'More Useful Resources' as the metal they contain may be able to re-enter the value chain via landfill mining and reprocessing. Because of this, landfills are not an insignificant resource. By way of example, the current reserve base for copper contained in ores is 90 million tons in the USA, while a further 40 million tons are contained in landfills (Zeltner et al., 1999).

This completes the explanation of each node in the material value chain presented in Figure 2-6. It shows a closed loop material value chain for one metal, which means that all material recycled returns to the same value chain. Not all material value chains are strictly closed loop and the closed loop assumption in this work represents an approximation. For example, consider the potential recycling zinc, not into the zinc value chain to make zinc again, but into the copper value chain as an additive to make brass.[6] This would be termed 'open loop' recycling – namely, where a metal leaves its value chain to enter the value chain of another metal.

This thesis develops a new approach for assessing improvements in environmental performance within a single, closed loop value chain. This focus provides the basis for identifying means for facilitating improvement, which can be extended to multiple value chains in future work.

By using a material value chain representation, the inter-relationship between material flows in parts of the network – which affect sourcing and preparing metal for use – are made salient. Flows are considered across spatial scales and Section 2.1.4 specifically describes the geographically distributed nature of resource flows in the copper industry.

2.1.4 *Geographic distribution of flows within the materials chain*

To provide further background to the current operation of sourcing and refining metals, the location of major copper flows worldwide is examined as an example. The materials value chain in Figure 2-6 represents a simplified, aggregated depiction of the complexity of the spatial domain over which sourcing and preparing of metals for use occurs. Each node simply represents a location-independent stage in the material chain. In reality, the largest source of copper is in the southern hemisphere (in Chile) and is then transported and used by the largest consumers in the northern hemisphere. To demonstrate the importance of geographic location in copper flows, Figure 2-7 shows the magnitude of mining, refining, consumption and secondary processing for main world regions (the specific countries in each region are defined in Table 7–8 in Chapter 7).

---

6 Alloys are usually re-processed to make new alloys, rather than their constituent metals as this is much cheaper (Henstock, 1996). The complexity of interconnected metal cycles is only beginning to be understood (see Reuter, 1998) and is not the focus of this thesis.

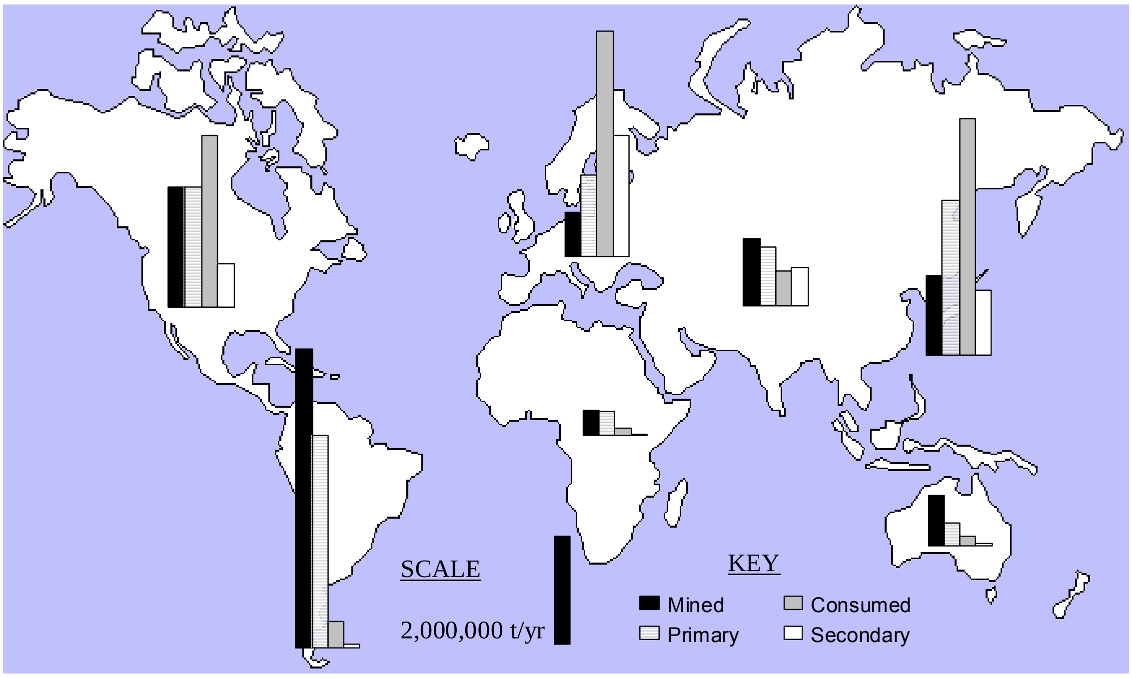


Figure 2-7: Geographical location of copper mining, primary production (from ore), secondary production (from scrap), and consumption (compiled with data from Edelstein, 1999)

The amount of mining, refining and consumption varies considerably between regions. Each stage of the value chain has a differing environmental impact; hence, there is a discontinuity of environmental impacts between where the resource is mined and consumed. Consequently, material flows and impacts are inequitably distributed between regions. This spatial variation is in addition to the differing spheres of interest and influence of actors linked to each node in the value chain. To make sense of this complexity, a new approach is required to characterise the materials value chain, which takes account of geographic scale.

Figure 2-7 highlights the interconnectedness in the flows of copper through the materials value chain across the globe via the quantities of ore and refined copper transported to overseas markets for consumption. Implicitly, it also shows that there is a huge processing infrastructure in place to service our current demand for metal. Consequently, changes to the materials chain in the medium term must be approached from the perspective of a system retrofit (acknowledging that processing infrastructure in place may still have a potentially useful life of several decades) rather than as a greenfield development (where the system is planned in the absence of any pre-existing infrastructure). However, there is first much insight to be gained by better characterising the impacts associated with the status quo of material and energy flows through current infrastructure.

A complex picture emerges from the description of the material chain in this section. Flows between stages in the material chain must be considered and within each stage material flows through different technologies must be modelled, to capture the differences in environmental performance associated with each technology. Material flows also vary with geographic location and impacts are not directly proportional to material flows due to different resource quality and technology infrastructure in each location. Beyond the physical flows of metals represented in the material value chain, several actors are linked with the current operation of the material value chain. Each of the elements associated with the current minerals and metals value chain will influence the way the issue of sustainability is addressed in the industry. Section 2.1.5 describes the actors and their relationship to different nodes within the value chain in order to illustrate that examining the minerals industry in the context of the material value chain means consideration of multiple parties.

2.1.5 *Actors in the materials chain*

Actors are defined by the resources they control and the nature of the activities they perform (Harland, 1996). The minerals and metals value chain contains many actors, including mining, processing and fabrication companies, governments, workers, consumers and recyclers. Each has a differing focus of interest within the value chain and a different potential influence on the operation of the chain which could be exerted to improve performance. Typical connections between actors include: mining companies that mine and either smelt or on-sell ore; refiners that source metal from both primary and secondary resources; competing goods manufacturers that buy metal from refiners and sell to product wholesalers and consumers. Consumers do not deal directly with mining companies and regulators have varying degrees of interest over state-owned and private companies.

The domain of interest of the actor and the actor's potential influence are not always concordant. For example, influential actors (e.g. governments) may be external to the day-to-day operation of the material chain, yet exert influence through policy initiatives. In the past, the mining industry has benefited from policies specifically designed to encourage minerals investment, for example, the tax-free status of gold mining profits in Australia from 1924–1991 favoured gold miners (Frost and Mensik, 1991). Future policy initiatives could include an ecological tax that increases taxes on environmentally damaging activities and uses the revenue to reduce taxes on employment and investment (Hamilton, 2003), Relationships between actors are complex and often drive the operation of the system in competing directions. For example, manufacturers aim to use less metal in their product to save cost whilst refiners strive to see more metal in product to generate a greater income. This is a complicating factor in achieving a preferred outcome for the system overall and reinforces the need to analyse the material value chain as a whole.

The implementation of innovation in the minerals industry is notably slow (Petrie, 2005). With large capital-intensive infrastructure supporting the minerals industry, once corporations invest in a particular technology, changes to the technology within 5-30 years are difficult to justify (Batterham, 2003). As mentioned earlier, this suggests the need to evaluate possibilities for improvement using both existing and new infrastructure. The ability of particular actors to influence change within the value chain is an important element of this thesis and further discussion is provided in Chapters 4 & 5 when considering the ability to change the current material chain to a more sustainable configuration.

In summarising this section, there are five key factors to note:

- many actors, rather than a single actor determine the operation of the material chain
- actors may act in their own interest rather than the interest of the value chain as a whole – there is a discord between their domain of interest and impact
- actors may also have a local or global presence whose influence varies across scales
- minerals industry actors are slow to implement innovative technologies
- the environmental impacts of decisions taken by actors must be better understood to enable improved performance to be achieved.

Section 2.2 explores sustainability concepts as a precursor to assessing the current implementation of sustainability initiatives in the minerals industry, their influence on environmental performance and what constitutes a sustainable vision for the industry.

2.2 SUSTAINABILITY AND ENVIRONMENTAL DRIVERS

This section examines sustainability issues from a theoretical perspective to determine their implications as drivers for the mining industry, with a particular focus on environmental impacts. Following a review of how environmental management has historically been practised in the minerals industry, current minerals-specific initiatives regarding sustainability and environmental management in particular are discussed. A future vision for sustainable metal cycles is presented to establish the context for the thesis and how the specific questions to be addressed in this work contribute to this aim.

2.2.1 *Sustainability concepts and approaches*

The pursuit of sustainability continues to become increasingly important within our society. It was thrust onto corporate and government agendas following the much cited 'Brundtland Report' of the World Commission on Environment and Development (1987) which defined sustainable development as that which 'meets the needs of the present without compromising the ability of future generations to meet their own needs'. The Brundtland Report superseded the no-growth solutions to environmental problems that were advocated during the early 1970s. It did this by showing that environmental quality and economic prosperity need not be viewed as incompatible – sustainability was now a 'reasonable concept' (Rees, 1990).

Since then, the acceptance of the goal of sustainability continues to grow (UN, 2002) within government, the community and industry; including the minerals industry (see MMSD, 2002). With sustainability established as a worthwhile pursuit, research is now focussed on how to more precisely define and implement sustainable practices.

The following paragraphs identify and contrast key elements of sustainability definitions as a background to historical and current environmental and sustainability initiatives in the minerals industry which are discussed in Sections 2.2.2 and 2.2.3.

Sustainability has been defined in many ways: from that which allows continuing system function over a specified time (Costanza and Patten, 1995) to a shift in focus away from simply 'me-here-now' to also consider 'others-elsewhere-in future' (McNevin, 2000). Definitions of sustainability vary with respect to preferences for what is more or less important to sustain and for how long. Commonly, definitions of sustainability may be placed within a range between 'weak sustainability' to 'strong sustainability' (Ayres et al, 1999; Turner, 1992). Weak sustainability assumes the intergenerational equity is maintained. When measuring equity, the utility of manufactured capital is assumed to be interchangeable with natural capital (provided for example by a healthy environment). Ayres and co-authors (1999) note that development consistent with weak sustainability can lead to environmental devastation. This occurred in Nauru with the profits from almost a century of phosphate mining being used to develop a trust fund that was to ensure the economic sustainability of the country, however due to unforseen factors this fund is now depleted, and the future of the country is limited (see Gowdy and McDaniel 1999). Strong sustainability asserts that manufactured and natural capital are not interchangeable, in fact human, environmental and economic capital must be independently sustained through generations. This is referred to by Daly and Cobb (1989) as providing 'non-diminishing life opportunities'[7] and requires the maintenance of ecosystems that support life on Earth. This recognition underpins the need to assess the environmental impact of human activities, including those that supply metal to the economy.

Within the framework of strong sustainability, an important issue requiring clarification is that of scale (see Costanza and Patten, 1995; Gibbs and Healey, 1997; Graedel, 2000; Odum and Odum, 2000) and at what scale we seek sustainability. Figure 2-8 presents the relationship between sustainable systems (defined with respect to this figure as those that reach their expected life span) at different scales. At a grand scale such as beyond our solar system, our actions are unlikely to limit the sustainability of the universe. Nor are they likely to hinder the sustainability of bacteria which are continuing to evolve at a microscopic level because their regeneration rates are quick enough to adapt to changing circumstances. Consequently, our principal domain of interest concerning sustainability is at the human level and in sustaining a human population on Earth.

---

[7] There is an even stronger position of 'very strong sustainability' linked with the 'deep ecology' philosophy that all life forms have a right-to-life and should be maintained. This overlooks our current dependence on primary resources and that in the natural world species and ecosystems are in a constant flux and human activity is itself a part of nature (Ayers et al, 1999) – it is not discussed in detail in this thesis.

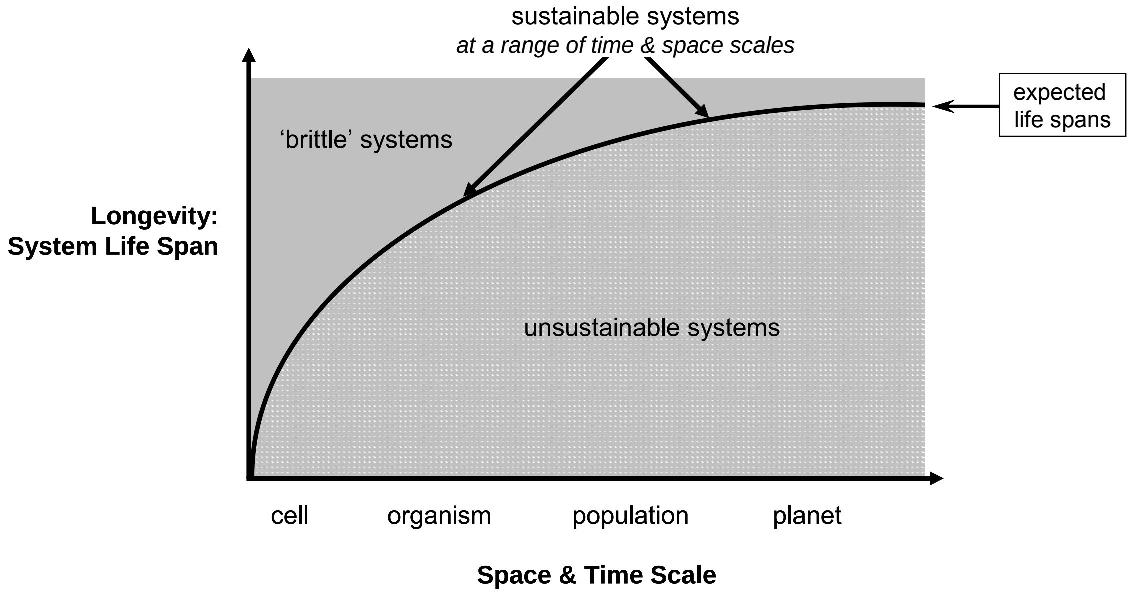


Figure 2-8: Sustainability as a scale dependent concept (Costanza and Patten, 1995)

This human scale is reflected in the 'present and future *generations*' referred to in the Brundtland definition of sustainability. Within our sustainable focus at a human level here on Earth, there are several spatial scales of importance: global, regional, national and local problems all affect anthropogenic and ecological systems in different ways. The ability to characterise and link our influence and impacts across each of these scales remains an element which has received little attention in the literature. This deficiency must be addressed to more equitably 'meet the *needs* of the present'. Only by better understanding the results of actor choices on the distribution of resource flows and impacts, can responsibility for actions become clear and provide the basis for charting a more sustainable future.

Beyond spatial scale, the Brundtland definition of sustainability highlights the need for longer term planning – again reflected in its reference to 'present and *future* generations'. Hence, time is also an important element of the sustainability debate. It is not immediately apparent which time horizon is best for sustainability – 30 years? 300 years? 3000 years? The choice is informed by factors including: the duration of impacts that our actions give rise to, if the impacts are reversible or not and how much we can anticipate the needs of future generations – again the human scale is important. In this thesis, a time horizon of 50 years is chosen (consistent with Graedel and Klee 2002; Larson et al., 2003). The basis for this choice, is that 50 years is close enough to have our understanding of the present and our current actions linked with this future, yet distant enough to make deliberate and significant choices about the systems we put in place to support our lives over this time period.

'The Natural Step' theory of sustainability (Robèrt, 2000) is a considered attempt to further define the concept of sustainability beyond Brundtland. It highlights the relationship between dynamic human economic systems and slower-changing ecological systems (Upham, 2000). A central theme is that nature's functions should not be exposed to increasing concentrations of substances extracted from the Earth's crust, in order to preserve ecological diversity.[8] One consequence is that society must decrease its reliance on non-renewable fossil fuels and implement metal and mineral recycling programs (Five Winds International, 2001; Sánchez, 1998). Considering the recycling of metals is consistent with the cyclical material value chain system boundary described in Section 2.1 (as opposed to a linear value chain considering only resource use-production-consumption-disposal as described by Jackson, 1996). The fact that fossil fuel usage largely underpins the current delivery of metals to society, means that such linked inputs must be included in any analysis of the environmental performance of the materials value chain.

An additional component of the Natural Step theory is that 'in order for a society to be sustainable, resources must be used fairly and efficiently in order to meet basic human needs globally' (Rosenblum, 2000). This requires a more equitable allocation of resources and impacts amongst people and more efficient use of resources to deliver required services. With a focus in this thesis particularly on the latter, resource efficiency can be improved *along* the materials value chain by altering the distribution of flows between different resource processing technologies, or, *within* the technology nodes themselves by making transformation processes more efficient (Rudberg and Olhager, 2003). It also suggests the need to consider impacts across geographic scales. To gain additional perspective on how to improve the performance of industrial networks in the context of sustainability, the field of industrial ecology is now examined.

Industrial ecology suggests that ideas regarding what a more sustainable future may look like can come from nature itself: that there are lessons for the way we run our industrial systems, based on the way the ecology of natural systems (Ehrenfeld, 2003;

---

[8] The precautionary principle underlies the aim of avoiding increasing concentrations of metals in the natural environment (Cowell et al, 1999). This is due to the uncertainty associated with what concentrations of metals (particularly metals which are toxic in small concentrations) cause environmental degradation – for example lead, whose anthropogenic flux is 28 times greater than its natural flux (Nriagu, 1990).

Spiegelman, 2003). The central characteristics of an industrial ecology elaborated by Erhenfeld (1994) include viewing Earth as a closed ecological system in which human and natural systems have co-evolved. Consequently, stocks of both natural and human capital should be maintained independently in line with the 'strong sustainability' view. Initiatives should focus on delivering services rather than products and consider the entire life cycle of products used in service delivery. The industrial ecology metaphor has cemented the need for a systems approach to analysing problems, requiring a focus on the entire materials value chain, however, it would benefit by aiming to *design* a more sustainable future for industrial systems, which may reach beyond merely emulating natural systems. This need for industrial ecology to equilibrate the scale of decision making with environmental impacts and actors was identified by Allenby (1992). In practice, actor decisions generally lead to ad hoc evolutions of industrial ecologies, due to the lack of a holistic material chain perspective. Actors fail to perceive how their actions affect those around them. Some success at a local scale has been achieved through eco-industrial parks (Cote and Cohen-Rosenthal, 1998), yet planning across scales for global and regional value chains has been limited.

At a more general level, we can use the foundation of industrial ecology to recognise that we are part of a connected network, and then as Dalmijn and co-workers (2003) propose: focus on collective responsibility. This means that a future for the *entire* value chain must be envisioned, followed by an exploration of transition paths and their required changes that will progress the system toward this end. Furthermore, actors who can bring about these changes, either individually or collectively, must be identified to show how changes would be implemented.

To provide categories in which sustainability performance is measured, the concept of a 'triple bottom line' has been strongly linked with the concept of sustainable development. It refers to focusing on economic prosperity, environmental quality and social justice in assessing the performance of projects and companies. It was a term coined by Elkington (1998) in demonstrating that sustainability goes beyond trying to harmonise the financial and environmental bottom line. Importantly though, it raises the difficult question of balancing competing economic, social and environmental objectives and their trade-offs. To model the difficulty in reconciling trade-offs between competing objectives, this thesis focuses on environmental performance and trade-offs between local, regional and global environmental impacts. In doing so social and economic performance measures are not included in the scope of the thesis. The motivation for this is to engage the minerals industry to assess non-financial impacts along the materials chain. Environmental impacts are more transparently related to material and energy flows than social impacts and provide the means to capture the attention of industry to undertake a more comprehensive analysis of its impacts which is in its own long term interests in order to retain a licence to operate from the community. Furthermore, industry must be prompted to explore new models for maintaining profitability within a material chain that has both greater resource efficiency and reduced impacts. The approach developed in this thesis considers multiple environmental impacts (see Chapter 5) and can be extended to consider multiple performance measures spanning social and economic impacts using a similar approach.

Companies are now expected to respond transparently to triple bottom line and sustainability drivers as part of a wider move to Corporate Social Responsibility (CSR). Multiple drivers seek to augment corporate social responsibility by companies, including (after Warhurst and Mitchell, 2000):

- **financial drivers**; in a globalised world with world-wide foreign direct-investment, granting equity is being conditional on social and environmental performance (to manage risk), the share of ethical investment funds is also increasing
- **societal drivers**; requiring, consultation accountability and disclosure plus pressure from employees and shareholders for responsible action
- **environmental drivers**; climate change and rising sea levels are a prominent public issue that need decisive responses
- **regulatory pressure**; regulations and legislation are becoming integrated across land, air, water and are beginning to embrace principles that include responsibility along the material chain (e.g. extended producer responsibility)
- **peer pressure**; both from direct competitors for reputation management and from companies along the material chain who seek to work with others that have verified social and environmental proficiency

As a means of response, the use of Life Cycle Assessment (LCA) and Life Cycle thinking has been endorsed by the minerals industry as a useful means for facilitating change for the improved environmental performance of a system (Stewart, 2001; Althaus and Classen, 2005), and will be the main basis for assessing environmental performance in this work. LCA is explained in more detail in Chapter 4. A key aim of this work is to show how LCA can be combined with models of material flows in the value chain to inform long-term planning and strategy regarding preferred futures for the industry.[9]

Having explored the concepts of sustainability and environmental drivers in a general sense in this section, the next sections (Section 2.2.2 and 2.2.3) give an overview of environmental management in the minerals industry and how sustainability concepts have been applied. The aim is to determine if the industry adopts a value chain approach, at what scale are performance improvements targeted and what time horizon and degree of system change these approaches propose. This will determine how effective current initiatives have been and establish the specific gaps that remain to be addressed.

2.2.2 *Environmental management in the minerals industry: an overview*

The history of environmental management in the minerals industry has evolved from passive management, through to reactive 'end-of pipe' treatments and now proactive 'cleaner production' initiatives (Hilson, 2003).

Passive management approaches referred to by Hilson (2003) progressed in the following order:

- abandoning the affected site with no remediation, so called 'foul and flee'
- 'dilute /disperse', such as occurred in pre-industrial society and through to the 1960s where the objective was to dilute wastes to a level at which they would not be of concern
- 'concentrate/contain', to manage highly toxic wastes (for example nuclear waste, spent pot linings from aluminium smelting).

Once it was realised that dilution and dispersion were ineffective strategies for managing point-source emissions, 'end of pipe' treatments were engaged to mitigate toxic emissions from waste streams. Graedel and Allenby (1995) explain that such treatments sought to meet environmental regulations in the present, but did not effect changes aimed at improving overall performance of the system for the future. Instead, their main focus was to comply with legislative requirements. End-of-pipe solutions were centred on part of the value chain only; had a plant-specific local focus; only considered improvements in the present or near-term future; and sought minimal changes to infrastructure. In the

[9] The usefulness of addressing this need was highlighted at a 2001 'Workshop on the Application of LCA to Mining, Minerals Processing and Metals' (Stewart, 2001).

mining industry, the outcomes of conventional end-of-pipe systems used to treat wastes have been 'average' at best (Hilson, 2000b).

Cleaner production superseded the end-of-pipe philosophy, with a drive to diminish polluting waste streams in the first place. Cleaner production is a systematic analysis of production aimed to reduce waste at the source, rather than treating it later with end-of-pipe technologies (Hilson, 2000a). It involves better management of resources in the process to reduce wastage through better technology, recycling or reuse (NSW Environment Protection Agency, 2000). Cleaner production has a 0–20 year time horizon and is achieved with product and process improvement (van Berkel, 2000). This represents a broadening from the end-of-pipe approaches targeting specific process areas, to a whole of process innovation with the potential to replace infrastructure with new technology. Cleaner production has been instrumental in improving the environmental performance of minerals operations at a plant level, for example reducing sulfur dioxide off gases from smelting processes with new technology (Hilson, 2000b). However, like end-of-pipe treatments, cleaner production strategies are largely focussed at making improvements at the production plant only, rather than along the entire material chain.

Beyond useful improvements at individual plants, the drive toward sustainability demands that impacts are considered throughout the production chain (Cano-Ruiz and McRae, 1998). This is illustrated in Figure 2-9.

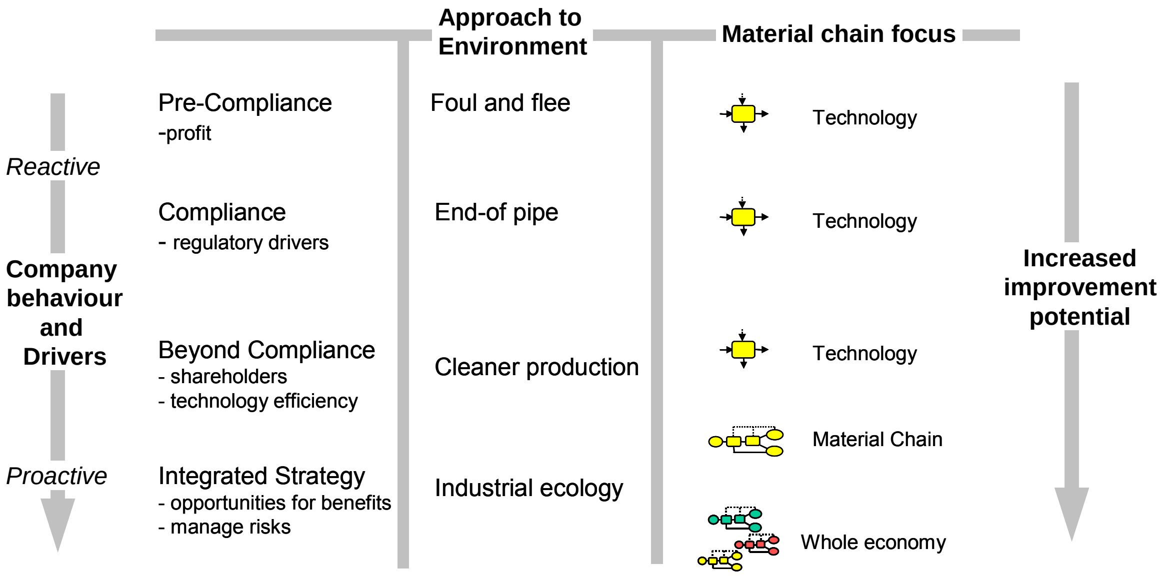


Figure 2-9: Company behaviours, drivers, approaches and material chain focus (adapted from Willard, 2005)

The progression of approaches to environmental performance have been linked in Figure 2-9 with examples of increasingly sustainable company behaviour (after Willard, 2004) and the required material chain focus. Companies must aim to move from their current behaviours of 'compliance' or 'beyond compliance' to adopting a proactive 'integrated strategy' that recognises both the business opportunities that arise from being more sustainable, and which better quantifies non-financial performance measures to manage risk and deliver improved outcomes for the environment. See Section 2.2.3 for further discussion on the increasing role that non-financials play in determining a company's value.

During the energy crisis of the 1970s, significant effort was directed toward reducing the energy associated with the production of metals across the material chain (for example see Gaines, 1980). This also lead to the useful development of energy analysis techniques to reduce energy requirements (Chapman and Roberts, 1983), since environmental impacts not only result from process plant emissions, but also from the energy used to drive the industrial systems supplying metal to market. However, these efforts were largely driven by a cost imperative and with the easing of the 1970s oil crisis, the industry's focus on this stalled. Many of the externalised pollution costs from mining over the last decades are still being paid by society at large. Some companies retreat from expenditures on social and environmental matters as they view it being detrimental to their bottom line (Humphreys, 2001). Closer to the end of the 20th century, there was a growing awareness that the mining industry couldn't afford *not to* embrace sustainable development (Humphreys, 2001). However, while an in principle willingness to engage with sustainability had dawned, 'The vision for a sustainable and responsible mineral industry still remains to be fully characterised' (McAllister et al., 1999). Consequently, a structured approach to environmental performance improvement across the value chain in the minerals industry is needed more than ever, yet is currently lacking.

2.2.3 *Current initiatives in minerals processing and the environment*

The relationship between mining activities and the environment is approached from several perspectives. In a current review of the literature, Bridge (2004) divides analyses into four categories:

1. technology and management-centred, with a focus on linking technological and organisational performance to environmental impacts

2. public policy studies, with a focus on approaches that capture benefits of mining and contribute to a country's development as well as preventing pollution
3. structural political economy, with a focus on land and mineral rights, and negotiating benefits in community partnerships
4. cultural studies, that use mining and development as a representative case for exploring themes of globalisation and corporate development.

The first and second categories are most relevant to the focus of work in this thesis and are discussed further here to assess the comprehensiveness of issues covered in the review. The first category traced the evolution of environmental management approaches from end-of-pipe through to pollution prevention and cleaner production as discussed in Section 2.2.2. Cleaner production seeks to reduce the impact per tonne of product produced, but does not consider the collective burden from the total amount of production and its collective burden in a region (Frederickson, 1999 cited in Bridge, 2004). Analysing impacts using a material chain approach provides the basis for future consideration of the supply-demand balance in addition to focus of this thesis which is on supply side options relating to virgin and secondary resource processing.

The second category of public policy studies, examines how the costs and benefits of mining are calculated and distributed. The costs of mining – in the form of environmental impacts – have been paid in different ways through time. At the beginning of the 20th century, compensation payments handled through the courts were common between smelters and farmers for lost animals affected by smelter pollution (Smith 1987, cited in Bridge, 2004). Prompted by the US Clean Air Act (1955) companies began to internalise the cost of local pollutants, and then through amendments to the Act (1977) regional pollutants (e.g. sulfur dioxide) were included. During the 1960s and 1970s water and solid waste were also included in regulation and the focus by polluters was on the cost of compliance. By the 1990s, 'command and control' approaches were superseded by more flexible performance-based targets to encourage the development of innovative ways to reduce pollution. As with the work in this thesis, the focus still largely remains on how to process minerals with less impact, rather than on approaches that seek to address demand. Such future approaches are both complementary and necessary and could include incentives for recycling and recovery, taxes on material consumption and the removal of subsidies for extraction (Bridge, 2004).

With respect to the benefits of mining, the review notes that mineral extraction and processing is viewed as contributing to sustainable development (in the weak sense) if revenues are used to stimulate lasting economic development within a country. However, other authors recognise that natural capital and economic capital are not interchangeable.[10] This raises the important question of what assumptions underlie different definitions for sustainable development used within the minerals industry.

Sustainability in the minerals industry may be described at different scales, namely,

- time scale – near future, long-term future
- geographical scale – city, region, planet
- organisational scale – single facility, company-wide, all institutions
- material / product life cycle – extraction, manufacture, use (Cowell et al., 1999).

Cowell et al, (1999) explore definitions used by minerals companies or organisations and show that these can be constructed to fit with the aims of the company rather than sustainability at a societal level. Broadly, the differences in definitions used align either with the 'opportunity cost' or 'fixed stock' paradigm of Tilton (1996). The opportunity cost paradigm proposes that the functions provided by resources are not exhaustible – as ore grades dwindle, prices will rise to curb demand or make economic either (a) recovery from lower grades resources (b) research into new processing technologies, or (c) resource substitution. By contrast, the fixed stock paradigm asserts that there are a fixed quantity of unique exhaustible resources which must be managed more efficiently. The notions of resource substitutability within the 'opportunity cost' paradigm and unique usefulness of resources that should be independently preserved in the 'fixed stock paradigm' are partly related to the concepts of 'weak' and 'strong' sustainability respectively. A fixed stock paradigm is used in this thesis, consistent with 'strong' sustainability view adopted in Section 2.2.1.

To explore how mining, minerals, metals and sustainable development could be reconciled, leading minerals companies, together with the World Business Council for Sustainable Development and the International Institute for Environment & Development, conducted a wide-ranging investigation was conducted over two years which was finalised in 2002 (see www.iied.org/mmsd). It forms the basis of current

[10] Critically, Bridge (2004) notes that authors readily accept one or other position and that little work has been undertaken to test the substitutability of natural and economic capital

thinking in the industry, and while it has raised important issues, detailed approaches to operationalise prescribed sustainability goals have yet to be developed.

The MMSD initiative tackled a broad range of topics grouped around the following four key themes (MMSD, 2002):

- *To assess the global mining and minerals sector in terms of the transition to sustainable development;*
- *To identify how the services provided through the minerals supply chain can be delivered in ways that support sustainable development;*
- *To propose key elements for improving the minerals systems; and*
- *To build platforms of analysis and engagement for ongoing communication and networking among all stakeholders in the sector.*

The outcomes ranged from the need to ensure industry viability and contribute to economic development; to the social, environmental and governance issues of mining, covering issues including land use, corruption and the roles of different actors within the value chain. Importantly, an integrated approach to using minerals was proposed under the themes of supply chain management, product stewardship and life cycle assessment in order to better connect production with use. However, while identifying key issues, it was beyond the scope of the project to develop concrete approaches to meet the specific challenges of the minerals industry.

In summary, the MMSD initiative engaged with scales from community to industry and governments at national and regional levels. The need for analysis across scales is well founded outside the minerals industry (Odum and Odum, 2000), especially with respect to environmental performance (João, 2002). While scales from global to local were identified as important, an integrated methodology was not developed for coherently evaluating improvement strategies across scales. No 'specific' long term time horizon for sustainability was specified by the industry.

In theory, a materials value chain focus is advocated by the MMSD initiative. It includes a decreased reliance on fossil fuels, provision for additional recycling and improvements not only from new technologies but also by collaboration across the network – where miners and recyclers could view each other as collaborators rather than competitors (MMSD, 2002). A need to actively envision a preferred future is highlighted, but a methodology and required tools – with the ability to link the influence of actors to alternate system configurations for the materials value chain – have not yet been developed.

As discusses in Section 2.2.1, Life Cycle Assessment is proposed as a means to link system performance with potential environmental impacts, to show trade-offs (Stewart, 2001) and as an input to decision making in the industry. However, the problems faced when applying LCA across scales to evaluate options for the minerals industry remain unexplored. Furthermore, the minerals industry has only partly overcome its inertia to using incorporate environmental information in its decision making .

The motivation for companies to seriously engage with environmental impacts and responsibilities along the material chain is growing (Dunphy et al, 2003). In part, this is driven by a recognition of the risks that a company exposes itself to by ignoring non-financial indicators. As shown in Figure 2-10, the overall value (market capitalisation) of a company has shifted from being dominated by what is represented in the financial balance sheet (tangibles) to being dominated by intangibles. These intangibles include environmental impacts, health and safety of employees perceptions of stakeholders and the community, strength of relationships with others in the material chain, including suppliers and customers. A focus solely on tangibles as providing sufficient information to manage the company no longer applies (ADL, 2002).

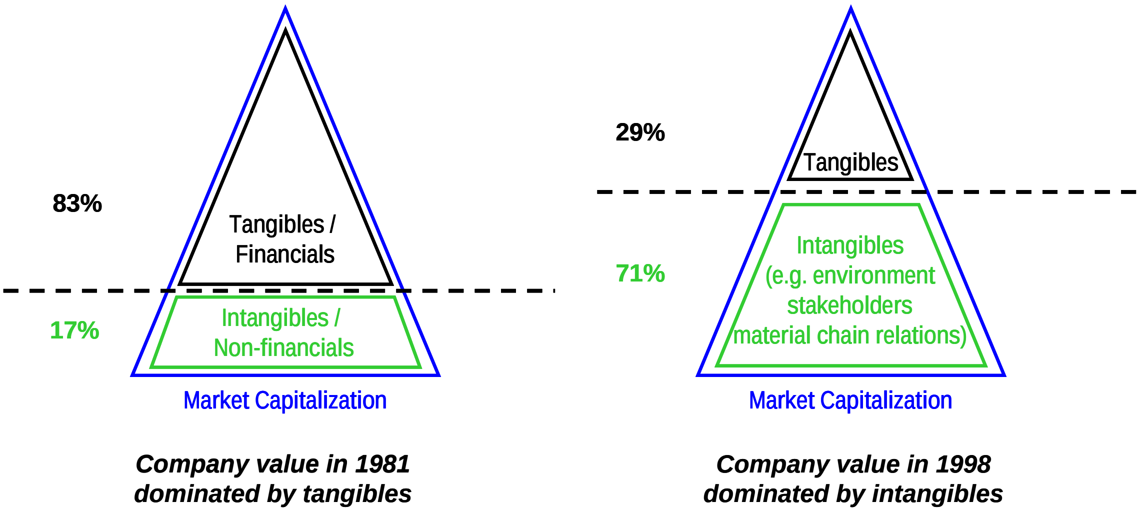


Figure 2-10: Company value iceberg showing increasing role of intangibles in the value of a company (after ADL, 2002)

As an example of the increasing focus on intangibles is the Carbon Disclosure Project (www.cdproject.net). This project now sees a growing number of institutional investors joining the Carbon Disclosure Project to collectively ask the Financial Times top 500 companies what risks and opportunities they perceive that climate change may bring and what they are doing about it. These institutional investors have the power to preferentially provide capital to companies with a better understanding of their non-financial risks. The rise in company response rates from 2003–2005 and in the number of institutional investors involved is shown in Table 2-5, illustrating the growing recognition that the impacts of environmental pollution must be better understood.

Table 2-5: Key statistics for Carbon Disclosure Project (CDP, 2005)

	2003	2004	2005
Companies surveyed	FT500	FT500	FT500
Companies who completed survey	45%	60%	71%
Number of institutional investors	35	95	155
- value of assets held (T = trillion US$)	$4.5T	$10T	$21T

Prominent companies within the minerals and metals value chain were part of the survey, for example, BHP Billiton, Anglo American and Rio Tinto. Of these, the response in 2005 by BHP Billiton is the most comprehensive, including charts of yearly averages for the greenhouse intensity of several metals and explicit acknowledgement of life cycle and material stewardship issues (BHP Billiton, 2005). However, under the pretext of life cycle considerations, Rio Tinto focuses disproportionately on the perceived benefits that metals will bring to reducing the life cycle emissions of products (e.g. by using aluminium to reduce the weight of transport components and consequently vehicle emissions or copper to increase the efficiency of motors) without due acknowledgement of the impacts associated with refining the metals themselves. These examples indicate that while the prominence of environmental and life cycle considerations is growing, a structured approach is required for integrating these elements into planning for a more sustainable materials chain. Such a task requires careful consideration, both to achieve a more sustainable outcome and to engage industry. For example, industry currently recognises – and opposes – the possibility of trade being restricted from companies with poor environmental performance, such as through the European Union's Green Paper on Integrated Product Policy (Hooke, 2004). Hooke (2004) who is the Chief Executive of the Minerals Council of Australia goes on to describe such policies as a form of protectionism which favours some countries to the detriment of others. Instead he prefers the concept of materials stewardship where responsibility for impacts is shared across the material chain. Currently, the methodology for such an approach remains ill-defined. Developing a structured approach to account for impacts at each stage of the material chain that highlights both the actors and required interventions to improve environmental performance provides the motivation for this thesis.

2.2.4 *Future vision for sustainable metal cycles and place of this work*

What is a preferred vision for sustainable metal cycles? and, How will the work in this thesis contribute toward this goal?

The vision for sustainable metal cycles must be to enhance the long-term wellbeing of societies through the use of metals. Strategies to meet this objective would:

- improve the efficiency of metal cycles by aiming to close the material loop
- limit the environmental impact of refining and using metals in society
- reduce the material intensity of providing services to the economy with metals
- balance benefits and impacts between metal-producing and metal-consuming societies

Achieving this vision will require significant efforts of industry and government. The work in this thesis targets the first two dot points as a priority which necessitates a more detailed understanding of the current system, its impacts and what components of the system must change as shown in Figure 2-11. Specifically, there is a need to account for current impacts along the material chain and to plan for a preferred future across the material chain. The lack of an approach for assessing the potential improvement in environmental performance along the value chain leaves a missed opportunity for industry and an unquantified risk for the future viability of individual companies and the sustainability of the material chain as a whole.

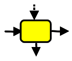
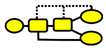
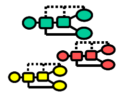
	Technology 	Material Chain 	Economy 
Aim	Technology efficiency	Close material loop Reduce impacts	Sustainable economy
Change	- Inputs/outputs - Technology	- Inputs/outputs - Technology - Splits of flows within material chain - Rate of cycling - Demand	- Reduce inputs/outputs - Technology - Splits of flows within & between material chains - Rate of cycling - Material intensity of economy
Requires	- New technology	- New technology - Information on flows / impacts / accountability along material chain - Plan for preferred future - Sharing of impacts / benefits	- New technology - New information - New trading mechanisms - Collaboration across material chains
Barriers	- Technology inertia - Cost (if externalities remain un-costed)	- Unquantified potential for performance improvement along material chain - Lack of system focus for planning	- Existing economic models - Profits based on unsustainable practices

Figure 2-11: Barriers and requirements for improvement at different scales

This thesis has a focus on making the case for change toward more sustainable practices, however, it is increasingly apparent that it will not be necessarily an altruistic 'save the environment' argument that will motivate industry into action. Rather the realisation that initiatives such as the Carbon Disclosure Project mentioned earlier highlight the necessity for industry to better quantify intangibles associated with their business operation, including environmental performance. The utility of this thesis is to then show how this can be done using the approach developed in Chapter 3, 4, 5 and demonstrated with case studies in later chapters. Furthermore, whilst particular companies may be making money in the short term from the unsustainable status quo configuration of the material chain, this research will allow the industry to assess future configurations of the material chain which are more sustainable to inform decisions on how they can remain profitable in this future context – namely, by transforming themselves from mining companies to resource management companies in the same way that, for example, BP (Beyond Petroleum) is changing its focus from that of an oil company to an energy provision company.

The modelling tools developed in this work will provide a basis for long-term industry planning on a material chain scale that takes explicit account of environmental impacts. Performance of current and future configurations of the material chain including those that utilise new technologies, can be easily compared with both average sector performance and best practice.

There are several specific questions requiring further consideration in order to meet the vision for sustainable metal cycles outlined earlier in this section:

1. characterise impacts for the services provided by metals in a sustainable society
2. establish a process to identify changes to metal flows patterns and processing infrastructure that will reduce environmental impacts along stages of the material chain at local and global scales
    a. examine the supply-demand balance in line with (1) to consider supply-side and demand-side strategies for reducing impacts
    b. link actions to impacts to account for environmental externalities as part of emerging corporate social responsibility drivers
    c. examine benefits and limitations to progress which can be made at a company level with new technology
    d. evaluate changes to the configuration of flows and technologies in the material chain with respect to multiple environmental criteria
    e. identify actor collaborations to achieve preferred futures
3. explore technology and policy interventions that can promote the realisation of the preferred material chain configuration, with respect to achieving social, environmental and economic goals.

By promoting a systems approach, this work seeks to link actions by the industry directly with impacts, even if they are manifested beyond the plant boundary. Better characterising these impacts is the first step in taking responsibility for the impacts and considering what policy instruments could be used to motivate reductions in these impacts that are part of a preferred future.

Points 1 and 2(a) listed are not the focus of this work – a continuing demand for metals in the economy is assumed. However, the outputs from this work provides input to the further exploration of these questions by assessing the contribution which supply-side options can make to performance improvement of the system. The process of first seeking to understand the role of supply-side options to improve performance is consistent with the focus on points 2(b), (c), (d), (e) in this work. This is both attractive and prudent for industry: attractive because supply-side options (whether from primary or secondary resources) require a similar business model to that currently in use; prudent as a risk management strategy because if governments impose taxes or other legislative instruments (point 3) to curb impacts of metal production and use in society, industry will be well-positioned to articulate the relative contributions to be made through supply-side and demand-side initiatives having examined metal production from a material chain perspective.

2.3 ADDRESSING CHALLENGES FOR METAL CYCLES: HYPOTHESES

This section provides further detail on the key outstanding challenges that were identified from Section 2.2.4. An analytical framework is then synthesised as a basis for assessing environmental performance in the material chain. Subsequently, the main hypotheses are proposed together with how they will be addressed in this thesis. Finally, the potential benefits of this research are stated, with a particular focus on the interest of industry and how the research may be applied to better industry's current position.

2.3.1 *Specific considerations for reducing the impacts of metals cycles*

The former Chief Scientist of Australia, Dr Robin Batterham, hopes and expects that 'in time, the once-through usage pattern that characterises mining, metal production and metal use will change to a process of continuous use and recycling where the only input to the system is renewable energy' (Batterham, 2003). This constitutes a vision for a sustainable future in the minerals industry with a focus on closing the loop. However, as mentioned in Section 2.1.2, full recycling is not currently possible due to constraints imposed by impurities arising from mixed metals being used in many products. In the medium term metal recovery from primary (ore-based) resources will remain an important activity (Petrie and Raimondo, 1997). Responsible environmental management of metal recovery from both primary (ore-based) and secondary (scrap-based) resources is required.

Based on the review and analysis of literature in Section 2.2, the key elements of an approach to address this task – and that is consistent with the principles of sustainability as discussed thus far – will involve careful consideration of:

- human scales from global to local
- understand performance of status quo
- consider extended time horizon for future (50 years)
- a material value chain focus
- including provision for recycling of metals
- decreasing use of fossil fuel (or other non-renewable components whose use underpins metal provision to society)
- improvement in performance of specific processing technologies
- improvements in value chain performance by changing process technologies and the configuration of flows between processes in the value chain
- actively designing preferred future
- different degree of system change
- balancing the use of new and existing infrastructure
- ability of actors to implement the preferred future
- measurement of environmental performance (for example using LCA) and clear trade-offs between performance measures, linked to decisions made by actors

The above list is used as a basis for the development of a novel analytical framework for assessing the environmental performance of the minerals value chain.

2.3.2 *Developing an analytical framework*

The analytical framework shown in Figure 2-12 is synthesised from the preceding discussion in this chapter. It contains the key elements that must be addressed improving the environmental performance of the material chain.

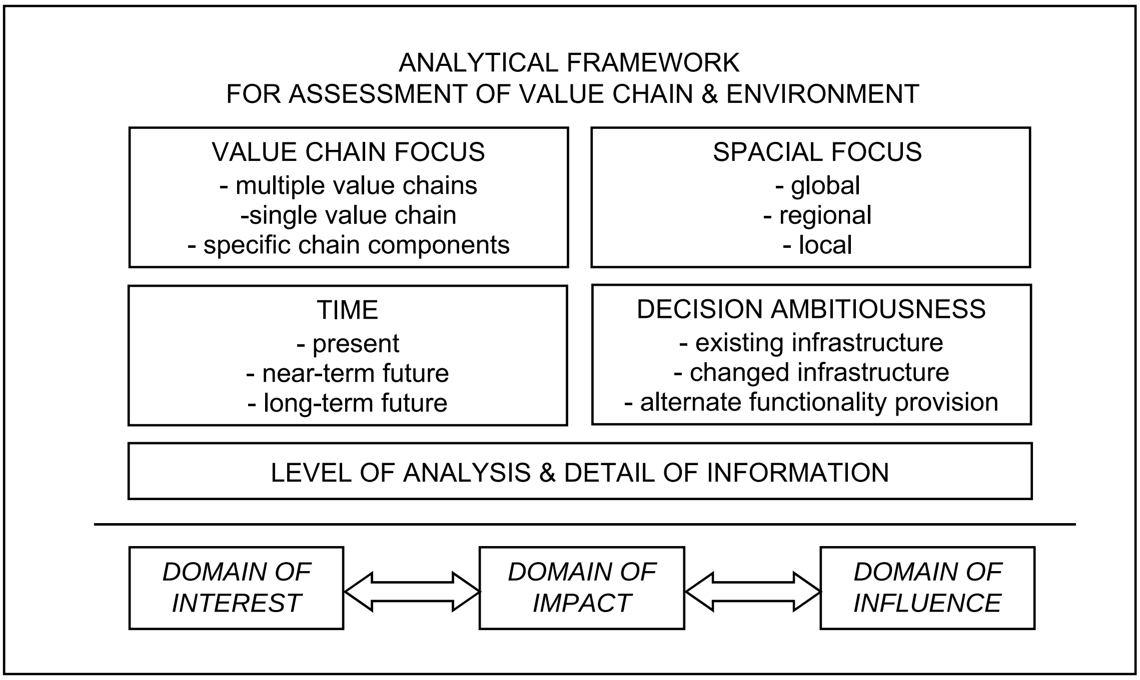


Figure 2-12: Analytical Framework for assessment of value chain and environment

The characteristics of 'value chain focus', 'spacial (geographic) focus', 'time horizon' and 'decision ambitiousness' are drawn from the list groupings in Section 2.3.1 and will now be discussed in more detail. The materials value chain focus may be specified at a number of levels: considering multiple value chains simultaneously; considering a single value chain; or considering component sub-sections of a single value chain. The characteristic of spatial detail in relation to material flows can be specified at three principal levels: global, regional and local. This represents highlighted focus areas across a continuum of space (e.g. regional could be national or continental, local could be city-specific or site-specific). Time horizon can consider historical data, the present and near-term or long-term futures. The consideration of near and long term futures is also linked with the degree of system change being proposed, with greater changes being possible over longer time periods. The degree of system change contemplated is termed 'ambitiousness of decision' in this work and can vary from changing no infrastructure, to changing part of the infrastructure in a system retrofit (such as replacing older technologies), to completely redesigning the system (such as creating metals atom by atom with a radically new process) (after Wrisberg et al, 2002).

The 'level' at which each of these characteristics is specified constitutes the 'level of analysis' and each level of analysis will demand differing 'information detail'. The relation between level of analysis and information detail is discussed further in Chapter 3.

The analytical framework also identifies the need to better link the 'domain of interest' with 'domain of impact' and 'domain of influence' with the aim of increasing the accountability of actions by industry,[11] reducing externalities and providing the information that allows more sustainable choices to be made. A brief comment is offered here to clarify these three phrases. 'Domain of Interest' refers to the system boundary of interest of the decision maker with respect to spacial and value chain focus. For example, a multinational mining company may have its domain of interest only in head office rather than at the field level or only on mining rather than across the entire metal cycle. The 'Domain of Impact' refers to the spacial and temporal scale at which environmental impacts manifest[12] and which parts of the value chain give rise to these impacts. The 'Domain of Influence' refers to the part of the value chain and spatial scale at which intervention by the decision making actor is possible.

It is proposed that there is currently a discord between decision makers' area of concern/interest, the level at which environmental impacts manifest and the level of influence which actors have to effect changes which improve performance. As evidenced by the presence of externalities (Section 2.1.1), the discord hinders efforts to become more sustainable. In beginning to address this issue, the nature of the discord must first be better understood. Take the example of European copper refiners supplying copper to their market. The demand for refined copper in Europe gives rise to impacts at the site of copper mining (in Chile) and refining (in Chile and in Europe). These impacts are both local (in Chile and in Europe) and global in nature. The ability to improve performance differs for European and Chilean actors, as does the location of any impact reductions. As a first step, approaches must be developed that can characterise the environmental

[11] Accountability will be increased by providing a transparent link between actions and impacts, thus eliminating the discord from 'out-of-sight, out-of-mind' due to spatial or temporal differences between actions and their resultant impacts.

[12] In a more general sense, if the measure of system performance were financial performance rather than environmental impact, then domain of impact could refer to the impact of financial gains/losses for different nodes in the value chain.

impact associated with production, and the actor decisions that could be taken to improve performance.

2.3.3 *Addressing performance improvement across scales*

The first hypothesis is that:

> *it is possible to develop a classification tool that facilitates the understanding of the interaction between actors, system flows and impacts across spatial scales in the material chain.*

Chapter 3 enhances the ability of the industry to engage with sustainability questions across geographic scales. This is achieved by developing a 'Reference Schema' for the minerals industry, in order to systematically classify system boundaries with respect to spatial domain from global to local, and material value chain comprehensiveness from part to whole. It assists not only in defining a physical system boundary of interest, but is used as a template to classify the region of influence of actors and the level at which impacts are manifested. Understanding how each of these elements are linked is vital to charting a preferred future that can be realised. A review of literature for different scales within the reference schema highlights current deficiencies at different scales and guides the development of modelling and assessment methods consistent with the scale of the question.

2.3.4 *Linking actors' influence in the materials chain to impacts*

The second hypothesis is that:

> *it is possible to develop tools that characterise material and energy flows across scales and link the ability of actors to change value chain configurations (technology infrastructure and material flow patterns in the value chain) and consequently the resultant environmental impacts.*

Having classified a range of decision problems to be addressed across scales in Chapter 3, Chapter 4 seeks to link current system configuration at any scale with performance at that scale as a baseline, against which future improvements can be measured. Models for material and energy flows of the material chain that inform environmental performance are tailored dependent on the scale of analysis, with a specific focus on the use of Life Cycle Impact Assessment. Then, beyond this system-impact link, the link between system variables and the decision making actors that can control them is added. This allows the current value chain to be characterised and provides the basis for being able to envision future states in Chapter 5.

2.3.5 *Realising a path toward a preferred future*

The third hypothesis is that:

> *it is possible to develop an approach which can evaluate dynamic transition paths from the current value chain configuration toward preferred future value chain configurations which can be used to guide more sustainable choices in the minerals industry.*

With the ability to model system performance across scales established in Chapter 4, Chapter 5 develops a new approach to identify alternate future states, select preferred states, and examines the ability of current actors to achieve them over time, in the context of changes to the external environment beyond the control of actors. The approach is then demonstrated for the copper value chain with case studies in Chapters 7, 8 and 9.

2.3.6 *Benefits and wider applicability of this research*

This research addresses the need for the minerals industry to firstly characterise the environmental impacts of its actions from a material chain perspective and then provides a methodology for evaluating supply-side options that improve performance.

Transparent decision making within corporate social responsibility requires characterising relevant actors, system variables, material flows and their impacts and benefits along the material chain. An added complexity when doing so for the minerals industry is that company operations and material flows are both local and global, requiring a systematic way for the industry to conceptualise problem boundaries at different geographic scale and for actors, variables, flows and impacts along the materials chain. The reference schema developed in Chapter 3 provides a basis for understanding these scale issues in the minerals and metals context. Its broader applicability however, could equally extend to other resource sectors.

Environmental performance, rather than social performance, has been targeted as the focus for measuring non-financial performance in this work as it is more transparently linked to material and energy flows. Environmental impacts are of significant interest to the industry currently and multiple indicators of environmental performance have been used in this research to illustrate how impacts can be traded-off. The trade-off approach provides a basis from which industry can consider multiple performance measures comprising both economic and environmental indicators.

The rationale for industry and government stakeholders in the material chain to use this research is twofold. First, the need for companies to understand the impacts of their actions beyond the plant boundary is being driven by more demanding regulations and stakeholders through corporate social responsibility initiatives – this requires a systems approach for industry to identify accountabilities for impacts as a precursor to establishing mechanisms for sharing benefits and responsibilities by different actors in the material chain. Secondly, by identifying preferred futures for the value chain and the required timing of interventions by actors to achieve them, benchmarks for best-practice metal production along the material chain can be set, increasing system efficiency and motivating industry to position itself as a profitable player within a more sustainable future.

CHAPTER THREE

Understanding scale: a reference schema

The minerals industry must address the complex task of improving performance across a range of scales to move toward a more sustainable future. Chapter 2 showed that current approaches used by the industry consist of broad visions which are un-actioned, or narrow approaches making ad hoc changes which ignore system complexity. The analytical framework developed in Chapter 2 identified key components to be included in a structured approach to addressing the problem. It concluded that a material chain perspective spanning spatial scales is required as a basis for improving environmental performance in the industry.

This chapter begins the development of a such an approach through the creation of a novel reference schema. The reference schema describes the entire decision space for the minerals industry in terms of spatial (geographic) scale and material chain focus. It is used as a common basis for classifying material flows, actors, system variables and information requirements for problem analyses at different scales. This structuring represents a significant contribution to managing complexity across scales. The literature is then reviewed at each scale within the reference schema to determine how material flows, impacts and actor influences have been characterised and/or linked and used to improve future performance of the value chain. The review identifies which decision spaces have been explored, with what tools and with what outcomes. It also seeks to determine if any literature considers multiple scales. This review identifies deficiencies in the literature which can be addressed by developing new modelling approaches to characterise the status quo for the value chain across scales (in Chapter 4) and to consider options that represent transition paths toward preferred futures (in Chapter 5).

3.1 IMPROVING CLASSIFICATION OF DECISION TYPES

This section reviews the existing classification of decision types with which the minerals industry engages, namely strategic, tactical and operational decisions. They are reviewed with respect to the key characteristics in the analytical framework (spacial focus, material value chain focus, time horizon, decision ambitiousness) to determine if there is any useful pattern in how each decision type aligns with the key characteristics. This provides the basis for developing a new approach to structuring decisions in the minerals context based on a value chain perspective.

3.1.1 *Existing decision classifications: strategic, tactical and operational*

The classification of decision types as strategic, tactical and operational in environmental decision making has been advocated (UNEP, 1999; Wrisberg et al., 2002). Similar classifications have been used outside environmental decision making for many years (see Anthony 1965; Higgins, 1980), originally with reference to planning military operations. The early concepts are attributable to Sun Tzu who lived in China in the 6th century B.C. (Griffith, 1971).

Strategic questions are concerned with 'big issues' (Stacey, 1990), with long-range time horizons (Dwyer, 1996), and with comprehending and adapting to new environments (Higgins, 1980). However, there is no clear value chain focus for strategic decisions. It depends on the perspective of the actor involved. For example, a strategic decision for a mining company may consider multiple value chains when deciding which value chain to operate within (e.g. should the company mine copper, nickel, zinc or all three?); a minerals processing company may consider part of one value chain, such as whether to refine copper from ore or scrap; for a government developing a sustainable resources policy, all of the value chain may be considered.

Tactical decisions relate to how organisational resources will be directed in the short and medium term to meet strategic objectives (Higgins, 1980). Examples of tactical decisions for a copper processing company would be the choice of technology used and site selection for a plant, to meet the objective of being a leading copper producer. The system change achieved through tactical decisions is incremental and spatial scale may be local or regional.

Operational decisions with respect to environmental decision making are the day to day routine decisions made within a short time-frame when a technology is already in place. An example of an operational decision is determining the optimum feed rate for energy efficiency in an operating smelting technology. Operational decisions are locally focussed and do not significantly change infrastructure in place.

The decision classifications used in environmental and decision sciences propose that the transition from operational to tactical to strategic decisions have an increased scope or 'reach' (Basson, 2004; Sutherland, 1992; Wrisberg et al., 2002). This broad definition is adopted in this thesis as outlined in Table 3-1 and is consistent with its usage in the Mining Minerals and Sustainable Development initiative (Stewart, 2001) described in Section 2.2.3. However, it is noteworthy that the relative scope associated with tactical and operational decisions in military usage (from where the terms are originally derived) is reversed with respect to usage in environmental decision making. In military planning terms, strategy regards planning and winning the war; operational decisions coordinate the ways, ends and means for an operational campaign; tactical decisions regard ordering combat units within battles, where many battles will be associated with a successful campaign (U.S. Joint Chiefs of Staff, 2001). For this reason, a clear definition of usage associated with the terms is required.

A summary of the domain of interest for strategic, tactical and operational decisions with respect to the key characteristics in the analytical framework is shown in Table 3-1.

Table 3-1: Characteristics of strategic, tactical and operational decisions

Level of Decision	Value Chain Focus	Spacial Focus	Time Horizon	Decision Ambitiousness
Strategic	Part or all of value chain or several value chains	Global to local	Mid to long term	Existing or new infrastructure or system redesign
Tactical	Part of value chain	Regional to local	Short to mid term	Existing or new infrastructure
Operational	Part of value chain	Local	Short term	Existing infrastructure

Table 3-1 confirms that strategic decisions are potentially concerned with a larger domain of interest with respect to: value chain and spacial focus, time horizon and decision ambitiousness. Beyond this, Table 3-1 and the preceding discussion offers little insight into how to approach performance improvement within the value chain across spatial scales. To address this point, the value chain focus associated with strategic, tactical and operational decisions is explored in more detail.

The strategic, tactical and operational classification for environmental decision making is discussed in detail by Wrisberg et al. (2002) who tabulate examples for each decision type as shown in Table 3-2. To the provided examples, a value chain focus is added here to assess the value chain focus for each decision type.

Table 3-2: Existing classification of decision types based on UNEP (1999) and taken from Wrisberg et al. (2002). Value chain focus added in this thesis.

Level of Decision	Examples of decision	Focus in Value Chain
Strategic	Policy Development	Company / Multiple chain node
	Strategies for development of new technology	Single chain node
	Strategies for R&D on new product lines	Company
	Investments in new technologies / production	Company
	Permit decisions	Company
	Acquiring another company	Similar chain node/ Next/previous node
Tactical	Product development	Single chain node
	Process development	One / two node
	Technology development	Single chain node
Operational	Marketing decisions	Company
	Environmental labelling	Company
	Environmental reporting	Company
	Compliance with regulation	Company
	Environmental management	Company
	Product stewardship and chain responsibility	Multi-chain nodes
	Supplier choice	Inputs to nodes
	Benchmarking	Company

Table 3-2 shows that none of the decision examples listed necessarily consider the entire value chain as their focus within the value chain, with most focusing at a company level. Planning to improve performance at a company level may provide an isolated improvement in performance, but not be beneficial to improving the performance of the value chain overall. As established in Chapter 2, a whole of value chain focus is a minimum requirement in moving toward a more sustainable industrial system, and therefore must be included in strategic industry planning. The lack of a coherent value chain basis to the existing definitions of strategic, tactical and operational leaves them flawed as a starting point for improving the performance of the materials value chain. A clearer value chain focus must be articulated.

3.1.2 *Improved decision classification based on 'scope' and 'vision'*

A new basis for describing decision contexts is proposed here, better quantifying strategic, tactical and operational decisions with respect to 'scope' and 'vision'. Scope represents the system boundary in terms of spatial domain from global to local and the extent of value chain considered from the entire network to a single component. Vision reflects the time horizon and extent of system change contemplated (ambitiousness of decision).

The correlation between time and 'ambitiousness' of decision or level of potential change/improvement is suggested indirectly by Wrisberg et al. (2002). The distinction in system boundary between physical space and network extent along the value chain is adapted from the geographical concepts of areal (physical) space and metaphorical (network) space described by Conti and Dematteis (1995), but is linked explicitly to define the scope of a decision context only in this thesis. The characteristics underpinning scope and vision are brought together as shown in Figure 3-1, driven by a need to better structure the classification of decision contexts across the materials value chain. This provides a starting point for building a 'reference schema', which will help the minerals industry better understand its place within a sustainable system, and, to better match analysis tools with decision problems at different scales.

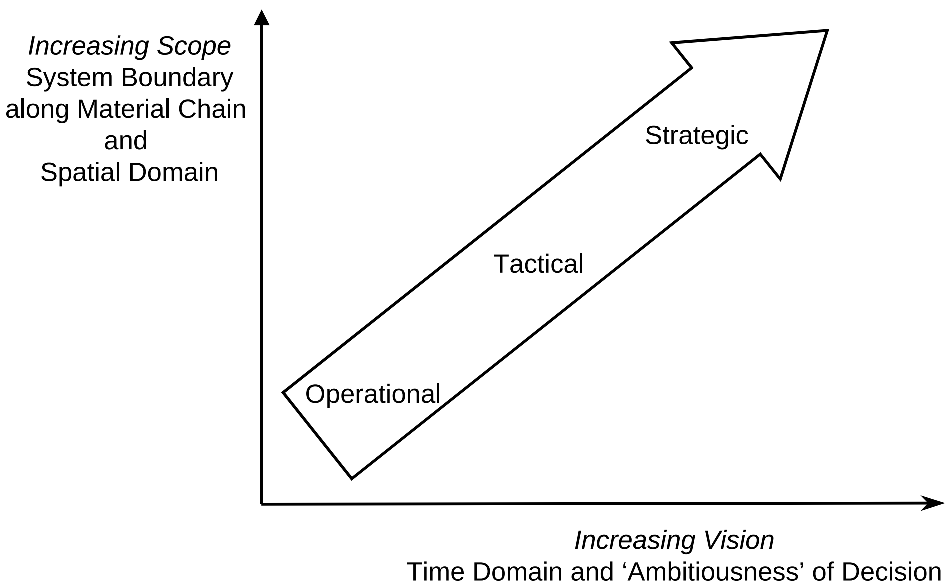


Figure 3-1: Relative relationship between 'scope' and 'vision' of strategic, tactical and operational decisions

For the purposes of the minerals industry looking to move towards sustainable futures, a way must be found to specifically articulate the scope; with respect to both spatial and value chain focus. The minerals industry must then seek to understand the relationship between decision contexts at different scopes to allow implementation of improvements within value chain components which are consistent with improved performance of the value chain as a whole. Additionally, the other elements of the analytical framework must be considered: namely, the level of information detail required to support decisions and the relationship between the 'Domain of Interest' (the system boundary in which actors seek improvement), the 'Domain of Influence' (the control actors have and the constraints they operate within) and the 'Domain of Impact' (with respect to environmental impacts). The current definitions of strategic, tactical and operational decisions do not provide the basis to address the aforementioned challenges: the definitions are inconsistent and too generalised.

To this end, a new approach to conceptualising decision space within the minerals industry from a value chain perspective is proposed in the form of a reference schema; this is developed in Section 3.2. It further structures the generalised relationship from the vertical axis in Figure 3-1. Firstly, the reference schema provides a taxonomy with which to evaluate current literature relating to material chain modelling and impact evaluation. The usefulness of such an approach to describe and evaluate methodologies is evidenced by Croom and colleagues (2000) for the supply chain literature. Secondly, the reference schema will assist conceptual understanding of the relationship between decision contexts at different scales (elaborated in Section 3.3). Thirdly, it acts as a practical tool to map the link between Domain of Interest, Domain of Influence and Domain of Impact for actors, and to structure information requirements for decision support at different scales within the reference schema.

3.2 CREATING A REFERENCE SCHEMA

Using the conceptual relationship outlined in Figure 3-1, the decision space in which the minerals and metals industry operates is structured according to spacial domain and value chain boundary to create a reference schema. The reference schema is then populated with representative decision contexts. The value in developing a reference schema is that it provides a structured basis for relating decision contexts at different levels to each other and it is also used as a point of reference for classifying to appropriate information detail, actor influence, models and indicators to inform further analysis, according to the system boundary represented in the reference schema. This will contribute to successful improvement in environmental performance which requires an expanded view of company responsibility along all phases of the product lifecycle and considers local, regional and global impacts (Thoresen, 1999).

3.2.1 *Reference schema: a matrix representation of scope*

The aim of the reference schema is to classify the decision space within which the minerals industry makes decisions. To fully represent the scope of the decision, classification is mapped for spatial detail from global to local, as shown in the 'reference schema' in Figure 3-2. The material value chain is divided under the mega, macro, micro classification.[1] The following representations are used:

- mega: multiple value chains and interactions
- macro: single value chain with one main metal (impurities, by-products or alloying elements may be noted separately)
- micro: specific parts or part of single value chain.

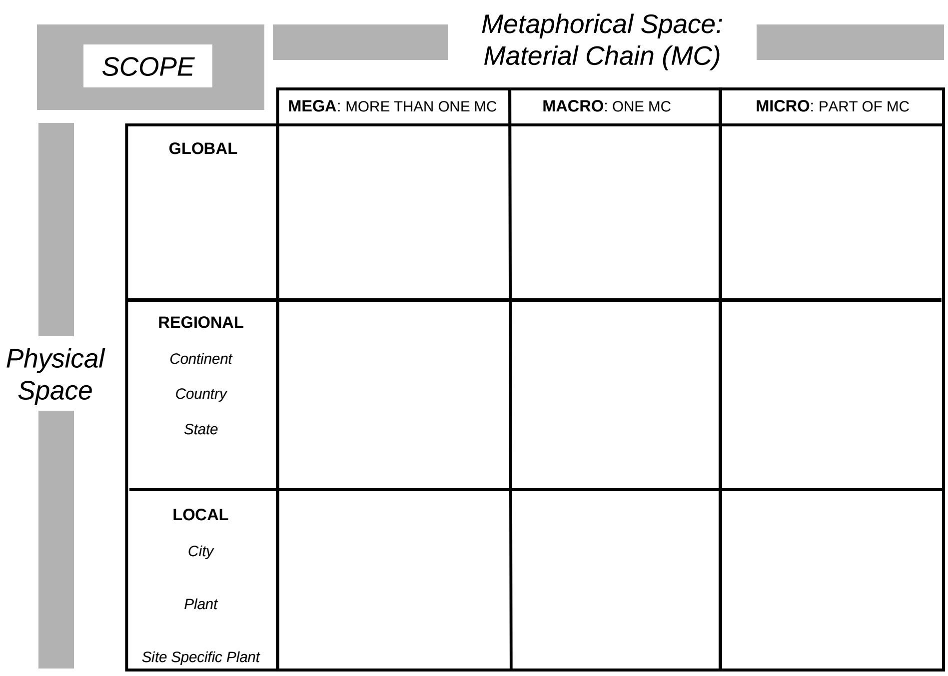


Figure 3-2: Breakdown of decision scope into spatial and material chain detail where the blank boxes represent particular subsets of decision space (these are populated with illustrative decision problems in Figure 3-3)

[1] The nomenclature of mega, macro, micro was adapted from Kaufman (1992) who used these terms to reflect planning at different scales.

For the physical (geographical) spatial domain, the classification of global, regional and local as discrete spatial entities is a specific representation of the continuous spatial domain. For example, the 'regional' classification may represent a continent, country or smaller region such as a state within a country. However, the delineation between global, regional and local is useful in practice for identifying decision problems of interest for the minerals industry in its quest for sustainability along the value chain. It can represent either the absolute spatial boundary of consideration or a boundary of comparison between other similar units; for example, a regional boundary may be chosen to compare regions across the world.

To illustrate the meaning of 'scope' at different levels (comprising value chain extent and spatial domain characteristics), Figure 3-3 provides examples of decision contexts for each scope. These examples have not necessarily been explored in the literature. A literature review of decision problems explored in the literature for each scope is given in Section 3.4 to identify gaps in questions being explored, and to assess the adequacy of models used to explore decision questions across scales.

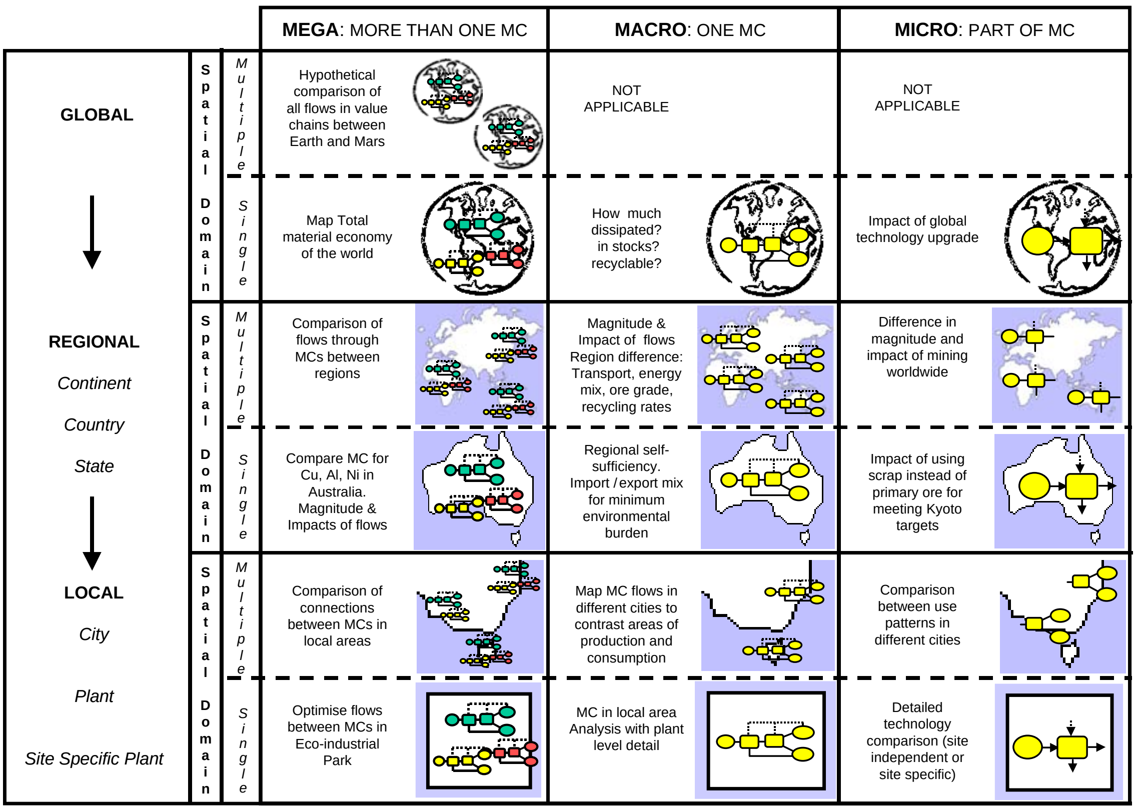


Figure 3-3: Reference schema populated with illustrative decision problems

The spacial domain for decisions contexts is divided into single and multiple regions. A 'regional' level of detail can thus represent analysis of one region only, or analysis between two or more regions using region-specific data. These cases are termed 'single spatial boundary' and 'multiple spatial boundary' respectively.

This reference schema for the minerals industry classifies the system boundary for individual decision problems in relation to those with a broader and narrower focus. This in itself, usefully assists in highlighting that system change can occur at a number of levels by different actors with different results. Consequently, a better understanding of the actors, system variables and impacts associated with decision problems at each level is required. Additionally, the reference schema helps to prompt a re-examination of the traditional narrower domain of interest of problems usually targeted by the minerals industry (which often falls within the plant boundary) and the need to engage with a breadth of scopes to be able to consider a more sustainable future for the entire materials value chain.

The reference schema has established a clear basis for defining the domain of interest for decision problems. To fully define each decision problem, the elements of time horizon and decision ambitiousness can also vary from short to longer time horizons, and decisions considering either negligible or significant changes to infrastructure. These characteristics are embodied in the concept of 'vision', discussed next.

3.2.2 *Considerations for reference schema relating to vision*

The reference schema as presented is initially grounded in the scope of the decision context rather than its vision. This is a deliberate choice as the proper definition of scope is a pre-requisite to including temporal variation in the system. This leaves a range of decision contexts with varying degrees of vision placed within the same matrix grid in the reference schema, as presented in Figure 3-3.

The potential variation in vision is shown in Figure 3-4. The dotted lines show feasible combinations between decision ambitiousness and time horizon for the minerals industry. Limited system changes (using existing infrastructure) can be envisioned for the present or near-term future. A retrofit (changing some infrastructure) is only possible in the near-term or long-term future, depending on the extent of changes. Finally, a radical system change is only possible in the long term. An example of a radical system change would be the transition to a hydrogen economy from an oil based economy. A change of this nature for the minerals industry is not considered in this thesis. Rather, futures which use the same infrastructure and also update infrastructure in the context of a retrofit are explored. This is informed by the minerals industry's conservative approach to adopting new technologies (Warhurst, 1994), the 50 year time horizon being considered, and the need to engage industry with a future it can relate to.

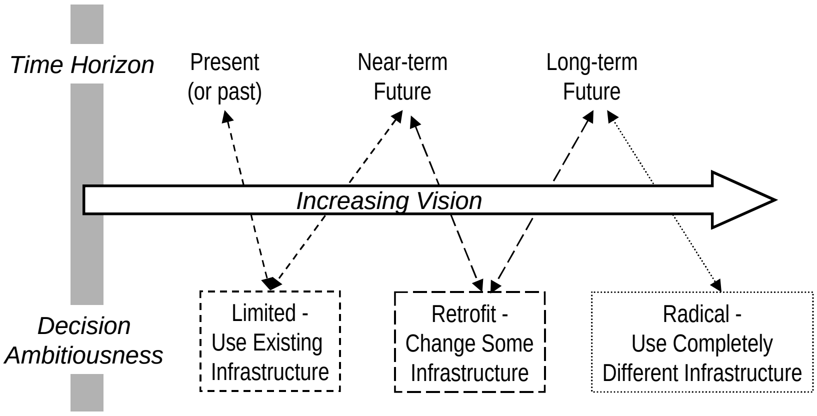


Figure 3-4: Dimensions of vision for a decision context of a specified scope

The reference schema based on scope provides a specification of the physical system boundary or 'domain of interest' for the decision context, from which system changes of varying degrees of ambitiousness can then be explored. Examples of possible changes with increasing vision are detailed in Figure 3-5.

	Increasing vision →		
Value Chain (nodes)	Keep existing infrastructure nodes (components) and just change flow rates through system	Change one or more nodes within domain of influence	Consider changes which extend beyond immediate domain of influence
Value Chain (flows)	Focus on processing flows of traditional material e.g. *ore, pure scrap*	Research new technologies for processing flows of non-traditional feeds, such as electronic scrap containing a complex mix of many metals	
Space	Plant changes e.g. *operating variables, furnace temperature, electrowinning cell voltage*	Local / Regional Changes e.g. *ore grade*	Global changes e.g. *new technology development and global implementation*
Time	Understand system behaviour for Status Quo	Look to future value chain configuration	Consider dynamic transition between now and future state
Decision Ambition	Feasible system state Change possible with domain of influence of individual actors		Hypothetical system state New partnerships required to realise change

Figure 3-5: Examples of changes with increasing vision

The reference schema is designed to assist decision makers understand the nature of their decision context with respect to the value chain and spatial domain. The categories within the matrix are not designed to be absolute, but to offer a guide to understanding not only the decision at hand, but also allied decision contexts and an integrated ability to plan across scales.

3.3 USING THE REFERENCE SCHEMA

The reference schema is useful in two ways. First, it provides a common structure for identifying the domain of interest for value chain systems, the domain of impact arising from value chain operation and the domain of influence of actors within the value chain who seek to make changes that will improve performance. Providing a common structure is the first step to better understanding the links between each domain. Such understanding is critical to making fully informed decisions regarding the future of the industry and is explored in Chapter 4. Second, the reference schema provides a structure for identifying spacial and value chain scales both within and beyond the decision problem's domain of interest or actor's influence, but which may contribute to determining overall impact. This is necessary to identify useful interventions currently beyond the actor's domain of interest and integrate planning across scales.

3.3.1 *Using the reference schema to classify actors and system variables*

The reference schema classifies decision problems according to their domain of interest in Figure 3-3. This section extends the use of the reference schema by showing how it is used to classify the domain of influence associated with particular system variables and actors. Potential decision variables across scales are shown in Figure 3-6.

	MEGA: MORE THAN ONE MC	**MACRO**: ONE MC	**MICRO**: PART OF MC
GLOBAL	Potential Variables • Demand for each commodity • Flows between value chains	Potential Variables • Demand • Splits between nodes	Potential Variables • Characteristics of node (e.g. comparisons between representative technologies)
REGIONAL *Continent* *Country* *State*	Potential Variables • Demand for each commodity • Flows between value chains • Import / Export	Potential Variables • Resource quality (primary and secondary) • Regional supplier inputs • Splits between representative technologies • Demand • Import / Export • Use patterns	Potential Variables • Resource quality (depending on region) • Average technology performance or splits between specific technologies • Suppliers (e.g. energy, depending on performance)
LOCAL *City* *Plant* *Site Specific Plant*	Potential Variables • Flows between plants • Local Industrial Ecology • Flows within plants	Potential Variables • Splits between plants • Changes in network structure or actor relationships	Potential Variables • Node characteristics (e.g. comparisons between site specific technologies) • Process design variables • Specific process inputs and suppliers

Figure 3-6: Decision variables at different scales

Important trends are as follows:

- the focus on variables changes from *between* value chains to *within* value chains to within particular value chain nodes when moving from the top-left corner of the matrix to the bottom-right corner. This is a result of both increasing value chain and spacial specificity, not just increasing value chain specificity.
- at the 'macro' level considering the entire value chain, the determination of material flow 'splits' between nodes is an important variable at all spacial scales.

'Splits' refer to the configuration of flow patterns in the materials chain (such as the split between the fraction of primary and secondary resources used to meet demand, or the split between flows through different refining technologies). The rationale behind listing potential variables for each scope within the reference schema is so that when the literature is reviewed in Section 3.4, the choices of variables and constants in the literature can be compared with potential variables described in Figure 3-6.

Similarly, potential actors can be identified with different scales within the reference schema as shown in Figure 3-7.

	MEGA: MORE THAN ONE MC	**MACRO**: ONE MC	**MICRO**: PART OF MC
GLOBAL	Multiple Actors • Governments • World Trade Organisation • Trading Blocs • Representative Companies • Representative Consumers	Multiple Actors • Governments • World Trade Organisation • Trading Blocs • Representative Companies • Representative Consumers	Single or Multiple Actors • Representative or Specific Companies (e.g. mining, refining, recycling) • Technology Vendors • Representative Suppliers • Representative Consumers
REGIONAL *Continent* *Country* *State*	Multiple Actors • National and/or Regional Governments • Regional Trading Blocs • Representative Companies • Representative Consumers	Multiple Actors • National and/or Regional Governments • Regional Trading Blocs • Representative Companies • Representative Consumers	Single or Multiple Actors • Representative or Specific Companies • Technology Vendors • Representative Suppliers • Representative Consumers
LOCAL *City* *Plant* *Site Specific Plant*	Multiple Actors • Local Governments • Industrial Parks • Specific Companies • Representative or Specific Consumers	Multiple Actors • Local Governments • Industrial Parks • Specific Companies • Representative or Specific Consumers	Single or Multiple Actors • Representative or Specific Companies • Technology Vendors • Representative or Specific Suppliers (energy, raw materials) • Representative or Specific Consumers

Figure 3-7: Potential actors at different scales

Important points to note are as follows:

- the term 'representative company' refers to a generic actor such as 'mining company' while the term 'specific company' refers to a specific actor such as, for example, 'BHP Billiton'
- multiple actors are involved at the mega and macro levels
- different actors will have different influences over the system variables described in Figure 3-6.

A proposed range of environmental performance measures across scales is given as a guide in Figure 3-8. Note that whilst measures such as global warming relate to a global impact, this will give rise to differential damage at regional and local scales in various locations around the world.

	MEGA: MORE THAN ONE MC	**MACRO**: ONE MC	**MICRO**: PART OF MC
GLOBAL	Space-independent measure (e.g. energy usage)	Space-independent measure (e.g. energy usage)	Space-independent measure (e.g. energy usage) Global Impacts (e.g. global warming) Regional Impacts (e.g. acidification)
REGIONAL *Continent* *Country* *State*	Space-independent impacts Global Impacts (e.g. global warming)	Space-independent impacts Global Impacts (e.g. global warming) Regional Impacts (e.g. acidification) Region-Specific Impacts (e.g. acidification in Europe)	Space-independent impacts Global Impacts (e.g. global warming) Regional Impacts (e.g. acidification) Region-Specific Impacts (e.g. acidification in Europe) Local Impacts (e.g. particulates, ecotoxicity, water usage, solid waste)
LOCAL *City* *Plant* *Site Specific Plant*	Space-independent impacts Global Impacts Regional Impacts Region-Specific Impacts Local impacts (e.g. particulates, ecotoxicity, water usage, solid waste) Local-specific impacts (e.g. water usage at ecopark)	Space-independent impacts Global Impacts Regional Impacts Region-Specific Impacts Local impacts (e.g. particulates, ecotoxicity, water usage, solid waste) Local-specific impacts (e.g. solid waste in city)	Global Impacts Regional Impacts Region-Specific Impacts Local impacts (e.g. particulates, ecotoxicity, water usage, solid waste) Local-specific impacts (e.g. ecotoxicity of waste from processing plant)

Figure 3-8: Environmental performance measures across scales

An increase in information detail used in decision problems when moving from top to bottom and from left to right potentially allows more detailed indicators to be used. The use of specific indicators at different scales will be explored in the literature review in Section 3.4. The literature review will also serve to examine the way in which actions taken at a particular scale to change system variables are linked to impacts and the scale at which the impacts manifest. This link will be required for a full understanding of one's actions and how they affect the material chain in moving toward a preferred future.

3.3.2 *Using the reference schema for planning across scales*

The reference schema assists in developing an approach for planning across scales for the minerals and metals industry. Namely, what domains of interest within the reference schema is it necessary to study to provide a comprehensive picture of the industry and what information between scales must be linked when studying decision problems at different scales.

The reference schema has created a new focus specifically on scale within the minerals industry. To assist in further discussions, key terms related to scales are briefly defined in Table 3-3.

Table 3-3: Definitions of terms related to scale (definitions from Gibson et al. (2000) and material chain example added here)

Term	Definition	Material Chain Example
Scale	The spatial, temporal, quantitative or analytical dimensions used to measure and study any phenomenon	A study of the whole copper material chain in North America is a study at the macro-regional *scale* as defined in the reference schema
Extent	The size of the spatial temporal, quantitative or analytical dimensions of a scale	The *extent* of the material chain focus for decision problems at the mega level is multiple value chains, the *extent* at the macro level is a single material chain
Level	The units of analysis located at the same position on a scale	A macro-global analysis and a micro-global analysis are at the same *level* with respect to spacial scale, but at different levels with respect to the extent of the material chain which they include
Resolution (grain size)	The precision used in a measurement	A study which includes unit operation detail for processing plants in a region has greater *resolution* than a study which describes the processing plant as a single unit. Greater resolution requires greater information detail

The scale, extent and resolution of any study will influence the patterns that may be observed – patterns apparent at a low level may not be apparent at a higher level (Gibson et al., 2000). Additionally, the focus will be on different actors at different scales, who in turn will be able to influence different system variables. This identifies the need to study the value chain at a range of scales and resolutions in the value chain and from multiple actor perspectives. This need has been identified in ecological systems (Costanza et al., 2001). However, for industrial systems, studies which consider material flows at different scales are only beginning to emerge (see Graedel et al., 2004). Beyond material flows, the reference schema aims to provide a basis for linking scales of material flows, environmental impacts and actor-controlled variables that can be manipulated to realise a preferred future.

Consideration of multiple scales requires different levels of information detail to support decisions at different scales. Collecting too much information can be just as unhelpful as collecting too little. Table 3-4 proposes guidelines for considerations of scale in the mineral and metals value chain.

Table 3-4: Consideration of multiple scales

Focus	Information Detail	Rationale	Example
Large scale	Low	Rapidly shows where to focus further attention. Gives broad understanding of high level issues	Analysis of global material chain at highly aggregated level
Mid scale	Medium	Explore mid level sensitivities, confirm that area for further analysis identified in large scale analysis was worthy of attention	Focus on processing technologies bringing metal to market within a region using average or region-specific information detail
Narrow scale	High	Explores issues and actor influences which require a high level of information detail to support	Detailed consideration of local technology operation (e.g. using plant specific data)
Mid scale	Medium / High	Broadens mid level analysis (e.g. additional actor perspectives, include external influences, future states) validated by understanding of system operation at large and narrow scales	Include influence of future supply and demand considerations on processing technologies bringing metal to market in a specific region

A combination of top-down and bottom-up approaches provides different insights, and metal commodity producers generally adopt a top-down approach whereas product manufacturers use bottom-up analyses (Berkhout and Howes, 1997). By combining analyses across scales, larger scale analyses can act as constraints on analyses below them, while narrower scale analyses offer insight into sensitive variables and the actors which can control them which may not be apparent at higher levels of analyses. Information regarding system configuration, system performance and which actors can control system variables must all be monitored. By knowing whether actors can influence particular variables across scales or at just one scale, potential partnerships could be highlighted. It is analysis across scales which highlights required interventions at different scales.

An approach based on the principles of industrial ecology suggests that the minerals and metals value chain be studied at different scales (Graedel et al, 2004). It is important to be able to conduct analyses at different scales because resource, technology and environmental consequences cut across levels and studies at different levels can reveal different insights that would not be uncovered when focusing at a single scale (Graedel et al., 2004). The reference schema provides a structure to facilitate analysis of the value chain at different scales, by clearly classifying decision space scales. The next section explores information detail and information requirements for system characterisation across scales. Following the discussion of information requirements, the literature is reviewed to determine how successfully current approaches characterise the value chain across scales.

3.3.3 *Information requirements across scales in reference schema*

'Level of analysis and detail of information' was identified as a key component of the analytical framework in Chapter 2. Understanding the range of information detail and how this varies with scales of analysis is the focus of this section.

Information exists in a variety of forms, including written language or equations, visual and auditory information; qualitative and quantitative; useful and not useful. Given an understanding of the context and origins of the information and how it is to be used, information can help us make decisions. Confusion about what gathered information was intended to represent and how it was to be used, can lead to poor decisions. In other words, good information detail incorporated in an appropriate decision making process, is a useful starting point for making good decisions.

In an analysis of the minerals and metals value chain, the information ranges from ore grades at particular sites, to global production figures, to qualitative information regarding the important system drivers. Approaches must be developed to provide 'information that fits the purpose' (Viljoen and Dann, 2000). Each decision problem in the reference schema will require different information to support it.

To date, little serious work has been undertaken in relation to information structuring for sustainability in the minerals industry and in particular, with regard to doing so across the value chain. The general importance of this undertaking is emphasised by Königer and Janowitz (1995) who state that 'Effective structuring work is one of the most effective contributions to the value of information'. To operationalise sustainable development, the actors must make decisions fully aware of the consequences of their actions across scales. In order for actors to accept responsibility for their actions, there needs to be a clearer link between actions and outcomes and at what scale each is manifested.

The level of information detail used to describe the system state and its performance will vary according to the decision problem's position within the reference schema. The range of information detail possible is introduced in Figure 3-9 and Figure 3-10 for the state of system and performance of system, respectively.

STATE OF SYSTEM
with specified scope ~ domain of interest

	Increasing information detail →		
Material Chain (nodes)	Main components aggregated e.g. *mining and refining = preparation for use* Links only between main components	Single component class e.g. *Smelting or Fabrication*	Specific component class e.g. *Flash Smelting, Reverberatory Smelting or Fabrication of wire, tube, cable etc*
Material Chain (flows)	Quantity of main material flow only e.g. *copper*	Quality & quantity of other components e.g. *copper, zinc, ...* Linked flows / inputs e.g. *electricity, coke, oil*	Include trace elements and minor linked flows
Space	SCOPE: varies from global............to regional..........................to local; conversely for Information detail, often not practical to go to greater detail when scope is large GLOBAL (large scope (so lower detail possible) e.g. *Average ore grade*	REGIONAL (less scope and more detail) *regional ore grade*	LOCAL (narrower focus higher detail) *plant specific ore grade*
Time	One Point in Time e.g. *Now, Past, Future*	Compare several time points	Continuous paths through time
Decision Ambition	Understand Status quo	Change specific nodes or flows within system	Completely innovate system to provide desired functionality

Figure 3-9: Range of information detail for describing the state of a system

PERFORMANCE OF SYSTEM
~ domain of impact

	Potential variations →			
Value Chain	Nodal performance for individual material chain activities			System wide performance
	Relative performance			Absolute performance
Material	Impacts associated with supply and flows of single material component			Impact of all components including linked flows
Space	On-site impact	Local Impacts	Regional Impacts	Global impacts
Time	Impact / Performance does not change with time		Impact time dependent -may increase or decrease	
Decision Ambition	Performance of existing system		Monitor performance along path to future sustainable state	

Figure 3-10: Range of information detail for describing the impact of a system

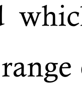
Describing the breadth of information detail provides the context for reviewing the literature to determine what information is used to support decisions, what links exist across scales and how value chains are characterised.

3.4 REVIEW OF LITERATURE AT EACH SCALE WITHIN REFERENCE SCHEMA

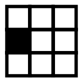
This section reviews the literature across each of the nine scale divisions within the reference schema. This will establish how the decision space classified by the reference schema has been interrogated to date – at what scales decision problems have been explored, with what modelling approaches and performance indicators, with consideration of the status quo only or also alternate futures, with what recognition there has been in the literature of the need to consider analyses between scales. The review also seeks to identify links between the domain of interest, impact and influence, namely, how effectively models of system flows are linked to environmental performance indicators and the ability of actors to change key system variables. These links will be required in order to realise paths toward preferred futures. Where gaps are identified in the literature with respect to the aforementioned criteria, this will inform the development of approaches to address these shortcomings in Chapters 4 and 5.

3.4.1 *Literature from mega level for global, regional and local cases*

The literature for analyses at the **mega** level (of multiple value chains) in the reference schema is reviewed at the global, regional and local levels, respectively. Consideration of multiple value chains is beyond the scope of this thesis, but reviewing this literature illustrates the current state of analysis for multiple value chains and shows where extensions to the approaches developed in this thesis could be applied at this level. The symbol next to each sub-heading illustrates which division within the reference schema is being discussed.

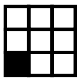
3.4.1.1 *Global-Mega* 

No literature was found which considers globally aggregated fluxes through multiple material value chains. A range of production and/or consumption figures are reported by industry institutes (ICSG, 1999; IISI, 2002), government organisations (USGS, 2002) or private mineral research institutes (Brook Hunt, 2002; Metal Bulletin, 2002) for various metals. The information covers mining and refining (supply), and consumption (demand). Supply from secondary sources (recycling) may also be given. Figures are not given for all stages in the material chain and flows between material chains are not recorded; furthermore no link to environmental impact is made. This decision space remains largely unexplored, in part due to a lack of information on flows through individual value chains and between value chains at a global level.

3.4.1.2 *Regional-Mega* 

The studies which consider multiple material value chains at regional levels are based on input-output analysis which is popular in the field of economics. Lenzen (2003) studies the interdependence of 134 industry sectors in the Australian economy using input-output analysis. System performance is quantified with respect to the environmental impacts of land disturbance, water usage and greenhouse gas emissions, each expressed per unit of economic activity (dollar). The aim was to identify key sectors whose development has a significant influence on the advancement of other sectors in the economy. This work provides a good foundation for establishing the importance of the minerals industry within a particular regional economy. However, the level of aggregation does not permit focus on paths of action that the minerals industry itself can embrace to achieve a more sustainable future, such as the implementation of a new technology – this was not the focus of the work.

Konijn and co-workers (1997) use an input-output analysis to investigate the energy usage associated with iron, steel and zinc in the Netherlands. While the sectoral scope is not as comprehensive as that of Lenzen (2003), the level of detail of the iron, steel and zinc investigation allows the impact of a technology change to be evaluated. This is a useful inclusion in the approach, as it is a potential system change which actors in the minerals industry have the ability to implement. However, only the status quo and an alternate future scenario are explored. Konijn et al. (1997) acknowledge the approach does not allow for an analysis of the transition path between states, due to the static nature of the approach. Developing the ability to analyse a path through time between status quo and alternate future is an important gap to be addressed, as the approach path to the alternate future could significantly influence the overall performance of the system through time.

3.4.1.3 *Local-Mega* 

Investigations considering multiple value chains with a local level of information detail are limited. The most comprehensive work is that of Reuter (1998). This paper uses a layered structure to allow the linking of several metal value chains to be explored. The nature of links between value chains is described at the top level of the model. Below this, links between stages within specific value chains are given (e.g. mining, refining etc.). Within the individual value chains, different technology options are specified, while the final level provides more (potentially locality-specific) process detail. The approach is designed to allow cycles to be analysed to various degrees of complexity and depth. A database program is coupled with simulation software to perform the analysis with outputs being material and energy flows. The strength of this work is its acknowledgement of the interconnectedness of metal value chains; however, there is limited treatment of the ability of actors to implement preferred futures. System flows are linked to environmental performance, but this is not linked back to the domain of influence of actors in the context of achieving preferred futures.

In the context of assessing the efficiency of flows between value chains at a local level, Hardy and Graedel (2002) look to the analogy between industrial eco-industrial parks and food webs. The idea is that by studying the 'connectance' (number of linkages) between industries within eco-parks, resource utilisation could be maximised and waste generation minimised. The authors deem the work to be preliminary and suggest that while higher connectance between industries allows for a greater potential for resource utilisation, it does not necessarily follow that the overall environmental impact of a more connected system is less, nor that they are more stable in the long term. This research is useful for promoting thought on what constitutes a desirable number of linkages within and between value chains and how this could be measured. Its application to minerals and metals would form a useful extension to the work undertaken in this thesis.

3.4.1.4 *Summary for Mega Analysis*

Table 3-5 presents a summary of the model and information detail used in the literature in relation to analysis at a mega level.

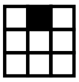
Table 3-5: Summary table for mega level of analysis

Mega Analysis	Global	Regional	Local
Decision Contexts Explored	—	Energy usage of metals in the Netherlands	Changes to structure of linked material chains
		Environmental performance across sectors in Australia	'Connectedness' between industries from different value chains as indicator of system performance
Information Detail	—	National	Local
			Plant-specific
System Characterisation		Mass flows	Flows and network arrangements
			Connections between firms
Material Flows Model		Input-output	Linear models
System Performance		Energy / Land usage, Water, CO_2	Emissions, Energy, Solid waste
System Variables		Technology	Distance / Connectedness
Actors Considered		Industry sector	Companies
Time Characteristic		Yes	Only some include
Actor-Impact Link	—	No	No
Links across scales	—	No	Yes (Reuter)
Design of futures		Yes (Konijn)	No
Outcomes	—	Ability to measure environmental performance across sectors in the economy	Ability to characterise links between value chains and environmental performance
Limitations		No path toward future	
		No link between actors, system variables, system state and impact	No link between actors, system variables, system state and impact

The summary in Table 3-5 shows that some studies are beginning to consider connected value chains. Better characterising material flows and their environmental performance has largely been the aim of these studies. The need to link across scales is also acknowledged. At this stage, more comprehensive studies seeking to plan for paths toward preferred futures for multiple value chains are not proposed, due to the complexity of the problem, limitations in available data and the lack of a structured approach to design and evaluate paths toward preferred futures.

Two issues must be addressed before these questions can be successfully tackled. First, a more detailed information structuring process to allow characterisation of flows and impacts for the status quo; and second, the development of an approach to design preferred futures and link choices by actors to the environmental performance of paths toward preferred futures. These elements will be addressed in this thesis for the case of a single value chain.

3.4.2 *Literature from macro level for global, regional and local cases*

3.4.2.1 *Global-Macro* 

At the **macro** level of considering a single material chain, globally reported production and consumption information can be used to partially characterise system flows in the material chain. Consider the aggregated representation of the copper material chain given in Figure 3-11: the available information covers mining, refining and consumption, secondary sources of scrap are also included.

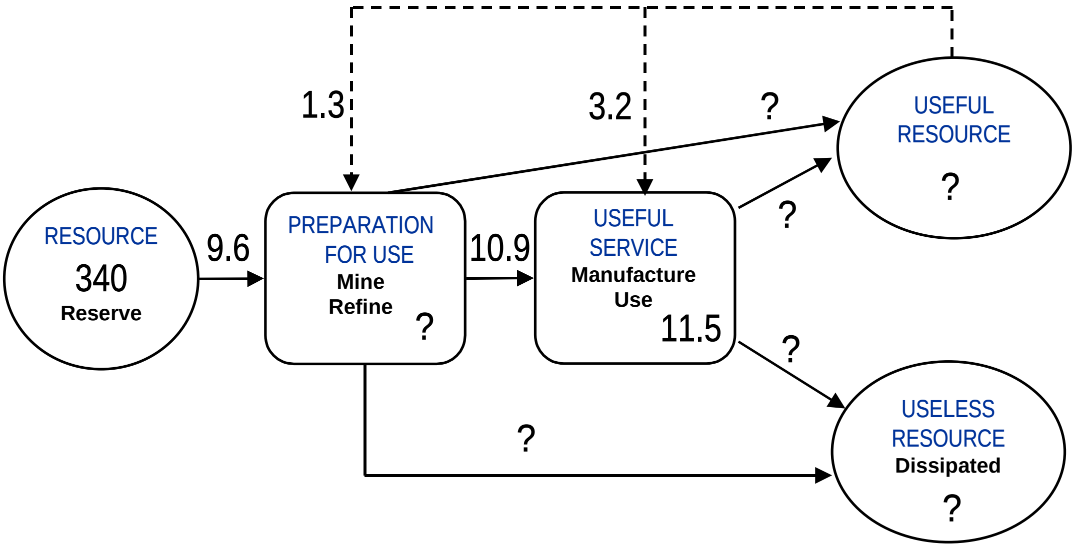


Figure 3-11: Aggregated representation of material chain with readily available global information for copper in 1998 included and missing information represented as '?' Figures are in millions of tonnes (Moreno, 1999)

The information available relates mainly to flows rather than stocks, except for ore reserves. The numbers quoted do not lead to mass balance closure, due to uncertainties in the figures and potential changes in stocks for the annual reporting period. Overall, readily available data are insufficient to populate the entire value chain.

Recent work undertaken by Graedel et al. (2004) has completed a comprehensive characterisation of the global copper cycle, which assists in overcoming previously lacking data. The work is unique in its specific focus on value chains at the country, regional and global scales. Graedel and co-workers do not link material flows with environmental performance assessment, but suggest this as an extension to their work, given that the data they collate on flows provide a sound basis for the characterisation of environmental performance associated with value chain flows. No specific actors are identified in their analysis, which is directed more at the policy level than to operating companies. It is also a static analysis for the year 1994 and does not consider preferred futures. However, it is an important validation of the need to study the value chain across scales.

The only value chain study found with an exclusively global focus is that of Williams (2003) who studied the global production chain for silicon and explored the impact of production trends on economic and environmental performance. Production trends depended on demand forecasts, which were generated using an exponential growth model, calibrated against historical data. In addition to the constant growth rate assumed, the material input/output table remained constant through time, which did not allow for technology changes in the system. The industry sector was considered collectively as an actor. Using energy as an indicator of environmental performance, the environmental performance associated with forecast demand increases was calculated. The emphasis was on predicting future states, rather than designing environmentally preferable futures.

3.4.2.2 *Regional-Macro*[2]

The analysis in this section shows that several authors have researched flows through material value chains at a regional level with partial successes, yet a comprehensive approach characterising value chains across scales and preferred futures has yet to be produced. The literature is grouped according to the authors' consideration of status quo or future states and environmental performance measure.

Characterising mass flows

Jolly (1993) aimed to quantify the total amount of zinc that had entered the environment in the USA from anthropogenic sources and the current pool of stocks. The methodology analysed historical data and described zinc losses at processes along the value chain. A cumulative result of stocks and flows for the time period from 1850–1990 was given. It concluded that dissipative uses and disposal to landfill has accounted for over 70% of possible zinc losses to the environment, with approximately 20% of losses from mining and smelting and only 5% from manufacturing. Consequently, an initial analysis of mass flows in the value chain is important for directing further attention to parts of the value chain that give rise to the greatest zinc losses. However, zinc losses to the environment are not the only contributor to environmental burden. It takes approximately 70 GJ/t to produce zinc from ore (cf. 270GJ/t for aluminium, 115GJ/t for copper and 30GJ/t for lead)[3] and an initial analysis aimed at directing further attention to highly impacting parts of the value chain should as a minimum also consider the energy requirements along the value chain, given that energy is a significant contributor to environmental burden.

Substantive work on the characterisation of copper cycles comes from a series of papers by Graedel (2002), Spatari et al. (2002), Bertram et al. (2002) and Rechberger and Graedel (2002). The first two papers deal with the data used to characterise a material

---

[2] The focus in this thesis is on metals with large tonnages circulating in the economy (e.g. copper, aluminium, steel) whose processing to deliver a metal product gives rise to significant environmental burdens. Material flows studies have also been undertaken for heavy metals (such as lead, cadmium, mercury) for which there are lesser absolute flows circulating through the economy, but for which a higher environmental impact is attributed to their dissipation into the environment rather than their processing to a metal product. This research has been advanced by van der Voet (1996) and is commonly termed Substance Flow Analysis. The focus in the case of highly toxic metals or metals with highly dissipative uses, is to better understand the distribution of the metal in the environment, for example through fate and transport modelling. See also Guinée (1999).

[3] Actual energy consumption will depend on specific ore grade and processing technologies in use (Henstock, 1996).

cycle and then the results of the copper stocks and flows for Europe in 1994 and will be discussed further here. The third has a focus on waste management and the fourth on using relative statistical entropy as an approach to compare the resource quality of copper (relative to that in the Earth's crust) at value chain stages. The need for analysis across scales is also highlighted in a related paper Graedel et al. (2004) as was discussed in Section 3.4.2.1.

Graedel (2002) evaluates the data quality and data availability for establishing a copper cycle for one year. While noting that data vary highly in quality and level of detail, it is concluded that despite the limitations, information is sufficiently available to characterise copper cycles at several spatial scales, although to date, national analyses have been most common. In general, it is concluded that data quality and availability are better for early stages in the value chain such as mining and refining. In developed countries only, there are acceptable data regarding the use phase; however, less accurate data and less availability are to be found regarding the waste management and disposal stages. These findings were significant in establishing the basis for the subsequent work of Spatari et al. (2002), who characterise the material value chain for copper in Europe using a snapshot model. The aim of the work by Spatari et al. (2002) is to assist resource management and policy analysis by providing insight into the stocks and flows within a region, but there is no focus on any specific actor. The same group of researchers also use a similar methodology to characterise the material chain for copper in other world regions, for example Latin America (Vexler et al, 2004), Africa (van Beers et al, 2003).

In summary, Graedel (2002) and Spatari et al. (2002) establish that adequate data is available to support an initial characterisation of the materials value chain for a widely used industrial metal, namely copper.[4] The analysis stands at a national and regional levels and looks toward methods for achieving analysis at other spatial scales. This is an important step in spanning scales to provide a comprehensive picture. The focus taken on material flows must now be extended to give an estimate of environmental impact across scales and an approach developed which can assess the ability of actor choices to realise preferred futures.

---

[4] This group of researchers also completed subsequent work on zinc cycles in Europe using a similar methodology: Gordon et al, (2003) and Spatari et al, (2003) are the papers for zinc which correspond to the copper papers of Graedel (2002) and Spatari et al. (2002) above.

Environmental performance

An initial attempt at linking material flows with environmental performance at the regional level is given by Gaines (1980). The focus in 1980 was more to achieve cost savings through energy efficiency, rather than to quantify the environmental performance associated with the energy-intensive nature of the copper value chain; however, in light of current drivers toward improved environmental performance, the methodology is useful to build upon. Gaines (1980) reconciles a comprehensive range of data sources to provide detailed material flows of copper in the US economy through production, manufacture and use, and, average energy requirements of major technology processing paths. The energy associated with process inputs is also considered in line with the method of Net Energy Analysis (Chapman, 1974). While useful, the impact of different forms of energy provision (e.g. coal vs. hydropower) is not explored and additional environmental indicators beyond energy are not considered. Furthermore, no assessment is made of a preferred future state nor path toward it.

Forecasts

The authors Ayres et al. (2001), van Vuuren et al. (1999) and Zeltner et al. (1999) all use similar methodologies to predict stocks and flows through the material chain up to the year 2100. From a policy perspective, they are interested in the implications for resource availability of an industrial system with the predicted metal flows (including primary resource exhaustion, amount of dissipative use, potential of landfills containing discarded goods to be a future resource) under different scenarios.

The method employed was to construct system-dynamics models. Zeltner et al. (1999) uses historical functions for copper consumption through time (either linear or logistic) to predict stocks and flows of copper in the USA under different scenarios. The model of the value chain uses generic process nodes (Mining, Crushing, Smelting, Semi-manufacture, Manufacture, Short term usage, Long term usage, Dismantling, Separation and Landfill) linked by flows between processes, subject to mass balance constraints. Individual scenarios varied the recycling rate, separation efficiency and residence time of copper in short and long term use. Changes in system variables were not linked to potential actors who control them. Parameters defining specific relationships between stream flows are calibrated against historical results and, according to the authors, this allows a first approximation of regional copper management with a relatively limited and inaccurate data set. The authors only consider mass flows and do not model the environmental performance of the system. This would extend the usefulness of their approach by being able to describe the preferedness of the future scenarios they model. While the probability of long-term forecasts is always difficult to assess, information describing the desirability and attainability of the proposed system changes would enable the industry to make more informed choices about its actions, which could alter the future configuration of the value chain. Preferred, feasible value chain configurations are explored in Chapters 4 and 5.

Van Vuuren et al. (1999) use a similar approach to that of Zeltner et al. (1999) but for iron/steel and the average behaviour of nickel, tin, zinc, lead and copper considered as one material. This succeeds in characterising the present state of material flows. However, there continues to be a shortage of an assessment of the environmental burden of the material value chain's operation and the ability to explore preferred futures.

Ayres et al. (2001) extend the model of Zeltner et al. (1999) to compare copper stocks and flows in four world regions: developed countries; reforming eastern Europe and former USSR; developing countries in Asia; and Africa / Latin America. Key variables changed in this modelling are economic growth and the intensity of use (consumption as a function of economic prosperity)[5] which together affect total demand. Recycling rate is the third key variable changed. The results of the forecasts are presented as a range of scenarios where the key variables take different values, with material flows predicted until 2100. Robinson (1988) questions the usefulness of current long term forecasting approaches to inform resource policy – first, because they have been shown to be unreliable, and their use as objective, value-free information is questionable. Second, because forecasts obscure the actor choices which will influence the future; 'the future is not predetermined' (Robinson, 1988).[6] Consequently, rather than aiming to predict the future in the long term, more information is needed about the range of future choices, their impacts and whether they lead to preferred futures. Developing an approach to overcome this deficiency for the minerals and metals value chain is a key focus for this thesis.

---

[5] The intensity of use hypothesis says that copper consumption will rise at low levels of economic prosperity (measured as GDP) and after a peak, begin to decline at higher levels of economic prosperity.

[6] Robinson highlights the difference between long term forecasts which involve deliberate choice, with short term predictions such as weather forecasting where choice is limited – i.e. no actor has control over changing the weather, they can simply modify their actions in response to the forecast.

3.4.2.3 *Local-Macro*

Decision contexts explored in relation to a single value chain at the local level have varied aims and are supported by a range of approaches. The task is to assess which approaches can be used to support decision making for a more sustainable future in the minerals industry.

Kuckshinrichs et al. (2000), Bauer et al. (no date), and Kuckshinrichs and Schwarz (2000) combine global economic models of the aluminium industry with technology models incorporating local detail to explore future scenarios. One example they explore is the greenhouse gas emissions resultant from an assumed growth in the aluminium market and industry deregulation. Using a linear modelling approach, process models and changes in demand dictated by the economic model give rise to changes in expected emissions (e.g. CO_2, CH_4, red mud etc) and to inputs associated with the given level of production (e.g. energy, lime, coke). The usefulness of this approach is in linking the process models with economic models to determine the environmental performance of individual components along the value chain.

Sagar and Frosch (1997) study an industrial ecology at a local level to the extent of describing interactions between individual firms within the copper value chain in the region of New England, USA. This articulates the interactions of individual actors such as smelters, refineries, manufacturers, scrap dealers and landfills in the value chain. It concludes that configuration of relationships and material flows within the New England area is such that little copper (only 0.5%) is lost to the environment. It highlights the need to focus on actors when considering the implementation of preferred futures.

Finally, supply chain literature describes flows of manufactured goods at the macro-local level. A good overview of the literature is obtained from the following authors: Min and Zhou (2002) and Croom et al. (2000). The focus of supply chain analysis is to describe for products (rather than materials such as metals) the network between raw material suppliers (inbound logistics), and the customers (outbound logistics) to whom the products are sold. Factors studied in the supply chain literature include: location, inventory, marketing, distribution channels, logistics and transport, and reverse logistics (product takeback).

Table 3-6 presents a summary of the model and information detail used in the literature in relation to analysis at the macro level. It illustrates that while in some cases material flows have been modelled along the value chain, such approaches do not also assess the environmental performance of future system configurations nor link impact to actor decisions.

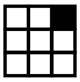
Table 3-6: Summary table for macro level of analysis

Macro Analysis	Global	Regional	Local
Decision Contexts Explored	Production and consumption differences (and trends)	Predict supply and demand, current stocks and flows (mass basis)	Logistic improvements (Supply Chain Analysis) Behaviour of industrial ecology system for metals, role of actors
Information Detail	Global	Regional, Country-specific	Plant specific / average data
System Characterisation	Mass Flows	Generic process nodes for whole value chain	Location, volume, network, inventory
Material Flows Model	None or Input-Output Material Flow	System-dynamic, stocks and flows	Stochastic / Deterministic, Conceptual Mathematical
System Performance	Mass flow (Graedel) Economic / Environmental (Williams)	Mass flows, cost, energy	Economics, liabilities
System Variables	—	Supply and demand	Material properties, utility, network routes
Actors Considered	Policy makers, industry as a whole	Policy makers, industry as a whole	Raw material suppliers, companies, customers
Time Characteristic	Modelled for change in demand	Yes	Yes
Actor-Impact Link	No	No	Some Yes / Some No
Links across scales	No	No	No
Design of futures	No	No (prediction)	No
Outcomes	System characterisation and performance	Future prediction	Actor relations, environmental performance of scenarios
Limitations	Linking flows to impact	Desirability of futures based on environmental performance of future value chain configurations	Linking actions to impacts

3.4.3 *Literature from the micro level for global, regional and local cases*

The decision problems explored at the **micro** level are varied as their focus is on a single part or parts of the material chain. A focus on one part of the value chain enables the particular problem of interest to be analysed in greater detail. However, given the need for a value chain focus to advance the industry toward a more sustainable future, it is important to ensure that detailed problem analyses for single parts of the value chain are understood and interpreted in the wider context of the entire value chain. This section of the chapter reviews how the decision space at the micro level has been explored in the literature, with what tools, performance measures and information detail, and whether or not the results have been linked to a value chain perspective.

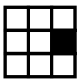
3.4.3.1 *Global-Micro*



Giurco et al. (2001) consider the environmental performance of material flows through specific parts of the copper value chain aggregated at a global level. With a focus on technology selection for the primary processing of copper sulfide ores, the effect of changing ageing reverberatory smelting technology with current flash smelting or solvent extraction technology is evaluated. Environmental performance is assessed using Life Cycle Assessment (LCA) and impact potentials are assessed for global warming, acidification, ecotoxicity and smog. Results were presented both on an impact per tonne basis and for the total global impact, considering the tonnages of copper produced via each processing technology. LCA impact categories were useful for highlighting trade-offs in performance between impact categories. The results were not placed in context of the entire value chain's performance.

No other studies were found representing global material flows, other than production and consumption figures already discussed in the context of multiple value chains in Section 3.4.1.1.

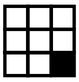
3.4.3.2 *Regional-Micro*



This section reviews literature with a focus on regional analysis for specific parts of the value chain.

Giurco et al. (2001) use country specific information detail to inform a comparison between the environmental performance of current technologies for processing copper from ore in Chile and Australia. Performance is reported with respect to water usage, energy usage, global warming, acidification, ecotoxicity and smog impact potentials. The study demonstrates that the inclusion of regional information detail with respect to ore grade processed and energy mix utilised (as opposed to using average global detail) significantly affects the overall environmental performance. The combination of generalised technology models with region-specific information detail allows mining companies to determine regional impact profiles associated with their technologies.

Graedel and Klee (2002) examine sustainable targets for resource use in a region based on limits of supply (from known reserves) and the current rates of recycling, to compare the current patterns of use with sustainable targets. Sustainable targets are calculated based on continued utilisation at current rates for the next 50 years. Representative case studies are given for zinc, germanium and carbon equivalents. Using limited information detail, this provides a first assessment of potential limitations on resource supply. This work is useful for informing national or international policy objectives based on current and sustainable usage rates.

3.4.3.3 *Local-Micro* 

Lunt et al. (2002) and Norgate and Rankin (2000) consider selected parts of the materials value chain with a view to improved environmental performance associated with minerals processing technologies in a cradle-to-gate analysis. Mass-based models are used and time is not considered as a variable. Inventory associated with production is linked to impact potentials in selected LCA categories as an indicator of environmental performance (acidification and global warming potential). Ore grade is shown to have a highly significant effect on energy consumption in copper production (Norgate and Rankin, 2002) and in turn, overall environmental performance, however the potential impacts arising from solid waste disposal are not addressed. The importance of this issue was highlighted in Chapter 2 and the development of a new approach to assessing the impact potential of solid waste in the context of LCA is undertaken through a case study in Chapter 8.

The limitation of these analyses to date has been the failure to include both primary and secondary resources as potential feed materials to existing technologies, in line with greater consideration of the components in the value chain. Furthermore, the dynamic nature of secondary supply has not been included and a clear link is not established between improved performance and the ability of actors to effect such changes.

3.4.3.4 *Summary for Micro Analysis*

The following table presents a summary of the model and information detail used in the literature in relation to analysis at the micro level.

Table 3-7: Summary table for micro level of analysis

Micro Analysis	Global	Regional	Local
Decision Contexts Explored	None - just reports production/consumption figures	Limits to supply, recycling policy, regional technology sensitivities	Comparison of mining & refining technologies
Information Detail	Global	Region or country-specific	Average plant detail (not location specific)
System Characterisation	Mass flows coupled with technology models	Primary Stock, Recoverable Stock, Usage, Technology	Mining and refining technology. Main and linked flows.
Material Flows Model	Steady-state	Snapshot	Mass balance, process models
System Performance	LCA impact categories	Mass rate of use / Stock	Global Warming and Acidification
System Variables	Technology	Change rate of use / Ore grade, energy mix	Ore grade
Actors Considered	Industry policy	National policy maker / Minerals company	Mining and refining companies
Time Characteristic	Historical data available year by year	No	No
Actor-Impact Link	Yes	No / Yes	No
Links across scales	No	No / No	No
Design of futures	Yes	Yes	Yes
Outcomes	Environmental impact of global technology upgrade	Setting of sustainable consumption targets, quantifying effect of country specific variables	First-pass comparison of copper processing technologies
Limitations	No linking across scales	No comparison between impacts of primary and secondary production using regional information	No ability of LCA impact categories to reflect stability of solid waste in minerals processing

Micro level analysis generally uses a local level of information detail in the decision problem. Local information detail could be expressed either site-specifically or independently as an average value for the local area. Historically, the minerals industry has focussed on analyses at the plant level, but without considering the results in the context of the entire value chain (Bridge, 2004; Petrie, 2005). Beginning with a value chain approach, may necessitate the use of aggregated or average data, which glosses over the effect of potentially important local variables. This confirms the need for an analysis across scales in the reference schema using a combination of top-down and bottom-up approaches.

3.4.4 *Mapping Literature Review onto Reference Schema*

A summary of the literature reviewed in relation to its position within the reference schema is presented in Figure 3-12. This provides a ready reference to how the decision space has been interrogated to date in relation to the minerals and metals industry. Overall, there is a lack of a comprehensive multi-scale approach to investigating the environmental performance of the value chain, a lack of future planning for the value chain as a whole, and only a limited connection between actor-decisions and the resultant value chain impacts they manifest.

			MEGA: MORE THAN ONE MC	**MACRO**: ONE MC	**MICRO**: PART OF MC
GLOBAL	Spatial Domain	*Multiple*	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE
		Single	USGS(2002) Production figures	Williams (2003) Mass & economic flrows for silicon Graedel et al (2004) Mass flows for copper	USGS(2000) ICSG (1999) Production figures Giurco et al (2001) Impact of global technology upgrade
REGIONAL *Continent* *Country* *State*	Spatial Domain	*Multiple*	None	Ayres (2001) Predicted copper flows Van vuuren et al (1999) Future supply and demand / flows	Giurco et at (2001) Contry-specific technology comparison for primary copper processes
		Single	Lenzen (2003) Input-output for Australian Economy Konijn et al (1997) Input-output Netherlands	Zeltner et al (1999) Copper US, use landfill as resource Gaines (1980) Material & energy Jolly (1993) Zinc flows Spatari et al (2002) Cu Stock / Flow 1yr Van der voet (1996) SFA	Graedel & Klee (2002) sustainable targets, based on rate of use/reuse
LOCAL *City* *Plant* *Site Specific Plant*	Spatial Domain	*Multiple*	Reuter (1998) linked value chains in LCA framework	Kuckshinrichs et al. (2000) Aluminium Min & Zhou (2002) supply chain models	
		Single	Hardy and Graedel (2002) Food web, connectedness in Eco-industrial parks	Sagar and Frosch (1997) Metal Industrial Ecology, actors/ links/ roles	Norgate & Rankin (2000) Technology LCA Lunt (2002) Technology LCA

Figure 3-12: Summary of literature reviewed

With respect to each level of analysis, the outstanding gaps are as summarised as follows.

MEGA: to move from an analysis of the status quo to considering preferred futures for connected value chains. This work falls beyond the focus for this thesis, but will be facilitated by building on the methodology developed for a single value chain herein.

MACRO: the outstanding challenge for the minerals industry is to see itself within the context of the entire value chain, to have the tools to identify more sustainable value chain configurations at global and regional levels and to understand the key sensitivities to improvement that currently lie within and beyond their control, in order to identify meaningful strategies for improvement.

MICRO: with an understanding of their place in the materials value chain, actors such as individual miners and refiners need confidence that the decisions which are within their sphere of influence are consistent with the wider principles of creating a more sustainable material value chain overall. This can only be achieved with a multi scale approach, considering performance of the value chain across levels.

GLOBAL: At a global level, there is a need to develop an initial value chain assessment tool for measuring environmental performance with limited information detail. This can be used as a point of departure for analysis across scales and direct attention to areas of the value chain to study in more detail, including regional and local sensitivities.

REGIONAL: At a regional level, there is an outstanding need to incorporate regional differences and information detail to system characterisation linked to environmental performance in order to determine improvements that can be made within existing infrastructure and in an alternate future. There is a need to determine preferred future configurations for the value chain and to link actors to the implementation of paths toward preferred futures.

LOCAL: with the increased information detail possible at a local level, there is a need for more detailed performance indicators to judge technology choices for parts of value chain, as well as the ever present need to link actors with system state and performance.

3.5 CONCLUSIONS

This chapter has undertaken several tasks which make a contribution to structuring the problems which face the minerals industry so that it can more purposefully begin developing itself as part of a more sustainable materials chain.

Existing classifications of decision types as strategic, tactical and operational do not have a coherent value chain focus. To implement a value chain approach to addressing performance improvement within the minerals industry across spatial scales, a novel reference schema to classify decision space was developed. It takes the form of a matrix, with mega, macro and micro scopes of the value chain (extent of material chain focus) as the columns, and spatial detail in the geographical sense from global to regional to local forming the rows. Temporal considerations and decision ambitiousness (representing the vision component) may be considered separately within each matrix cell which fixes the scope.

In addition to identifying the domain of interest for the decision problem (comprising the system boundary of material and energy flows to be analysed), the reference schema is used to classify actors, system variables (domain of influence) and impacts reflecting environmental performance (domain of impact). To enable the implementation of preferred futures, actors must be fully aware of the impacts their actions give rise to across scales. These links are developed in Chapter 4, supported by the structure provided by the reference schema.

The reference schema also clearly identifies distinct scales of analysis. This assists in reviewing current performance across scales and developing an approach to consider multiple scales.

Using the reference schema to order the literature according to the scale of analysis of the decision problems, the literature was then reviewed to identify:

- which approaches to modelling system flows and environmental performance are used at different scales and with what supporting information detail
- gaps in the way which the information and models used in the literature successfully meets the requirements for addressing that decision context and linking to the wider aims of improvement in performance of the materials value chain and the ability of actors to implement such performance improvement.

The main gaps identified are:

- ♦ the lack of analysis across scales
- ♦ the lack of link between actions on the part of actors and the changes in impacts they effect
- ♦ the lack of future planning at an entire value chain level.

These identified gaps provide guidance on the additional modelling capacity needed to answer outstanding decision contexts, addressed as case studies in later chapters. In Chapter 4, models are developed with the ability to characterise value chain flows and environmental impacts at different scales, to monitor changes to system variables which actors can effect and to describe the resultant performance outcomes. In Chapter 5, these models are used to characterise preferred future states and additional modelling capacity is developed to assess the impact of alternate paths to future states which actors can implement individually or in collaboration with others.

CHAPTER FOUR

Characterising current material chain configurations and performance

Chapter 3 demonstrated the current lack of a structured approach to assessing the environmental performance of material chains across scales and the lack of available approaches to modelling preferred futures for the material chain. As an initial step in addressing these challenges, this chapter develops a structured approach to characterising environmental performance of value chains across scales. The approach links physical material and energy flows, with environmental performance measures appropriate to the scale of analysis and can be applied across scales. Current configurations of the value chain (i.e. status quo) are analysed. This provides insight into current operations and delivers a baseline assessment against which the performance of alternate futures can be compared. Structured approaches to decision making require an understanding of the performance and sensitivities associated with current value chain configuration, before considering preferred futures. Given that different actors control different system variables which, in turn, affects environmental performance, the last part of this chapter classifies the ability of actors to influence system variables and hence affect environmental performance. The value chain characterisation approach developed in this chapter (and demonstrated through case studies in Chapter 7 and Chapter 8) informs the development of a new approach to explore sustainable futures for the value chain; presented in Chapter 5.

4.1 BACKGROUND AND MOTIVATION

This chapter has three principal aims:

(a) to show how the reference schema developed in Chapter 3 can be used in structured approaches to environmental decision making by guiding information requirements across scales

(b) to develop the tools to characterise and link material flows, environmental performance, sensitivity to changes in system variables and actor influence over system variables, for the status quo of the value chain at different scales

(c) to show how an analysis of the status quo for the minerals and metals value chain provides the basis for developing preferred futures.

There is a need to better characterise links between actor-decisions that change system variables and their resultant impacts on value chain performance as a whole. This requirement was established in the analytical framework of Chapter 2 and re-enforced in Chapter 3, which demonstrated the lack of existing approaches to do so across scales. Furnishing the information required to address this deficiency would mean that the consequences of individual or collective future action by industry actors, could then be represented in terms of the performance improvement they effect and be used to guide decision making for preferred futures.

A structured approach to value chain characterisation across scales is developed in this chapter. This characterisation will provide information on:

- baseline environmental performance,
- sensitivity of performance to changes in system variables and
- the ability of actors to control system variables.

The information will be used to strengthen environmental decision making around designing preferred current and future configurations for the value chain. A background to the general field of environmental decision making is discussed first, to show how the improved characterisation approach will be incorporated into the overall decision making process for designing preferred futures.

4.1.1 *Structured approaches to environmental decision making*

Environmental decision making requires the use of environmental information to make informed decisions. Choices between actions with differing environmental impacts are complex – they can involve long time horizons, multiple stakeholders and trade-offs between desired objectives. For the minerals industry, the need to consider the entire material chain at a range of scales adds to the complexity of making decisions. As a result, conceptual frameworks have been developed which assist in guiding the decision making process, not only for environmental decisions, but more generally in the field of decision analysis (see Keeney, 1982; Mingers and Brocklesby 1997; Mingers and Rosenhead, 2004; von Winterfeldt, 1980). They provide guidance on where to start examining the problem, what information to consider and a structured methodology to arrive at a final decision, which assists in managing the complexity of the problem.

Decision analysis splits consideration of the problem into two principal phases (see for example Simon, 1960; Rosenhead, 1996; Seppälä et al, 2002)[1]:

- problem structuring, and
- problem analysis.

Problem structuring involves consideration of the following elements: a careful definition of the problem, the identification of actors, objectives, performance measures and alternatives (von Winterfeldt, 1980; see also Rosenhead, 1996 for further discussion on problem structuring methods). Undertaking problem structuring makes the problem amenable to problem analysis. Problem analysis evaluates the different alternatives. The evaluation gives due consideration to the performance of the alternatives, the trade-offs between objectives, the actor preferences regarding the importance of each objective and the key uncertainties and problem sensitivities, before choosing an alternative.

In proposing a structured approach to improving the future environmental performance of the minerals industry, it has already been established in Chapter 3 that the question of scale must be addressed. An explicit consideration of scale as defined through the reference schema is not currently part of the problem structuring exercise in

[1] Seppälä et al. (2002) further split the problem analysis phase into consideration of alternatives, followed by a separate sensitivity analysis phase whilst Simon (1960) includes an initial 'intelligence' phase to ascertain if the problem even requires a decision.

decision analysis literature. Consequently, the reference schema will be used to identify the scale at which the analysis is undertaken. This novel approach is crucial to more accurately determine which actors operate at each scale, the principal system flows at each scale and potential interventions to improve performance, all of which are scale-dependent. The consideration of scale will be in addition to the following common problem structuring questions taken from von Winterfeldt (1980), namely: what is the purpose of the analysis? for whom is it performed? and which alternatives can the decision maker control? Answering these questions effectively and structuring desired objectives for a preferred future, requires further characterisation of the status quo.

To do this, consider the process of environmental decision making in its simplest form. This can be carried out by responding to four questions (Turner et al., 1997):

1. Where are you now?
2. Where are you headed?
3. Where do you want to be?
4. How can you get there?

These questions listed by Turner (1997) show that before consideration of the future, it is important to begin the characterisation of the material chain with a focus on the status quo, namely, the 'where are you now?'. While a background to current environmental issues was given in Chapter 2, the analytical framework highlighted the need to link the domain of interest, domain of influence and domain of impact in value chain characterisation. Furthermore, Chapter 3 showed the lack of a coherent approach to characterising performance across scales, which is one of the aims to be addressed in the remainder of this chapter. What could be achieved if such characterisation information were to be available for the status quo? There are two clear benefits. The first is the insight derived from a thorough analysis of the system across scales itself. The second provides the necessary information for the problem structuring phase of preferred futures.

The way in which status quo characterisation information will be used in considering preferred futures is shown in Figure 4-1.

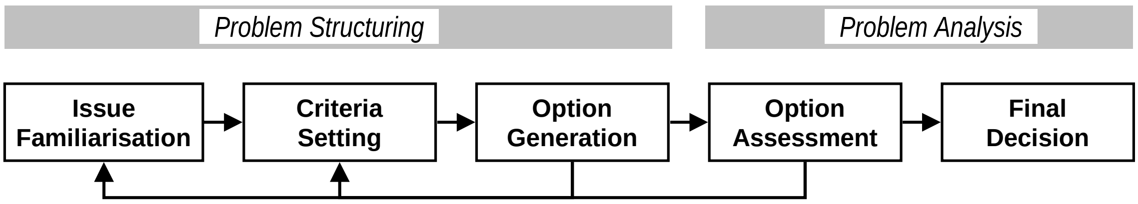


Figure 4-1: Decision steps in environmental decision making (Turner et al., 1997; Wrisberg et al., 2002)

Figure 4-1 is a schematic representation of the environmental decision making process with the decision analysis phases of structuring and analysis indicated above.For the designing of preferred futures for the value chain, an analysis of the status quo across scales will be part of the 'issue familiarisation' stage. In decision analysis terminology 'issue familiarisation' is the first component of problem analysis.

The outcome of the characterisation should be a clear connection between the environmental impact associated with key stages in the value chain, the key sensitivities and the actors who can control key system variables – this is discussed further in Section 4.1.2. This information will direct the analysis of futures which can be implemented by single actors or collectively and their relative performance.

The next steps are to determine objectives and the criteria by which futures will be judged; to generate alternate futures; and then to assess them before deciding on an appropriate course of action. These steps are further discussed in Chapter 5, which considers paths toward future states. The approach to value chain characterisation for the status quo is developed further in the remainder of this chapter.

4.1.2 *Requirements for system characterisation: linking actions to impacts*

The first step in making more informed and sustainable choices is to better characterise the consequences of actor decisions. To do this, Figure 4-2 shows the link between actors (making decisions) and impacts. It shows that actors can change system variables, which alters the system state (configuration of infrastructure and flows in the value chain) and the resultant environmental performance (impact).

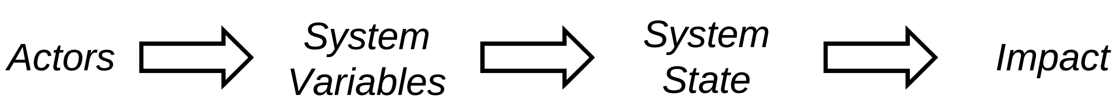


Figure 4-2: Relationship between actors-variables-system-impact

The term 'system variables' is used to refer to both design variables (e.g. choice of technology) and decision variables (e.g. choice of feed for technology). Understanding the impacts of actor decisions is complicated by impacts manifesting at different spatial and time scales from when the decision was made, as discussed in Chapter 3. In addition, external variables, beyond the control of the actor, will affect the final impact. These factors are included in the development of a more comprehensive approach to material chain characterisation and evaluation, which is the focus of this thesis.

Secondly, a sustainable system then requires that an understanding of impacts guides more sustainable choices by actors via an appropriate response signal.[2] This thesis shows how information provided by material chain characterisation can be used in environmental decision making.

To establish an operational link between actor, variable, system and impact, a generic approach to characterisation of the value chain is required which can be applied across scales. Information requirements for characterisation will be affected by the need to link actions to impacts which may occur at different scales, and will vary according to the objectives of the analysis.

The remainder of the chapter is divided into four principal sections. First, a discussion of objectives and useful measures of environmental performance for the value chain across scales are reviewed in Section 4.2. The generalised approach to value chain characterisation across scales linking system flows to impacts occurs in Section 4.3. This is compared with existing approaches in Section 4.4. Finally, consideration of the ability of actors to change performance by changing system variables is described in Section 4.5, completing the link between action and impact. This is summarised in Figure 4-3.

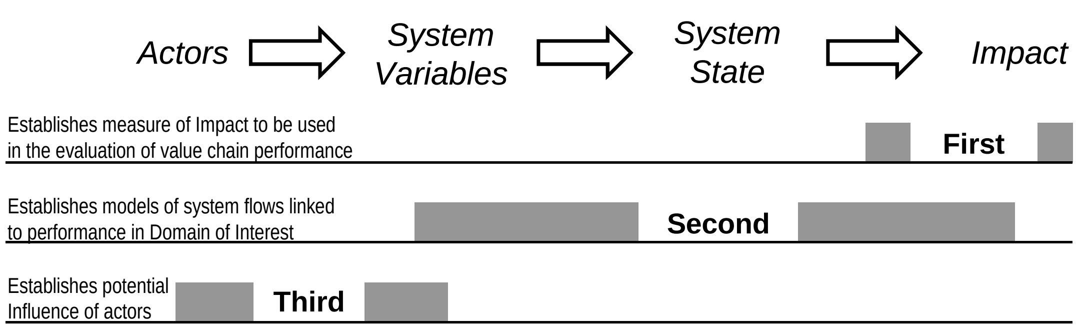


Figure 4-3: Development of remaining sections in Chapter 4

[2] Using an economic analogy, this would be termed 'getting the prices right' while the first step would be 'getting the information right' (O'Rourke et al., 1996).

4.2 OBJECTIVES AND PERFORMANCE MEASURES

4.2.1 *Background*

Determining appropriate objectives and performance measures is the first step in proposing a characterisation approach for the status quo of the value chain across scales. The broad objective for this work established in Chapter 2 was to improve the environmental performance of the minerals and metals value chain, primarily using LCA due to its focus along the material chain and its endorsement by the minerals industry (Stewart, 2001). However, the literature review from Chapter 3 showed that different performance measures were used at different scales and a summary from the literature reviewed is shown in Figure 4-4. These indicators are discussed in greater detail, and compared and contrasted to determine their appropriateness at different scales.

	MEGA: MORE THAN ONE MVC	**MACRO**: ONE MVC	**MICRO**: PART OF MVC
GLOBAL	Mass Flows	Mass Flows	Mass Flows LCA Indicators
REGIONAL *Continent* *Country* *State*	Mass Flows	Mass Flows LCA Indicators Energy	Mass Flows LCA Indicators
LOCAL *City* *Plant* *Site Specific Plant*	Mass Flows LCA Indicators	Mass Flows LCA Indicators	Mass Flows LCA Indicators Energy Exergy / Entropy

Figure 4-4: Summary of environmental performance indicators used across scales

The following paragraphs outline criteria against which appropriate indicators can be evaluated, followed by a general overview of potential initiatives which may be implemented to improve the performance of the value chain. Each indicator described in Figure 4-4 is then evaluated against the established criteria and the context of its potential use.

Indicators are designed to represent relevant and valuable information by condensing system complexity into a manageable information set, which can be used to guide decision making (Bossel, 1999). The chosen indicators need the following properties as shown in Table 4-1.

Table 4-1: Characteristics of indicators (ANZECC, 2000)

Required properties of chosen indicators
Be useful for measuring trends at a range of spatial scales
Reflect concerns for which the decision maker wishes to evaluate performance and be readily interpretable
Accurately reflect the state of the system (robust indicator of change and scientifically credible)
Provide the ability to discern between options

Indicators should also be cost effective from the standpoint of monitoring, and be relevant to policy and management needs. The choice of appropriate indicators is linked to the chosen objective, which will ultimately depend on the decision context. Generally, this may either be an analysis to better understand the system of interest, or an analysis linked to environmental decision making. Analyses for system understanding may be performed:

- to quantify performance in a system that has not been studied before
- to raise awareness associated with flows and impacts
- to reveal unforseen insights which result from an investigation of the system
- to provide a background to further analysis to inform environmental decision making

For these cases, the chosen indicator will depend on the scale of analysis, resolution of available information, desired level of understanding and intended audience. Possible variations in information detail were discussed in Chapter 3.

For analyses linked to decision making for improving environmental performance in material value chains, general strategies have been classified into the following four groups (Kandelaars, 1999) in order to provide general guidance to the choice of performance indicator which will vary according to improvement strategy:

1. Substitution
2. Recycling and reuse
3. Technological change
4. Changing consumption patterns

The first improvement strategy of material substitution is not the focus of this work. To evaluate the effects of substituting, for example, copper with aluminium in electrical transmission wires, requires consideration of multiple value chains. For a single value chain, recycling and technology change are two strategies which can be influenced by mining and refining companies. Consequently, measures of environmental performance must be targeted to reflect the relative merits of these two options. While the fourth strategy of changing consumption patterns is in the hands of consumers more than producers, the minerals industry must understand the magnitude of changes which it can effect in the context of changes to performance associated with changing patterns of consumption. This is considered in Chapter 5, but for the present, indicators should be chosen to reflect changes to technology and recycling patterns as starting points.

4.2.2 *Mass based indicators*

Mass flows as an indicator of performance in Materials Flux Analysis (MFA) have been used to inform policy decisions (Daniels and Moore, 2002). With respect to the aforementioned indicator selection criteria from Table 4-1, the monitoring of mass flows is easily applied across scales and can accurately reflect the state of mass flows in the value chain. However, it provides little ability to discern between options associated with technological change. A new technology may process the same mass flows, but with less of an environmental burden; this is not captured with a mass flow indicator. For this reason, it is only useful in highly aggregated situations where representing differences between technologies is either not a realistic or an important requirement, such as where there is insight to be derived from understanding the distribution of material across material chain stages.

Another mass based indicator is Material Intensity Per unit of Service (MIPS) or the 'ecological rucksack' concept developed by Schmidt-Bleek (1993). Rather than the MFA approach of considering bulk flows within a region or of a single commodity along its value chain, MIPS considers the total amount of material 'input' required to provide a desired service or product. It is called an 'input' indicator because it is based on inputs to processes rather than outputs of wastes. Examples of the amount of material required to produce a tonne of common metals are given in Table 4-2.

Table 4-2: Examples of MIPS factors for common metals[3]

Metal	Tonnes of material disturbed from its natural environment to deliver one tonne of product
Steel	9
Primary Aluminium	37
Secondary Aluminium	1
Primary Copper	350
Secondary Copper	2
Gold	540 000

MIPS provides an initial indication of environmental burden when comparing different value chains. However, like mass flow considered alone, it provides limited scope for differentiating between technology options. Furthermore, as an input based indicator, it can produce misleading results in the case of low MIPS processes with high toxicity processes appearing more favourable over high MIPS low toxicity processes which can be the case for some metals (Hoffmann et al., 2001).

Monitoring mass flows also assists in characterising resource depletion. How should resource depletion be viewed for the minerals and metals value chain? Further to the discussion in Chapter 2, in this thesis, the 'fixed stock' paradigm of Tilton (1996) is adopted, meaning a focus on more efficiently using our 'stock' of resources, rather than expecting the market to solve the problem of resource scarcity by increasing the price and making ore deposits of lower grades economic to exploit or favouring substitution (called the 'opportunity cost' paradigm).

Are metal stocks depleted when they are extracted from the Earth's crust? Following the discussion in Chapter 2, the short answer is no. It is now accepted that the mining of metals does not deplete the resource stock (Five Winds International, 2001) as the products they make can be recycled. Recycling dates back to the Vandals in the 5th century, who after conquering Rome, melted Roman monuments made from copper and bronze to service their needs (Prain, 1975). To illustrate difference between metals and other resources, a distinction is drawn between renewable resources and those recyclable to a pure form, as shown with examples in Table 4-3. It shows that metal and water are both recyclable to a pure form. Wood can be recycled through re-manufacture into particleboard for example, but it cannot be recycled back to its original form as a tree. Coal, once burned, cannot be recycled back to coal. While metals are not

[3] http://www.wupperinst.org/Projekte/mipsonline/

renewable, their atomic structure means that they can be repeatedly recycled and hence as a resource they are only 'depleted' in practice through dissipative uses from which the metal is not practically recoverable. The only caveat is that recycling requires energy which may deplete non-renewable fossil fuel resources and the presence of impurities prohibits full recycling. Pure products (e.g copper wire) are more easily recycled than complex mixtures (e.g. electronic scrap containing copper and other metal and non-metal compounds) (Henstock, 1996).

Table 4-3: Classification of materials according to renewablity and recyclability

	Renewable	Not renewable
Recyclable to pure form	Water	Metal
Not recyclable to pure form	Wood	Coal

As metals are theoretically recyclable to a pure metal form, this suggests that for metals, a cut-off percentage which classifies as a dissipative use, beyond which the metal is not practically recoverable could serve as a useful indicator of resource depletion to be included among other indicators and which could be applied at the level of an overall value chain. A similar approach is proposed by Stewart and Weidema (2004), who also consider the available technologies to recover metal from dissipative uses in defining the ability of metal to be recovered into the materials chain.

In summary, while mass flow indicators are applicable across scales, they do not provide information on a range of impacts relevant to decision makers nor sensitivity to technology change.

4.2.3 *Energy*

At first glance, there appears to be a discrepancy in the literature as to the usefulness of energy as an indicator of environmental performance. Schmidt-Bleek (2001) cites a difference in material intensity of 50 in delivering electricity to the grid from different sources (such as coal, gas, hydro), as a reason not to use energy alone as an indicator. Graedel (1998) suggests that in streamlined analyses, energy is often a reasonable surrogate for overall environmental performance. The ready availability of energy consumption figures makes them an attractive starting point.

Upon consideration, both points can be used to answer different questions. Energy is useful as an initial screening indicator for a general comparison between the amount of energy used by different processes; for example, when comparing the energy used in production of metal from ore compared to metal from scrap. Then, for more detailed comparisons where the specific location and energy mix is available and relevant to the analysis, the difference in the environmental burden of energy arising from nuclear power, coal based power or any other form can be noted specifically and included in the analysis.

4.2.4 *LCA impacts*

This section discusses LCA impact categories and gives an overview of the LCA methodology to which LCA impact categories are linked.

4.2.4.1 *Methodology*

Life cycle assessment (LCA) has become a well established tool for reporting the potential environmental performance of products (Corbiere-Nicollier et al., 2001; Guinee et al., 1993), and also now processes (Azapagic, 1996). It is increasingly being integrated into decision analysis approaches to environmental decision making (Miettinen and Hämäläinen, 1997; Seppälä et al., 2002). The most notable feature of LCA is the way it generates an environmental perspective based on rigorous process analysis of the inputs and wastes to resource extraction, the process itself, use and re-use of product through to final disposal (Clift and Longley, 1995). In short, the LCA involves defining a system boundary consistent with the life-cycle of the product or process, compiling an inventory of inputs and waste and then characterising the impact caused by these inputs and wastes through the use of equivalency factors to give a performance score in a recognised set of environmental impact categories (for a detailed description see SETAC, 1992).[4] The focus of this section is on evaluating the use of these impact categories as performance indicators in the value chain assessment methodology which is developed in this thesis.

---

[4] The four principal components of the LCA approach are
i) goal definition and scope (defining system boundary and level of information detail in the analysis);
ii) inventory analysis (compiling a list of inputs and wastes from process models);
iii) impact assessment (evaluating potential impact of inventory for chosen impact categories, this may include normalisation of performance scores – such as contribution to total global impact in that category– to put the magnitude of the performance score in context. In some cases, a (subjective) weighting is applied to each impact category based on their perceived importance which is then used to calculate a single overall performance score;
iv) interpretation (identifying significant environmental issues and present conclusions and recommendations).

4.2.4.2 *Impact categories*

The basis for life cycle assessment has been to report on a recognised set of environmental concerns spanning global to local, which can then assist decision makers to balance trade-offs and make an informed decision. A selection of LCA impact categories is provided in Table 4-4. These LCA indicators are taken from the problem-oriented approach of CML (PRè, 2000). They are termed mid-point indicators as they represent the contributions associated with specific environmental problems such as global warming and acidification. Another approach used in LCA literature called the EcoIndicator approach, reports impacts with respect to damaged end-points: namely, damage to human health and damage to ecosystem health. While the emission of SO_2 leads to acidification (midpoint), the endpoint of concern is the damage which an increased acidification effect has on human and ecosystem health (such as the loss of biodiversity). For further discussion on mid-point / end-point indicators see (Goedkoop et al., 2002).

Table 4-4: Description of selected LCA impact categories

Impact Category	Description
Greenhouse Effect	Contribution to global warming due to the Greenhouse Effect.
Acidification	Decreasing the pH of natural systems through mechanisms such as acid rain.
Eco-toxicity	In this study, Eco-toxicity means toxicity to aquatic ecosystems. It is reasoned that any terrestrial toxicity will eventually appear in groundwater and is covered under aquatic toxicity.
Human Toxicity	Based on established Human-Toxicological Classification Values. Not an indication of the potential of the process to kill people, rather how close the process approaches exposure limits set by, for example, the World Health Organisation. This impact category is not related to occupational health and safety.
Ozone Depletion	Potential to deplete the ozone layer.
Eutrophication	Excessive algal production in rivers and shallow water courses (algal bloom) caused by an environment rich in NO_3 and PO_4.
Smog	Atmospheric pollution in the form of photochemical smog.

The impact categories detailed in Table 4-4 can be used to guide decision making regarding technology changes or increased recycling across scales in the minerals and metals value chain. The use of LCA for decision making in the minerals and metals value chain has been widely endorsed (Stewart, 2001; Berkhout and Howes, 1997; Althaus and Classen, 2005). A further consideration when assessing multiple environmental impacts is how to handle preferences for different importance-ratings that are assigned to each impact category by the decision maker(s) when evaluating the preferred option. For example, option A may have a low greenhouse impact, but a high acidification impact, whereas option B may be the reverse. The final option chosen will depend on whether the decision maker views improved performance with respect to acidification as more or less important than for greenhouse impacts. This can be addressed by the use of Multiple Criteria Decision Analysis (MCDA) methods (see, for example Seppälä et al., 2002). These methods provide a basis for structuring preferences between impact categories in option selection for trade-off analysis (inter-impact preferences), including the sensitivity of the preferred option to changes in relative preferences between impact categories. Additionally, MCDA methods can incorporate 'intra-impact preferences' that reflect the degree to which the same relative improvement over worst (or best) performance is valued in one category compared to another (represented by a value function – Seppälä et al., 2002).

4.2.4.3 *Deficiencies for minerals-specific contexts*

Despite their general endorsement, the use of life cycle assessment indicators in the minerals context gives rise to certain problems. LCA offers the advantage of providing a performance score regarding impact potentials, independent of site-specific information, which is useful for strategic choices regarding the general configuration of the value chain. However, the performance score reported is only a measure of potential impact (rather than likely impact), based on the inputs and constituent components of effluent streams. Furthermore, this impact potential is aggregated over space and time. For example, global warming potentials in LCA are generally reported relative to a time horizon of 100 years. In this case, methane has a global warming potential approximately 25 times greater than carbon dioxide (Jensen et al., 1997)[5], while over a 20 year time horizon methane has 62 times the global warming potential compared to carbon dioxide. For impacts such as global warming, such an approach is acceptable, provided that the time horizon is specified. However, for local impacts, the approach is less robust.

In the minerals and metals industry, significant local impacts are associated with the large solid waste burden from the industry. Currently, and for example, the impacts at the mine site associated with mining sulfide ores that give rise to Acid Mine Drainage are underestimated (Althaus and Classen, 2005). Additionally in the refining stages, the

---

[5] More recent estimates suggest a factor of 21 times (instead of 25).

potential for impact could be very high if the waste contains heavy metals, but the likely impact will be much less if the toxicants are bound in a stable form in the residue (rather than in a less stable form when they could leach to the surroundings). This problem is of most concern when comparing two technologies such as hydrometallurgical and pyrometallurgical processes, which have vastly different solid waste stability profiles (pyro- often being more stable than hydro- due to the high reaction temperatures in pyrometallurgical smelters which act to 'set' the wastes). To address this deficiency in LCA indicators for the industry, an enhancement to reflect the stability of the solid waste was developed as part of the work in this thesis, in a case study in Chapter 8. The temporal nature of solid waste impacts from the minerals industry is addressed by Hansen (2004). Despite these deficiencies, LCA has the ability to be applied across scales and is linked to rigorous process models, making it a useful approach.

A further factor to consider is data availability and reliability. Berkhout and Howes, (1997) report that data has been more widely shared in LCAs conducted by commodity producers than by product manufacturers who may conduct LCAs internally and keep results confidential to gain competitive advantage. Commodity LCAs are often conducted eternally by industry associations, but public availability of final reports varies. The life cycle inventory data used to link material and energy flows to impact categories is currently deficient (Stewart, 2001; Ayres et al., 2001) and is being addressed to increase the reliability of LCA analyses.

4.2.5 *Other measures: exergy and entropy*

4.2.5.1 *Exergy*

Exergy has been advocated as a useful environmental performance indicator by several researchers (Ayres et al., 2001; Bakshi, 2002; Seager and Theis, 2002). Its stated advantage is that by being based on thermodynamics, it offers an 'objective' view of process performance. Exergy is a measure for a substance of how far it is from equilibrium with its environment. As an example, copper sulfide ore has an exergy of 0.2 kJ/g while cathode copper has an exergy of 2 kJ/g – the exergy of refined copper is higher as its composition is further away from the average concentration of copper in the natural environment. With respect to solid waste, exergy can be considered as a driving force reflecting the capacity of the substance to continue to undergo reaction (hence a lower exergy waste would be more benign). It suffers the drawback of the need for a thermodynamic reference state – often taken to be equilibrium concentrations of materials in the environment globally, however, locally this may be inappropriate. For example, if the exergy of a solid waste product is reported relative to a global average and the local conditions are less than this value, the ability of the solid waste to drive further reactions and harm the environmental will be greater than suggested by its exergy value. Location-specific information is not readily available and furthermore, the calculated exergy value does not readily translate into recognised environmental problems. For these reasons, it is not used in this thesis.

4.2.5.2 *Entropy*

Entropy has been offered as an single indicator for resource use in the minerals and metals industry by Gößling (2001). Entropy is a measure of the disorder of a system, (also expressed as a measure of the thermal energy not available to do work). For example, unburned coal has a low entropy (it is ordered and can do useful work), however when burned, the heat and gas products generated are not ordered and have less thermal energy available for doing further useful work, hence these products have a higher entropy. It is argued that the use of entropy avoids the problems of an equilibrium reference state for exergy calculations. Entropy production can be linked to exergy consumption with only the ambient temperature as additional information being required.

The rationale behind not using entropy in this thesis stems from it being a single indicator not linked to recognised environmental problems. Thus, it cannot show trade offs between environmental concerns for different alternatives. Consequently, single indicators are better suited to initial screening exercises, at which point it is most useful if the single indicator requires little information detail, such as the use of energy figures which are readily available. Entropy analyses require detailed mass and energy balances to provide the required information, meaning a more detailed decision context and analysis is required. If modelling to this level of information detail, LCA should be used in preference to entropy, to provide a comprehensive portrait of the trade-offs involved with respect to recognised contributions to environmental problems.

4.2.6 *Summary*

In summary, the review of indicators used in the literature shows that the scales at which they have been currently used is largely appropriate. The only indicators whose use has spanned scales are mass flows and LCA indicators. Mass flows do not provide sufficient ability to discern between recycling and technology options. Consequently, LCA indicators are chosen as they generate performance measures related to recognised environmental concerns. They are also endorsed for use in industry decision making. LCA has detailed information requirements based on mass and energy and may be simplified when conducting preliminary analyses at larger scales. There is the potential to extend the use of energy consumption as an indicator at broad scales as a screening indicator.

An approach to modelling of mass and energy flows within the system is needed to support the use of LCA indicators for environmental decision making. The system model must fulfil the requirements of linking system flows with impact and create a link back to actors who can change systems variables to achieve improved performance. Existing approaches are reviewed against these requirements in Section 4.3 and a generic approach applicable across scales is developed in Section 4.4.

4.3 APPROACHES TO MODELLING SYSTEM FLOWS

The review of decision contexts from Chapter 3 showed that different levels of information detail regarding material and energy flows were associated with different investigations, depending on their position within the reference schema. For example, Zeltner et al. (1999) at the macro-regional level considered material flows only, while Norgate and Rankin (2000) at the micro-local level included consideration of material and energy flows. Guidance is needed as to what information detail is appropriate for decision making in the minerals industry at different levels and how this information can be linked across levels. This section looks in detail at methods for characterising material and/or energy flows for parts of the value chain and the value chain as a whole. The aim of this review is to provide the background necessary to develop a new approach or combination of existing approaches suitable for characterising system flows which:

- ♦ can be applied across scales
- ♦ can inform the use of LCA indicators for assessing environmental performance
- ♦ can link actor-controlled changes to variables to changes in impacts
- ♦ and which can be extended to consider of paths toward preferred futures in Chapter 5.

4.3.1 *Materials Flux Analysis*

The stated goal of Material Flux Analysis (MFA, also known as Material Flow Accounting) is the management of materials and substances aimed at resource efficiency (Wrisberg et al., 2002). This goal of MFA is supported on the premise that by understanding where materials are flowing through the economy, we are better placed to inform policy choices about how to manage the system. For example, an MFA analysis may show that most of the metal entering the material value chain is used as metal-in-products rather than for dissipative uses. In this case, the policy focus can proceed with investigating how to reuse the metal in products to achieve greater resource efficiency. On the other hand, if dissipative uses were high, further investigation may look into fate and transport models of how the (possibly toxic) metal is distributed in the environment or how dissipative uses could be reduced.

As demonstrated with the literature review in Chapter 3, MFA has been applied at a range of scales within the reference schema. MFA in its classic sense studies the flows of several materials within a region while a MFA of a single material is termed Substance Flow Analysis (SFA). Notable SFA examples include the study of chlorine (Ayres, 1997), copper (Spatari et al., 2002) and cadmium and nitrogen (van der Voet, 1996). However, most studies have a country or continent focus which ignores the global nature of the flows which are connected to that region. Consequently, applying MFA at an aggregated global level, would provide a useful starting point for an initial characterisation of the value chain, suitable for providing a background understanding to the magnitude of material flows.

What models does MFA use to achieve its goal? Could they link with LCA for the characterisation of the status quo of the value chain across scales? Udo de Haes et al. (1998) identify three basic model types: book keeping, static and dynamic. Book keeping models provide a snapshot of the flows for a given time period (such as a year) and will be referred to as 'snapshot' in this work. Static models build on the snapshot to allow inputs to be calculated from outputs, so that for a different time period with different inputs, the overall distribution of flows within the system can be mapped. Finally, dynamic models can be used to account for time lags between stocks, such as when copper pipe is manufactured for use and when many years later it becomes scrap available for potential recycling. McLaren et al. (2000) further distinguish between linear and non-linear models for both the static and dynamic cases. A example of the difference between snapshot, static and dynamic models for the value chain is illustrated in Table 4-5.

Table 4-5: Illustration of difference between snapshot, static and dynamic models

Model	Example Form	Comment
Snapshot	*F = constant*	Flow is a constant
Static	$F = f(x, y)$	Flow is a function of system variables, if the system variables change value, flow will change accordingly
Dynamic	$F = f(x(t), y(t))$	Flow is a function of system variables (which change through time) and the relationship between system variables and flow may also vary with time

Snapshot and static models are most common (for example Matthews et al., 2000; Spatari et al., 2002). This is because questions regarding historical or present distributions of material within a region or along a value chain can be answered with this limited information detail. However, to explore the future, dynamic models are required as there are significant time dependent influences on value chain flows (see Ayres et al., 2001; Zeltner et al., 1999), in particular changes in demand, use patterns and resource availability. The role of dynamic modelling in exploring futures is clarified in Chapter 5. Snapshot models are sufficient to characterise the status quo for a background analysis, but cannot link to informing preferred futures as the performance consequences of changes to actor-controlled variables cannot be assessed. Static models are thus preferred to snapshot models for analyses that include desired futures, as flows for the whole value chain can be re-calculated based on changes to system variables in the model.

MFA models partially fulfil the requirements for linking with LCA indicators. LCA indicators require an inventory of inputs and wastes from each process in the value chain. The mass flows described by MFA models refer only to the flow of the principal material of interest through the value chain (e.g. copper) and are thus only one component of the inventory requirement for LCA. Furthermore, they track the quantity of material flowing, but not the quality of material (e.g. ore grade) which can affect the environmental performance of processing technologies (Giurco et al., 2001; Norgate and Rankin, 2000).

4.3.2 *Supply chain models*

Supply chain models are used to improve the coordination between interconnected companies involved in the manufacture and distribution of a product as shown in Figure

4-5. While the focus for most supply chain literature is on inbound and outbound logistics, there are now authors considering product take-back and reverse logistics (see Fleischmann et al., 2000).

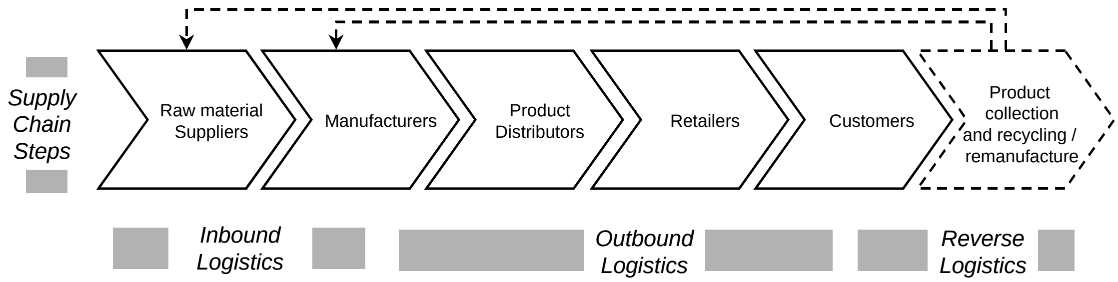


Figure 4-5: Generic supply chain: adapted from (Treitz, 2002) & (Min and Zhou, 2002)

The company and product focus is a distinction from the methods described in Section 4.3.1 which focus on material flows (in kg) rather than product flows (in product units). In terms of material and energy flows, supply chains can incorporate additional inputs to the production process (e.g. reagents, other materials and energy required to make the products), and stocks (inventory), however the focus remains on the creation and distribution to a satisfied customer of a particular manufactured good such as a television, rather than of a commodity such as copper.

The literature associated with supply chain management comes from a variety of sources, including purchasing, logistics, system engineering, organisational behaviour and strategic management (Croom et al., 2000). Variables in supply chain models include size of workforce, extent of outsourcing, delivery sequence, network centralisation and location (Min and Zhou, 2002), which are often linked to operational decisions. Consequently, many supply chain models are at company level planning rather than sector level planning which is required for sustainability in the minerals and metals industry. However, one relevant aspect of supply chain literature for the minerals and metals value chain relates to the relationships between actors.

A conceptual diagram of a generic supply chain is given in Figure 4-6.

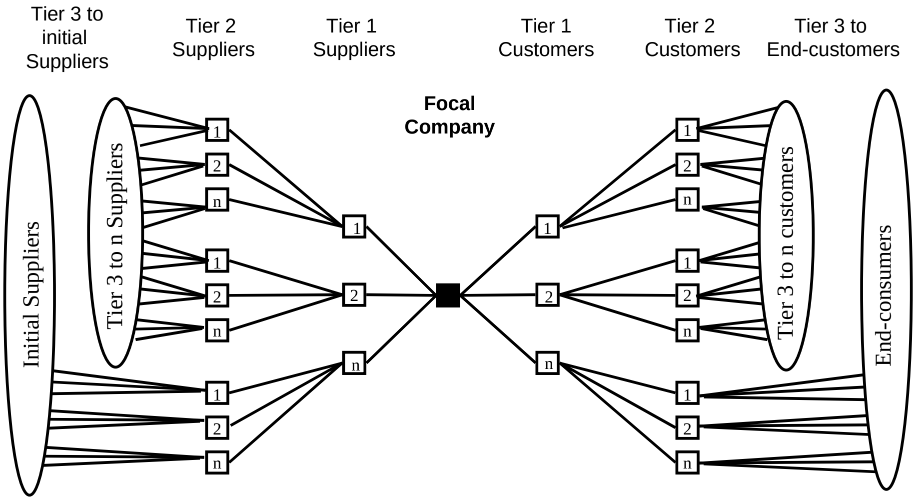


Figure 4-6: Supply chain network structure from (Lambert et al., 1998)

From this figure it can be seen that supply chains include interactions with multiple upstream and downstream companies. The ability of the company to move toward improving performance for the system will be influenced by the perception of clear benefits to individual actors, longevity of business relationship between actors and the central firm's power position in the network (Romano, 2003). This applies equally in the minerals and metals value chain, highlighting the need to be able to clearly articulate the effect that decisions by individual actors have on the value chain as a whole. While supply chain literature emphasises the importance of relationships (Seuring, 2004), it does little to characterise actor influence over particular system variables and their resultant impact. An indication of actors' ability to influence system variables will be required to understand the potential offered by collaboration between actors and is discussed further in Section 4.5.

4.3.3 *Technology models with inventory detail*

'Material and process flow models' is the general term given to models linking mass flows in a process and/or processes within a value chain, with energy flows and environmental performance. Examples in the literature pertaining to the minerals industry include Gaines (1980), Reuter (1998) and Reuter et al. (1995).

The approach of Gaines (1980) is akin to a materials flux analysis which also notes energy flows. It incorporates unit operation detail within processes, but is only a snapshot model, hence is unsuitable as a basis for time dependent characterisation.

In Reuter et al. (1995), a range of processes for producing zinc are described by a series of connected unit operations in a static model. Mass balance constraints apply around each unit operation, and the distribution of each element into the product stream from the unit operation is set by 'split factors' which are derived from industrial data where possible, or else approximated. Both the quality and quantity of mass flows are tracked. The energy and environmental costs are determined as a function of mass flows through each unit operation. There are additional splitter functions which act as decision variables, determining the flow between unit operations from within those which can feasibly be connected. These are optimised to minimise total cost. Reuter (1998) extends this approach to multiple processes connected in a value chain, all using process specific detail.

The usefulness of the approach is that it has the potential to incorporate varying levels of information detail. A 'unit operation' could represent a unit operation in a process (as per Reuter (1998) and Reuter et al. (1995). It can also represent a typical process in the value chain (as in this thesis), thus reducing the information detail required to describe the value chain at a more aggregated level. Additionally, it allows changes to the configuration of the existing infrastructure to be made in order to reduce environmental burden. However, there is no consideration of new infrastructure, nor of a path through time toward an alternate future and consideration of which changes to infrastructure actors could implement. The work of Reuter has been extended recently to include dynamic elements (see Verhoef et al., 2004).

Notwithstanding, the system characterisation approach of Reuter based on process nodes (unit operations) with splits between nodes as decision variables has merit for use as the basis for modelling mass and energy flows, as used in this thesis, due to its applicability across scales. It could also be extended to define system performance through time, by introducing functions for actor behaviours which change system structures (split variables) and functions for other factors influencing system performance such as demand.

4.3.4 *Summary*

This section has reviewed methods for characterising material and energy flows for the value chain. Snapshot, static and dynamic models for materials flux analysis were identified, however to inform a preferred configuration of the minerals and metals value chain, they must be coupled to a measure of environmental performance. Additionally, the emphasis in the supply chain literature on actor relationships, confirmed the need to include a measure of actor influence over system variables to better understand the potential offered by collaborative actions. The material and process flow models of Reuter provide a means of characterising material and energy flows across scales which can be linked to environmental impact. Furthermore, the choice of splits between process nodes equates to potential decision variables identified in Chapter 3. For this reason a similar approach is chosen as a basis for characterising the value chain flows in this thesis.

The next section attempts to address the inadequacies of existing approaches taken to meet all criteria outlined at the start of this section by developing a generic approach to characterising system flows and environmental performance. It is specifically developed to facilitate linking with the exploration of preferred futures in Chapter 5.

4.4 GENERIC CHARACTERISATION OF FLOWS & PERFORMANCE ACROSS SCALES

This section describes a generic representation of a materials chain, able to model flows within the value chain and their resultant environmental impact at different scales. The approach can accommodate varying levels of information detail depending on the scale of the decision context within the reference schema. Examples of decision problems specified at different scales and levels of information detail are presented.

4.4.1 *Representing material chain structure*

The materials chain is modelled as a collection of connected nodes. Nodes may either represent a stock, a process or both. Stocks may accumulate or deplete and be imported or exported and the composition of stocks entering the node is the same as the composition of stocks leaving the node. Processes may change the metal concentration (e.g. mining and refining upgrades the purity of the metal from a low grade ore to a high grade metal, manufacture of products downgrades the concentration of the metal in product) and may introduce a lag-time between material entering and leaving the process (e.g. in the use phase where material may not leave the use phase to become available for scrap until it is discarded, years after entering use).

Any node representing a process model, may itself be decomposed into more detailed nodes either in series (linear) or parallel as shown in Figure 4-7.

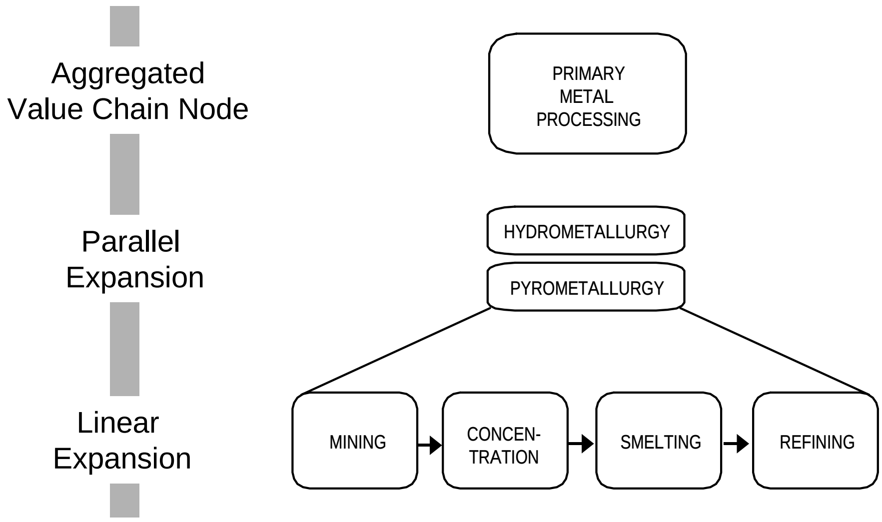


Figure 4-7: Increasing detail for material chain nodes

When considering how the representation links to environmental decision making, parallel expansion introduces a new decision variable (alternative to be evaluated) in the system, in this case the percentage split between hydrometallurgical and pyrometallurgical processes for primary metal processing. It requires more information detail regarding process-specific performance (to discern between the options) but offers the potential for a more accurate system description. Introducing such a decision variable is useful when it is relevant to the actors in the decision context (namely, the variable matches the ability of actors within the decision context to influence or potentially influence the decision variable) and when there is a significant difference in performance. Consequently, the final system representation for the status quo may be the result of an iterative process involving: initial modelling of system flows, assessing performance, assessing influence of actors and performance sensitivity of system variables and then a more detailed model of system flows with additional information detail if required.

Linear expansion of a process node as shown in Figure 4-7 does not necessarily introduce additional system variables. It is useful for understanding more about the components which make up the aggregated node and their individual contribution to the environmental performance of the node. No new system variables are introduced when an aggregated process is replaced by a disaggregated process (as is the case in Figure 4-7). However, if the aggregated process is replaced by a combination of process and stock nodes (for example, concentrate being imported and exported between continents), then imports and exports from the stock node and their destinations must be specified.

To simplify the modelling of the value chain, it is divided into two parts. This allows for varying levels of information detail, depending on the decision context. The first sub-model, the *value chain flows* model, tracks the *quality* and *quantity* of material flows through the value chain. It is a function of the specified splits of flows between individual nodes in the value chain and of the overall demand for material. The second sub-model comprises a set of *process performance* models, providing node-specific detail about the non-material inputs (e.g. transport, energy) and the associated performance of that node.

Considering both models an expression for the environmental performance of the value chain as a whole (or the parts of it for which there are process models) to be represented as follows:

$$E(t) = \sum_{j=1}^{j'} f[P(j,t), m_j(t)] \quad \text{where } t_0 \le t \le t_{final} \qquad \text{Equation 4-1}$$

$$m_j(t) = g[D(t), R(t)] \qquad \text{Equation 4-2}$$

$E(t)$ = is the total environmental performance vector at time t
(the vector contains total performance scores for each performance criteria)

$P(j,t)$ = the specific environmental performance vector of node j at time t
(from process performance models)

$m_j(t)$ = is the vector of material flow and material quality entering node j at time t
(from the value chain models)

$D(t)$ = is the total system demand at time t

$R(t)$ = is the system configuration vector of splits between all nodes at time t
which may be specified explicitly as a result of decisions by actors (or for example be a function of the environmental performance of the value chain at $E(t_{-1})$, it is discussed further in Chapter 5).

To model the configuration of the value chain at a fixed point in time as for the status quo, time does not need to be considered, simplifying the above equations. However, it was included at this stage to link forward to the modelling of time-dependent factors for paths toward preferred futures in Chapter 5.

4.4.2 *Material chain flows*

The information requirements for process nodes in the *material chain flows* model are as follows:

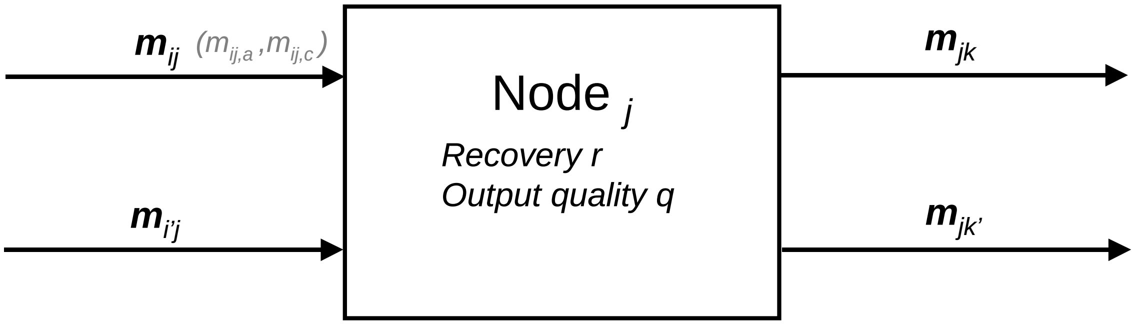


Figure 4-8: Information requirements for value chain node

where $\boldsymbol{m}_{ij}$ is the vector containing the mass flow of value-chain material $m_{ij,a}$ in from value chain node i to node j (for example in a copper value chain, copper would be labelled the 'value chain material') and its concentration $m_{ij,c}$. 'Source' nodes would only have outputs and 'sink' nodes would only have inputs. From this information, the amount of non value-chain material $m_{ij,b}$ in from node i to node j can be calculated as $(m_{ij,a}-m_{ij,a}\cdot m_{ij,c})/m_{ij,c}$. Similarly, for mass flows $\boldsymbol{m}_{i'j}$ in from node i' to node j and for $\boldsymbol{m}_{jk}$ and $\boldsymbol{m}_{jk'}$.

Component mass balance equations around the node can be constructed as follows:

$$m_{ij,a} + m_{i'j,a} = m_{jk,a} + m_{jk',a} \quad \text{Equation 4-3}$$

$$\frac{m_{ij,a} - m_{ij,a}m_{ij,c}}{m_{ij,c}} + \frac{m_{i'j,a} - m_{i'j,a}m_{i'j,c}}{m_{i'j,c}} = \frac{m_{jk,a} - m_{jk,a}m_{jk,c}}{m_{jk,c}} + \frac{m_{jk',a} - m_{jk',a}m_{jk',c}}{m_{jk',c}} \quad \text{Equation 4-4}$$

The definition of recovery r (to stream $\boldsymbol{m}_{jk}$) and output quality q (of stream $\boldsymbol{m}_{jk}$) is:

$$r = \frac{m_{jk,a}}{m_{ij,a} + m_{i'j,a}} \quad \text{Equation 4-5}$$

$$q = m_{jk,c} \quad \text{Equation 4-6}$$

Rearranging gives the following explicit expressions for all output components:

$$m_{jk,a} = r(m_{ij,a} + m_{i'j,a})$$ Equation 4-7

$$m_{jk,b} = \frac{r(m_{ij,a} + m_{i'j,a})}{q} - r(m_{ij,a} + m_{i'j,a})$$ Equation 4-8

$$m_{j'k,a} = (1-r)(m_{ij,a} + m_{i'j,a})$$ Equation 4-9

$$m_{j'k,b} = \frac{m_{ij,a} - m_{ij,a}m_{ij,c}}{m_{ij,c}} + \frac{m_{i'j,a} - m_{i'j,a}m_{i'j,c}}{m_{i'j,c}} - r(m_{ij,a} + m_{i'j,a})\left[\frac{1-q}{q}\right]$$ Equation 4-10

These equations define the flows through the value chain model. The aim of the value chain model is to track flows through nodes (particularly through time which is explored in Chapter 5).

As mentioned earlier, nodes may represent a processing technology or a stock of material. First, consider the process node as shown in Figure 4-9, which may represent any level of detail from an aggregated generic process such as 'copper recycling' to a unit process within a specific technology, such as the 'electrowinning stage' within hydrometallurgical copper processing. To simplify the modelling of processing technologies, mass 'in' equals mass 'out' (there is no accumulation).

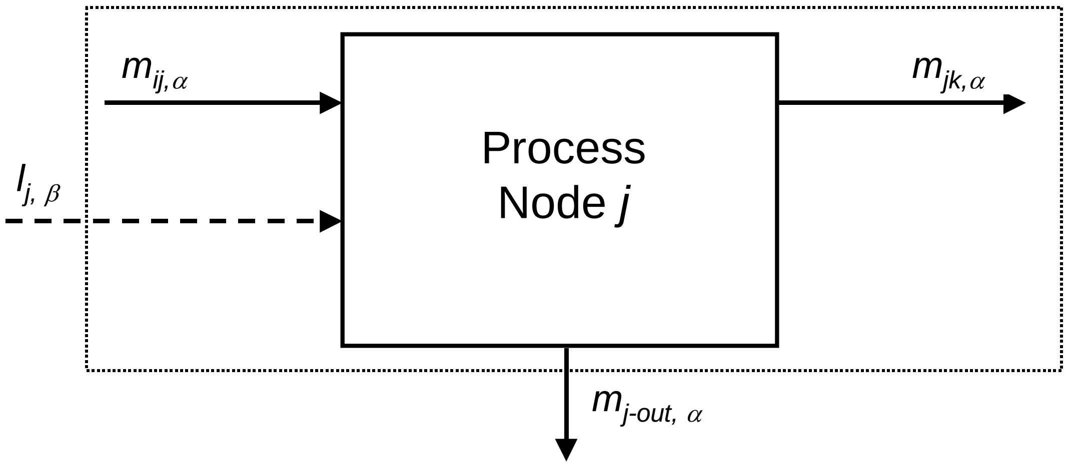


Figure 4-9: Generic representation of a process node (showing dotted system boundary)

There are three features of the process node needed to model the environmental performance of the process. Feature one: the mass flow vector into node *j* from node *i*, $\boldsymbol{m}_{ij}$ specifies additional component detail α for the non-value chain flows (e.g. inerts, contaminants) such that:

$$m_{ij,\alpha} = x_\alpha \cdot m_{ij,b} \text{ and} \qquad \text{Equation 4-11}$$

$$\sum_{\alpha=1}^{\alpha_{total}} x_\alpha = 1 \qquad \text{Equation 4-12}$$

For the process node in Figure 4-9 only one process input stream $\boldsymbol{m}_{ij}$ and one process output stream $\boldsymbol{m}_{jk}$ linking nodes within the system boundary have been shown to simplify the explanation (other streams are possible, as per $\boldsymbol{m}_{i'j}$ in Figure 4-8).

Feature two: a waste stream is shown $\boldsymbol{m}_{j\text{-}out,\alpha}$ which represents a process stream which crosses the system boundary and contributes to a potential environmental impact which depends on the composition of the stream.

Feature three: there are additional inputs from outside the value chain boundary which are associated with operating the process $\boldsymbol{I}_{j,\beta}$, for example energy, transport and reagents. There will also be an environmental impact attributable to process node *j* associated with the use of these inputs. This is further elaborated in Section 4.4.3.

Next, we consider the specification of stock nodes as shown in Figure 4-10.

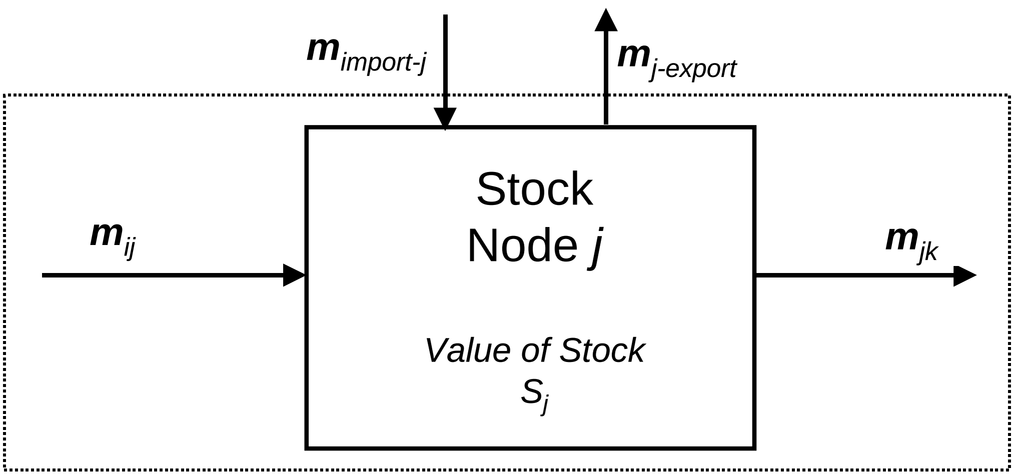


Figure 4-10: Generic representation of a stock node (showing dotted system boundary)

There are three particular features of stock nodes. Feature one: as mentioned earlier, stocks which act as a source of material (such as ore in the ground) will not have an input stream and stocks which act as a final sink (such as the stock of dissipative uses) will not have an output stream. This contrasts with process nodes which have both an input and an output stream. In the representation in Figure 4-10 a single input stream $\boldsymbol{m}_{ij}$ and a single output stream $\boldsymbol{m}_{jk}$ between other nodes in the system boundary is shown.

Feature two: stocks can be imported and exported from regions external to the system boundary being considered. If the regions were within the system boundary, the flows would simply be represented as standard flows between nodes within the value chain.

Feature three: stock nodes can accumulate material meaning the value of the stock node S_j at any time can be calculated, based on specification of all incoming and outgoing flows.

For stocks, the quality of material 'in' is equal to the quality of material 'out'; all incoming and outgoing stream flows are specified (rather than recovery and output quality which is the case for processes). Environmental impacts are not directly attributable to stock nodes, transportation flows associated with stocks are counted when the material reaches the next process node. Connections between nodes are made equivalent to the infrastructure in place for describing the status quo. The introduction of new infrastructure and changes to the splits between flows within the value chain for alternate futures is discussed further in Chapter 5. The next section considers how the representation of the processes within the value chain is used to inform environmental performance.

4.4.3 *Process performance*

The performance with respect to a specific impact for each node in the value chain is expressed as $P(j)$. The measure of performance varies with the mass flow to node j and the quality of the feed to node j. All non-material flows (e.g. energy and transport), material flows from outside the value chain (e.g. reagents) and waste stream flows (e.g. gaseous or to landfill) are modelled as functions of the flow rate and quality of feed to the node. This generates an inventory in inputs $\boldsymbol{I}_{j,\beta}$ and wastes $\boldsymbol{m}_{j\text{-}out,\alpha}$ associated with the flow through the node.

$$\boldsymbol{I}_{j,\beta} = \begin{bmatrix} I_{j,1} \\ I_{j,2} \\ I_{j,3} \\ .. \\ I_{j,\beta'} \end{bmatrix} \qquad \text{Equation 4-13}$$

$$\boldsymbol{m}_{j-out,\alpha} = \begin{bmatrix} m_{j-out,1} \\ m_{j-out,2} \\ m_{j-out,3} \\ .. \\ m_{j-out,\alpha'} \end{bmatrix} \qquad \text{Equation 4-14}$$

This structure facilitates assessment using LCA, of the environmental impacts associated with the inputs and wastes to processes. The impact for a particular mass flow of a specific input or waste is related to the performance for each impact category by an equivalency factor. For environmental performance category P_c the vector of performance equivalency factors for unit <u>inputs</u> $\boldsymbol{P_c eq}_{\beta,inputs}$ to node j is represented as:

$$\boldsymbol{P_c eq}_{\beta,inputs} = \lfloor p_c eq_{1,input} \quad p_c eq_{2,input} \quad p_c eq_{3,input} \quad \cdots \quad p_c eq_{\beta',input} \rfloor \qquad \text{Equation 4-15}$$

The performance score for impact category P_c from inputs to node j is then calculated by multiplying the inventory of inputs vector $\boldsymbol{I}_{j,\beta}$ by the vector of performance equivalency factors for unit inputs $\boldsymbol{P_c eq}_{\beta,inputs}$ to give

$$P_{c,inputs} = \lfloor I_{j,1} \cdot p_c eq_{1,input} + I_{j,2} \cdot p_c eq_{2,input} + I_{j,3} \cdot p_c eq_{3,input} + ... + I_{j,\beta'} \cdot p_c eq_{\beta',input} \rfloor \qquad \text{Equation 4-16}$$

and similarly the performance equivalency factors for unit <u>wastes</u> $\boldsymbol{P_c eq}_{\alpha,wastes}$ to node j is represented as:

$$\boldsymbol{P_c eq}_{\alpha,wastes} = \lfloor p_c eq_{1,wastes} \quad p_c eq_{2,wastes} \quad p_c eq_{3,wastes} \quad \cdots \quad peq_{\alpha',wastes} \rfloor \qquad \text{Equation 4-17}$$

The performance score for impact category P_c from wastes from node j is then calculated by multiplying the inventory of wastes vector $\boldsymbol{m}_{j\text{-}out,\alpha}$ by the vector of performance equivalency factors for unit wastes $\boldsymbol{P_c eq}_{\alpha,wastes}$ to give

$$P_{c,wastes} = \lfloor m_{j-out,1} \cdot p_c eq_{1,wastes} + m_{j-out,2} \cdot p_c eq_{2,wastes} + ... + m_{j-out,\alpha'} \cdot p_c eq_{\alpha',wastes} \rfloor \qquad \text{Equation 4-18}$$

This process can be performed for as many impact categories as are monitored. The performance of the value chain overall for a specific impact category c is obtained simply by summing the performance scores for the inputs and outputs from each process node from j to j' in the value chain (no impacts are associated with products):

$$P_c = \sum_{j=1}^{j'} P_{c,inputs} + \sum_{j=1}^{j'} P_{c,wastes} \qquad \text{Equation 4-19}$$

Impacts can be specified per node, unlike LCA which traditionally aggregates impacts across processes. This value chain approach is helpful for identifying sources of principal impact and controlling actors, when seeking to improve the performance of the value chain.

The information detail required for determining environmental performance of the status quo will be decision context specific and can vary in:

- the number of impact categories selected
- the number of components specified in process flows between nodes
- the aggregation of process nodes and resolution of information detail.

The following section provides examples of different representations of the value chain flows and case studies in Chapters 7, 8 and 9 demonstrate the use of different performance indicators at different scales.

4.4.4 *Examples of value chain specification for different decision problems*

In order to provide guidance on how many nodes to include in the network specification, specific examples of decision problems at different scales within the reference schema are given. They are formulated with the following principles in mind:

- need to capture major mass and energy flows
- need to explore decision variables at a range of scales, corresponding to a range of potential actor influences (individually & collaboratively)
- initially separate major classes of processing technology such as hydrometallurgy or pyrometallurgy (a more detailed analysis is likely to determine whether there are significant differences within a group such as between pyrometallurgical processing technologies)
- need to highlight major changes in concentration of process streams
- need to allow for import / export when considering multiple regions.

An aggregated initial global analysis (positioned at the macro-global level in the reference schema) based only on a snapshot model of mass and energy flows is explored in Chapter 7 and provides useful preliminary insights concerning:

- annual primary demand compared to available resources (initial estimate of resource scarcity - are the running out? does the loop need closing?)
- split between potentially recyclable and dissipative uses (no point investigating further recycling for the commodity if most use is dissipative)
- energy difference between primary and secondary processing (is additional recycling likely to offer any significant energy savings?)

A value chain representation useful for this analysis is shown in Figure 4-11 where each node represents the following:

- n_1 stock resources for mining from ore
- n_2 preparation of resource for use via primary processing (mining and refining)
- n_3 use of metal (in manufacture and use of goods)
- n_4 stock of discarded metal available for recycling
- n_5 stock of metal dissipated and unrecoverable
- n_6 preparation of resource for use via secondary processing

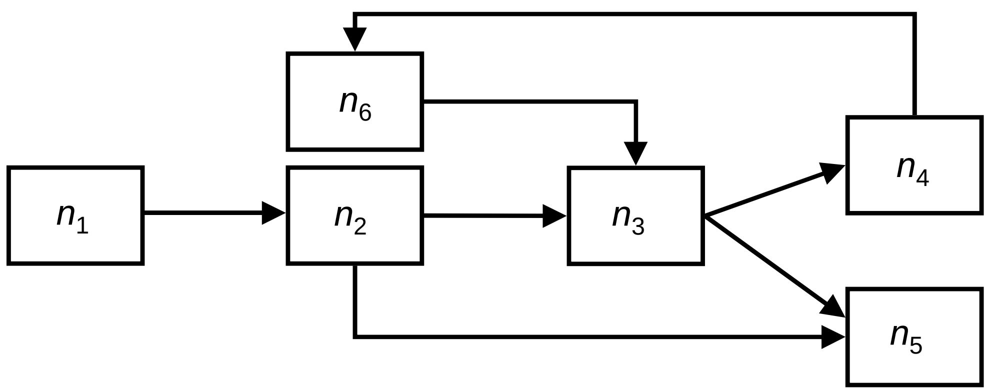


Figure 4-11: Aggregated representation of value chain for initial global analysis

A focus on the supply side of bringing metal to market, would necessarily then increase information detail on nodes 1, 2, 6 to discern between the major processes in these nodes. The decision contexts represented in this case are at the micro level within the reference schema (with a focus on part of the value chain only). These analyses could then determine if there were significant differences between the impacts associated within the processes within each node when disaggregated. Additionally, the difference between global, regional and local information detail used to characterise the performance could be assessed (for example, how does the ore grade vary between regions, how does this influence performance). In order to differentiate between technologies, as a minimum the major process stages should be modelled as separate nodes. An example is given in Figure 4-12 which could be used to compare different smelting technologies (nodes are not numbered but stocks are represented as circles and processes as squares). This better aligns with domain of interest 'real' actors, (for example, mining often occurs remotely to refining).

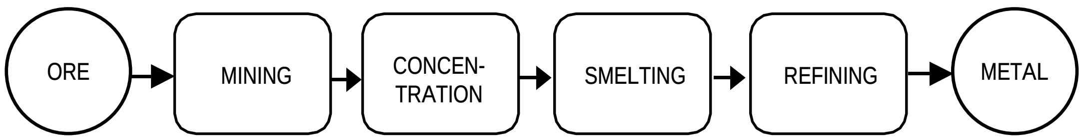


Figure 4-12: Example of minimum technology detail

In addition to analysis which differentiates between processing technologies, other elements of the value chain require modelling. For example, understanding the effect on environmental performance of changing demand for metal, changes in primary resource quality (ore grade) and secondary resource quality (itself dependent on usage and collection patterns and residence time in use). Such a case study requires dynamic models and is only explored in Chapter 9; however, the representation shown for the case of copper in Figure 4-13 demonstrates the ability to represent the value chain at a range of scales and with varying information detail.

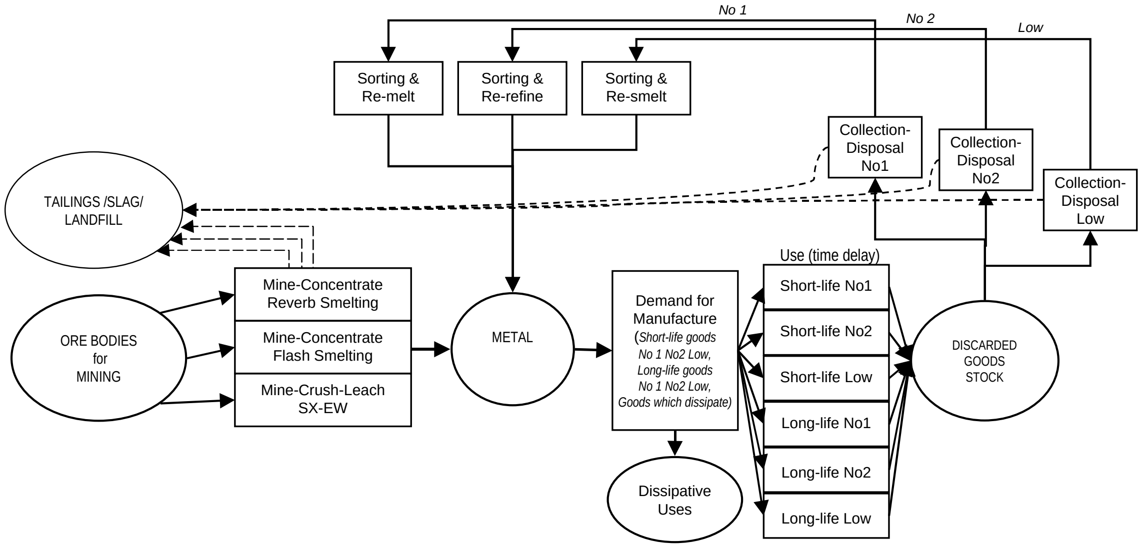


Figure 4-13: Representation of nodes for dynamic modelling

It depicts three main classes of primary processing technology, three main classes of secondary processing technologies which are linked to the quality of scrap (No1 99% Cu, No2 95% Cu or Low 30% Cu). In this representation, demand for the goods in use are specified for those goods which go on to become either No1, No2 or Low grade scrap and a distinction is made between those goods with a 'short' and 'long' residence time.

This discussion has illustrated a range of possibilities for representing the processes and material flows within the value chain. Such examples will be investigated further in case studies in Chapter 7 and Chapter 9. Through the case studies, the characterisation of both value chain flows and environmental performance at different scales will be demonstrated. The next task is to describe, practically, how such value chain and process modelling for the status quo can be undertaken practically using Microsoft Excel® and Visual Basic.

4.4.5 *Spreadsheet modelling: static case*

This section describes the conceptual approach to modelling specific processes within the value chain. All process models can be constructed in the Microsoft Excel / Visual Basic environment. A static model of processes is required to fulfil both aims of the status quo analysis. While a snapshot model would provide a measure of baseline performance against which future states could be compared (first aim), only a static model allows sensitivities to be understood. This provides valuable information in the context of using the analysis as part of problem structuring for preferred futures (second aim). For this reason, all assumptions have been linked on one spreadsheet, enabling linked flows to be calculated when any assumption changes. The general components of detailed process models are shown in Table 4-6 (less detail would be required for characterisation of the value chain at an aggregated global scale). To characterise the status quo of the value chain with technology specific detail, all processes in the value chain are modelled and flows through each process are calibrated to reflect current practice.

Table 4-6: General structure of spreadsheet models

Worksheet	Features
Assumptions	Maintains all important assumptions together in one place regarding each process stage (e.g. energy usage/t, resource quality, product demand). Changes to assumptions will change flows and impacts.
Process stage 1	Mass and energy flows to give inventory of inputs and wastes for first process stage
Process stage 2 etc...	Mass balance on second process stage, linked to first process stage and calculates inventory of inputs and wastes
Stocks	Noted as separate process stages when required
Summary of Inventory	Summary matrix of Inputs to each process stage, Wastes from each process stage and final product flow
Equivalency Factors and Impact Summary	Details matrix of equivalency factors for each impact category and multiplies these by component flows through each process stage to give impact. Impacts for each process stage summed to give overall impact for inputs and wastes

To illustrate the generic modelling process, a simplified example is given for the material chain representation in Figure 4-11 and components described in Table 4-6 have been grouped onto one sheet for clarity. Two components within mass flow streams are monitored: (a) copper and (b) other. In cases where more information detail is warranted, the 'other' stream would be divided into a greater number of component flows. The mass flows in from primary resources n_1 and for node n_2 (itself split into mining & concentrating and smelting & refining) are shown in Table 4-7. The refining process is represented by a pyrometallurgical smelter, as this accounts for over 80% of primary processing worldwide (Biswas and Davenport, 1994). Sub-types of pyrometallurgical processes are not differentiated in this example, but are considered in case studies in Chapter 7. Two additional inputs *I* are included: electricity (coal-based) and hydrocarbon fuel. To simplify the example, no gaseous process emissions are included (however the impacts of emissions from electricity generation and fuel combustion are included with the inputs – in effect, the input of fuel which is subsequently burned can be treated as an input of 'burned fuel'). Significant quantities of sulfur dioxide can be released from pyrometallurgical smelting of copper sulfide ores, meaning the representation of environmental impact for acidification is likely to be inaccurate. For this reason, the impact categories of global warming potential and ecotoxicity were chosen to illustrate the approach.

Table 4-7: Simplified model of *primary mining and concentration* and *smelting and refining* (Biswas and Davenport, 1994; Gaines, 1980; Norgate and Rankin, 2000; PRè, 2000)

PRIMARY PYROMETALLURGICAL MODEL		Reference
Key Assumptions (shaded)		
Resource Quality (%Cu)	1.00%	Biswas and Davenport (1994)
Recovery Ore to Conc	83%	Gaines (1980)
Recovery Conc to Prod	97%	Gaines (1980)
Overall Recovery	81%	Calculated
Concentrate Quality	30%	Biswas and Davenport (1994)
Product Quality	100%	Biswas and Davenport (1994)

Mining Concentrating	Ore Input	Concentrate Product	Waste - Gangue
Mass Flows Cu	1.2	1.0	0.2
Mass Flows Other	123.0	2.4	120.6
Mass Flow Total	124.2	3.4	120.8

Associated Inputs	Rate	Mine Total	Reference
Elec (kWh/t ore)	50	6210	Norgate and Rankin (2000)
Fuel (t/t ore)	0.0020	0.2	Norgate and Rankin (2000)

Smelting Refining	Concentrate Input	Metal Product	Waste - Slag
Mass Flows Cu	1.03	1.0	0.03
Mass Flows Other	2.4	-	2.4
Mass Flows Total	3.4	1.0	2.4

Associated Inputs	Rate	Smelt Total	Reference
Elec (kWh/t Cu product)	730	730	Norgate and Rankin (2000)
Fuel (t/t concentrate)	0.08	0.08	Derived from Norgate and Rankin (2000)

Performance Equivalency Factors	Greenhouse Potential (kg CO2 equivalent)	Eco-toxicity (Ecotox Units)	Reference
Input of			
Electricity (coal) kWh	1.02	6.9E+03	Prè (2000)
Fuel (t)	80.0	4.7E+05	Prè (2000)
Output of			
Cu in Gangue & Slag (t)	-	2.0E+09	Prè (2000)
Other in Gangue (t)	-	5.0E+08	Gangue assumed to contain less toxic metals
Other in Slag (t)	-	2.0E+10	than the slag

Potential Impacts from Inputs	Greenhouse Potential (kg CO2 equivalent)	Eco-toxicity (Ecotox Units)
Mining Conc (Elec)	**6.3E+03**	4.3E+07
Mining Conc (Fuel)	2.0E+01	1.2E+05
Smelt Refine (Elec)	7.4E+02	5.0E+06
Smelt Refine (Fuel)	6.4E+00	3.8E+04
Total from Inputs	**7.1E+03**	4.8E+07
Total from Wastes	-	**1.1E+11**
Overall Total	**7.1E+03**	**1.1E+11**

Potential Impacts from Wastes	Greenhouse Potential (kg CO2 equivalent)	Eco-toxicity (Ecotox Units)
Mining Conc (Cu)	-	4.2E+08
Mining Conc (Other)	**-**	**6.0E+10**
Smelt Refine (Cu)	-	6.2E+07
Smelt Refine (Other)	-	**4.8E+10**
Total from Wastes	-	1.1E+11

Table 4-7 shows the key assumptions for the processes of mining & concentrating and smelting & refining (shaded). These are typical values taken from literature. The total amount of copper metal made from primary refining in this example is one tonne. Note that there is mass balance closure for both copper and 'other' at the mining & concentrating stage and at the smelting & refining stage.

Using the performance equivalency factors shown, the potential environmental impacts from inputs and wastes are calculated and summed to provide an overall environmental performance score for both global warming potential and ecotoxicity potential. The significant components contributing to overall burden are highlighted in bold.

The results show that the most significant global warming burden arises from mining and concentrating the ore. This is attributable to the high energy requirement to finely crush and grind the ore which is necessary to liberate copper particles. For ecotoxicity, the burden is predominantly from process waste (slag) exiting the refining process and from the waste gangue from mining and concentrating.

A similar approach is used for secondary processing and is presented in Table 4-8 and for demand and use in Table 4-9 (as represented by n_3 in Figure 4-11). The quality of scrap processed has been represented as 'high' and 'low'. In this case, high grade scrap is melted and re-refined, while low grade scrap is re-smelted. One tonne of secondary metal from scrap is produced (0.5 tonnes from high grade and 0.5 tonnes from low grade). This means that the illustrative demand of 2 tonnes of copper is met half by primary and half by secondary. This was chosen to illustrate the approximate difference in impact between primary and secondary processing routes, however in practice, the current material chain configuration would be closer to 70% primary and 30% secondary.

Table 4-8: Simplified model of secondary processing (Biswas and Davenport, 1976; Biswas and Davenport, 1994; Energetics, 1999; Gaines, 1980; MIM, 1999; PRè, 2000)

SECONDARY PROCESSING MODEL

Key Assumptions (shaded)		Reference
High Grade Scrap Quality (%Cu)	95%	Biswas and Davenport (1994)
Low Grade Scrap Quality (%Cu)	30%	Biswas and Davenport (1994)
High Grade Scrap Recovery	95%	Estimated from Gaines (1980)
Low Grade Scrap Recovery	80%	Estimated from Gaines (1980)
Product Quality	100%	

High Grade Scrap Processing	Hi Scrap Input	Metal Product	Waste
Mass Flows Cu	0.6	0.5	0.1
Mass Flows Other	0.03	0.0	0.0
Mass Flow Total	0.6	0.5	0.1

Associated Inputs	Rate	Total	Reference
Elec (kWh/t product)	400	200	Biswas and Davenport (1994) use 300-400, MIM (1999) use 450
Natural Gas (t/t scrap)	0.1	0.0	Energetics (1999)

Low Grade Scrap Processing	Lo Scrap Input	Metal Product	Waste
Mass Flows Cu	2.1	0.5	1.6
Mass Flows Other	4.9	0.0	4.9
Mass Flow Total	6.9	0.50	6.4

Associated Inputs	Rate	Total	Reference
Elec (kWh/t product)	400	200	Biswas and Davenport (1994) use 300-400, MIM (1999) use 450
Natural Gas (t/t product)	0.02	0.0	Energetics (1999), Biswas and Davenport (1976)
Coke (t/t scrap feed)	0.09	1	Energetics (1999)

Performance Equivalency Factors	Greenhouse Potential (kg CO2 equivalent)	Eco-toxicity (Ecotox Units)	Reference
Input of			Allows for burning of fuel in furnace
Electricity (coal) kWh	1.02	6.9E+03	Prè (2000)
Natural Gas (t)	3,050	2.41E+05	Prè (2000)
Coke (t)	2,000	1.17E+05	Prè (2000)
Output of			
Cu in Waste(t)	-	2.0E+09	Prè (2000)
Other in Waste High Grade (t)		2.0E+10	Prè (2000)
Other in Waste Low Grade (t)	-	4.0E+09	Prè (2000)

Potential Impacts from Inputs	Greenhouse Potential (kg CO2 equivalent)	Eco-toxicity (Ecotox Units)
High Grade Processing (Elec)	2.0E+02	1.4E+06
High Grade Processing (Gas)	1.4E+02	1.1E+04
Low Grade Processing (Elec)	2.0E+02	1.4E+06
Low Grade Processing (Gas)	3.1E+01	2.4E+03
Low Grade Processing (Coke)	1.2E+03	7.3E+04
Total from Inputs	1.8E+03	2.9E+06
Total from Wastes	-	2.3E+10
Overall Total	**1.8E+03**	**2.3E+10**

Potential Impacts from Wastes	Greenhouse Potential (kg CO2 equivalent)	Eco-toxicity (Ecotox Units)
High Grade (Cu)	-	1.1E+08
High Grade (Other)	-	5.7E+08
Low Grade (Cu)	-	3.2E+09
Low Grade (Other)	-	1.9E+10
Total from Wastes	0.0E+00	2.3E+10

Table 4-9: Simplified model of demand and use

PRIMARY PYROMETALLURGICAL MODEL

Key Assumptions		Tonnes	
% Demand met from Primary	50%		1.00
% Demand met from Secondary	50%		1.00
% Secondary Demand from High	50%		0.50
% Secondary Demand from Low	50%		0.5
Total Demand (t)			2.00
	GHG	Ecotox	
From Primary	7.1E+03		1.1E+11
From Secondary	1.8E+03		2.3E+10
Total Impact Potential	**8.9E+03**		**1.3E+11**

In this example, no environmental impact has been attributed to the eventual use of copper in society, which is beyond the scope of this thesis. Additionally, there is no impact attributable to stocks n_4 or n_5 in this example.

This section has provided an insight into the practical aspects of characterising the environmental performance of the value chain in technology specific detail for the status quo. To complete the characterisation of the status quo, however, we require insight into the key sensitivities of the models and which actors control them.

4.5 SENSITIVITIES ANALYSIS & ACTOR INFLUENCE

Chapter 5 will consider alternate futures and paths toward them. These alternate futures will arise as a result of changes in decision variables which are controlled by actors. Variables within actor control and external to actor control will be treated differently when envisioning alternate futures and assessing those which can be readily achieved. For this reason, even at this stage of considering current material chain configurations, it is important to understand actor controlled variables for different decision contexts and the effect of changes to variables on impacts. An initial list of actors and system variables within the reference schema was proposed in Chapter 3, but there was no classification of which actors controlled which system variables and who had control of significant system variables.

4.5.1 *Parametric sensitivity analysis*

The purpose of a parametric sensitivity analysis is to determine which parameters have the greatest influence on the output of the model. Insignificant parameters may be discarded following a sensitivity analysis and greater attention can be paid to ensuring that important parameters are specified accurately (Hamby, 1994). The accurate specification of important parameters may require further research, but reduces the uncertainty of the final results. Performing a sensitivity analysis is an essential feature of process plant design (Sinnott, 1989) and so it should also be for the design of preferred futures for the value chain.

Several techniques are available for parametric sensitivity analyses of environmental models (see Hamby, 1994). The simplest is to vary a single parameter by plus or minus 20% from its base case value and note the resultant impact as a percentage deviation from the base case impact value (while keeping other parameters fixed). This is then repeated for each parameter in the model. The generalised approach is shown in Table 4-10. From these illustrative values it is observed that the performance with respect to impact A is more sensitive to changes in x_n than in changes to x_{n+1}.

Table 4-10: Example of sensitivity analysis table

Case	Value of Variable	Value of Impact A	Example Change in Impact A
Base case (x_n)	x_n	y_{base}	–
+20% sensitivity	$1.2 \times (x_n)$	y_{+20}	+10%*
–20% sensitivity	$0.8 \times (x_n)$	y_{-20}	–7%
Base case (x_{n+1})	x_{n+1}	..	–
+20% sensitivity	$1.2 \times (x_{n+1})$	..	–2%
–20% sensitivity	$0.8 \times (x_{n+1})$	..	+2%

*Calculated as $\frac{y_{+20} - y_{base}}{y_{base}} \times \frac{100}{1}$ and similarly for other changes

Specific values from the example presented in Section 4.4.5 are given in Table 4-11, Table 4-12 and Table 4-13. The points to look for in these sensitivity tables are the top three or four parameters with the highest sensitivity relative to other parameters and for points of difference where there is a high sensitivity to global warming potential but not to ecotoxicity impact. The actual percentage change is less important. Table 4-11 shows high sensitivity to resource quality and recovery (and also to product quality, but this is not an uncertain parameter as product quality is known accurately). The difference in the magnitude of sensitivity for recovery and resource quality depending whether the parameter is increased or decreased, reflects a non-linear relationship. Global warming potential (noted as green house gas GHG in the table) is also sensitive to the electricity input. It is interesting to note no sensitivity to ecotoxicity potential for change in electricity. This is likely to be a function of the limited data quality for ecotoxicity associated with electricity production that is available.

Table 4-11: Parametric sensitivity analysis of primary processing

Parametric Sensitivity Analysis - Primary Processing

Base Case	Base	+20%	20%	Change	GHG	Ecotoxicity	Change
				-----	7.1E+03	1.1E+11	
Resource Quality (%Cu)	1.00%	0.012	0.008				
Plus 20%				-15%	6.1E+03	9.9E+10	-10%
Minus 20%				22%	8.7E+03	1.2E+11	14%
Rec Ore to Conc	83%	0.99	0.66				
Plus 20%				-15%	6.1E+03	9.9E+10	-10%
Minus 20%				22%	8.7E+03	1.3E+11	15%
Rec Conc to Prod	97%	1.164	0.776				
Plus 20%				-15%	6.0E+03	9.0E+10	-17%
Minus 20%				22%	8.7E+03	1.4E+11	25%
Conc Quality	30%	0.36	0.24				
Plus 20%				-1%	7.1E+03	9.8E+10	-11%
Minus 20%				-1%	7.1E+03	1.3E+11	15%
Prod Quality	100%	1.2	0.8				
Plus 20%				17%	8.4E+03	1.3E+11	23%
Minus 20%				-18%	5.8E+03	8.3E+10	-24%
Other Parameters		+20%	20%				
Mine Conc Elec	50.00	60	40				
Plus 20%				17%	8.4E+03	1.1E+11	0%
Minus 20%				-18%	5.8E+03	1.1E+11	0%
Mine Conc Fuel	0.002	0.0024	0.0016				
Plus 20%				0%	7.1E+03	1.1E+11	0%
Minus 20%				-1%	7.1E+03	1.1E+11	0%
Smelt Refine Elec	730.00	876	584				
Plus 20%				2%	7.3E+03	1.1E+11	0%
Minus 20%				-3%	7.0E+03	1.1E+11	0%
Smelt Refine Fuel	0.10	0.12	0.08				
Plus 20%				-1%	7.1E+03	1.1E+11	0%
Minus 20%				-1%	7.1E+03	1.1E+11	0%

Table 4-12 shows again that recovery, quality and electricity are important parameters.

Table 4-12: Parametric sensitivity analysis of secondary processing

Sensitivity Analysis High Grade Processing

Base Case	Base	+20%	20%	Change	GHG	Ecotox	Change
				-----	6.9E+02	1.4E+09	
High Grade Scrap Quality	95%	1.14	0.76				
Minus 20%				34%	9.3E+02	9.5E+09	596%
High Grade Scrap Recovery	95%	1.14	0.76				
Minus 20%				19%	8.2E+02	2.2E+09	62%
High Grade Elce	400	480	320				
Plus 20%				12%	7.7E+02	1.4E+09	0%
Minus 20%				-12%	6.1E+02	1.4E+09	0%
High Grade Gas	0.09315	0.1118	0.0745				
Plus 20%				8%	7.5E+02	1.4E+09	0%
Minus 20%				-8%	6.4E+02	1.4E+09	0%

Sensitivity Analysis Low Grade Processing

Base Case	Base	+20%	20%	Change	GHG	Ecotox	Change
				-----	3.0E+03	4.5E+10	
Low Grade Scrap Quality	30%	0.36	0.24				
Plus 20%				-26%	2.2E+03	3.0E+10	-34%
Minus 20%				47%	4.4E+03	7.4E+10	64%
Low Grade Scrap Recovery	80%	0.96	0.64				
Plus 20%				-14%	2.6E+03	3.7E+10	-17%
Minus 20%				21%	3.6E+03	5.7E+10	26%
Low Grade Elce	400	480	320				
Plus 20%				3%	3.0E+03	4.5E+10	0%
Minus 20%				-3%	2.9E+03	4.5E+10	0%
Low Grade Gas	0.02	0.024	0.016				
Plus 20%				0%	3.0E+03	4.5E+10	0%
Minus 20%				0%	3.0E+03	4.5E+10	0%
Low Grade Coke	0.09	0.108	0.072				
Plus 20%				17%	3.5E+03	4.5E+10	0%
Minus 20%				-17%	2.5E+03	4.5E+10	0%

Table 4-13 shows a greater sensitivity to overall demand, than the secondary processing technology used to supply secondary copper. Note that the analysis has been performed twice using the 50% demand from primary split (and hence 50% from secondary although this figure is not mentioned specifically in the table) as per the example and also the more realistic split of 70% from primary (and hence 30% from secondary). This shows that while the magnitude of the sensitivity to a change in relative demand from primary sources changes, it remains a sensitive parameter in both cases, providing affirmation of its importance. Two cases are also shown for the breakdown of secondary material coming from high grade scrap (with the remainder coming from low grade scrap). In the first case, there is a 50% split coming from high grade scrap (hence 50% also from low grade scrap). In the second case there is an 80% split from high grade (with 20% from low grade).

Table 4-13: Demand sensitivity analysis

Demand Sensitivity

				Change	GHG	Ecotox	Change
Base Case	Base	+20%	-20%	-----	8934.794	1.32E+11	------
% Demand from Primary	50%	0.6	0.4				
Plus 20%				12%	9990.031	1.49E+11	13%
Minus 20%				-12%	7879.557	1.15E+11	-13%
% Secondary from High	50%	0.6	0.4				
Plus 20%				-3%	8707.355	1.28E+11	-3%
Minus 20%				3%	9162.233	1.37E+11	3%
Base Case	Base	+20%	-20%	-----	10635.88	1.59E+11	------
% Demand from Primary	70%	0.84	0.56				
Plus 20%				16%	12304.26	1.86E+11	17%
Minus 20%				-16%	8967.497	1.31E+11	-17%
% Secondary from High	80%	0.96	0.64				
Plus 20%				-2%	10417.54	1.54E+11	-3%
Minus 20%				2%	10854.22	1.63E+11	3%

This approach provides a first-pass evaluation of the relative importance of each variable in the model. It does not require an estimate of the expected range of values nor any measure of the probabilities associated with the expected range of values as required by more detailed approaches to uncertainty. The Monte Carlo is one such approach which requires the input of likely probability density functions for each uncertain variable. Then using a random sampling technique from the probability distribution of each variable, a probability distribution of expected values can be simulated (Schuyler, 1996). The process is computationally intensive. Such an approach is helpful in articulating the implications of the combined uncertainty of several variables which are likely to vary within a specified range. However, for the design of preferred futures in the minerals and metals value chain, the emphasis is not on the *likely* future performance of the value chain, but on the performance associated with *desirable* futures. The performance associated with desirable futures requires consideration of key variables (which are identified here through the sensitivity analysis) and then importantly, consideration of which actors control these variables at which scale. This will influence which futures can be implemented by single actors acting alone, and through collaboration. From this, areas to target to facilitate the transition to desirable futures will be identified.

The importance of the sensitivity analysis of the material chain is twofold: first, to ensure sensitive variables are being specified to sufficient information detail and second, to highlight sensitive variables in order to focus on which actors can control them.

4.5.2 *Actor influence*

This section proposes an approach for the characterisation of actor influence over sensitive system variables. This information will be useful to suggest potential partnerships between actors and to identify the current limits within which actors operate for the status quo of the system, which in turn will limit the futures they can realise without collaboration. The classification process is as follows, for each actor, system variables are classified as either:

- controllable variable by the actor (A);
- partially controllable or potentially controllable in future (P) or
- not controllable, that is, external (E) to the influence of the actor.

For an actor to influence a potentially controllable variable, collaboration is required. The classification will be scale dependent and variables against which actor influence is assessed are appropriate to the scale of analysis. An example demonstrating the classification of influence is shown in Table 4-14.

Table 4-14: Example of actor influence table

	$Actor_A$	$Actor_B$	$Actor_C$	$Actor_n$	Highest Level of Control*
$Variable_1$	P	P	E	...	P
$Variable_2$	E	A	E	...	A
$Variable_3$	E	E	A	...	A
$Variable_4$	E	E	E	...	E
$Variable_n$	...	...	...	...	

*Note: 'highest level of control' is the greatest level of control exerted by any actor where A>P>E

A schematic representation showing the control of different actors over different system variables is given in Figure 4-14. Mass flows between nodes in the value chain are represented by the solid grey arrows. Nodes represent stocks of material or technologies. Impacts are associated with inputs to each node (e.g. energy, reagents, transport of materials) and with outputs (e.g. emissions). In this example, actor 2 can control the choice of using either Node I or Node J (system variable 2) to supply material to Node K and potentially has control over system variable 1 (e.g. the energy source) used in process Node I which is shown as a dotted line. Control over this variable may only be possible via collaboration with another actor 1 who is indirectly linked to the material flows in the value chain (e.g. energy provider). The provision of input 1 contributes to impact 1, while output 1 contributes to impacts 1 and 2. Actor 2 controls system variable 3 which represents the split of streams within Node K, while the outflow from Node K (e.g. demand) is externally controlled.

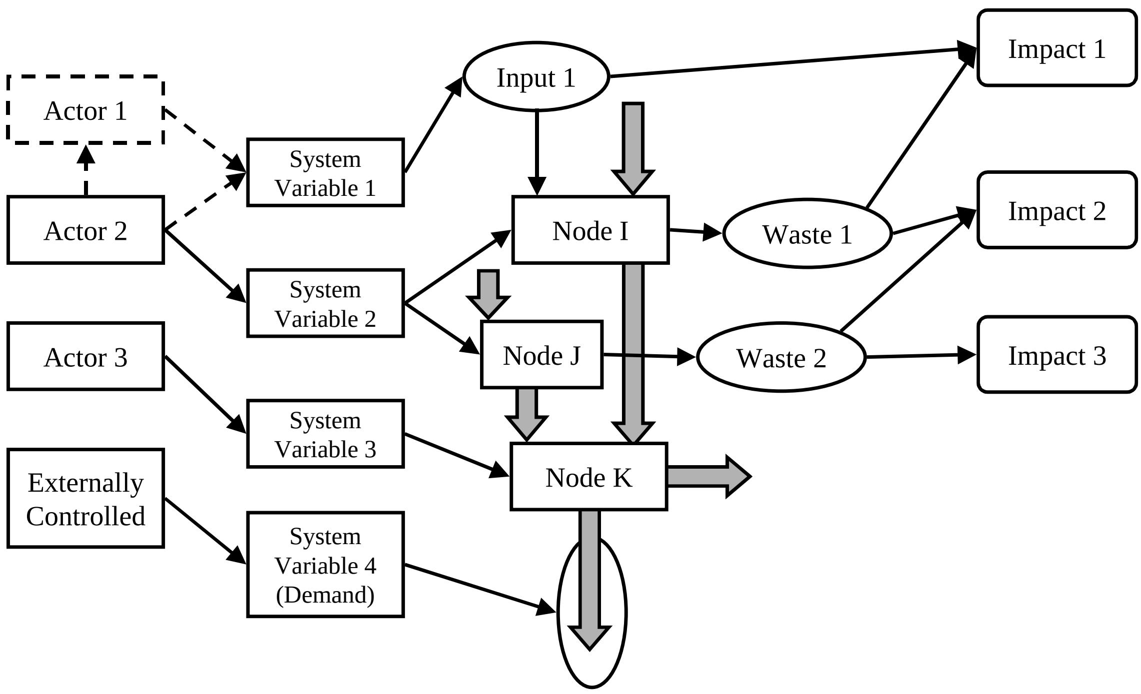


Figure 4-14: Link between actor, system variables, system and impact

This classification is useful for understanding more about who the influential actors are in realising a preferred future. Actor controlled variables will present no constraint on an alternate future, while potentially controllable variable could require collaboration or some other change to fully implement change and hence would be a potential constraint to an alternate future. External variables cannot be influenced, but their influence on futures must be better understood. This is discussed further in Chapter 5.

4.5.3 *Combining sensitivity and actor influence*

By combining the sensitivity analysis and classification of actor influence, the actors in control of sensitive variables can be determined for a specific scale. The process can be duplicated for analysis at different scales. In itself, the characterisation of actor influence is equally as important as the characterisation of environmental performance when addressing the problem of how to improve performance in the value chain.

A table was constructed to represent the actor influence over sensitive variables effectively (see Table 4-15).

Table 4-15: Example table for actor control of sensitive variables

Sensitivity	Variable	Direct Actor Control (A)	Partial / Potential Actor Control (P)
Highest	$Variable_2$	Actor B	—
Next highest	$Variable_1$	—	Actor A Actor B
Next highest	$Variable_3$	Actor C	—
.....	.....	.....	....

The table is constructed by ranking from largest to smallest, the most sensitive variables with respect to the chosen criteria (a new table must be created for each environmental performance criteria). The top four or five variables should be included in the table as these are likely to account for most of the uncertainty in the system (Schuyler, 1996). The variable, the controlling actors and potentially controlling actors are then listed in adjacent columns. From the example in Table 4-15, it is clear that actor B controls the most sensitive variable, $Variable_2$ and that the next most sensitive variable, $Variable_1$ is not exclusively controlled directly by any one actor, but can only be influenced through the collaboration of Actors A & B, thus identifying a potential collaboration to be investigated in more detail with reference to achieving a preferred future.

The following observations highlight the working of the table linking sensitive variables and actors:

- Scale and Grouping of variables: a separate table can be made for each scale of analysis to highlight the key actors at different scales. It may also be convenient to separately compare sensitivity within each node and then between nodes at the scales of representation

- Criteria: by comparing the rank order of sensitive variables for different performance criteria, actors can be identified who will be involved in key trade-offs
- Relative and absolute impact: the sensitivity analysis determines relative importance with respect to making changes for the future, for the status quo of the value chain the importance of actors will also be dictated by the impacts attributed to their domain of interest. For example, an actor could control a large part of the value chain to which environmental performance is not sensitive on a per tonne basis, but which in absolute terms is significant.

4.6 IMPLICATIONS FOR DECISION MAKING

There are three clear benefits from the characterisation of the value chain across scales which impact on decision making. Firstly, the analysis provides the necessary baseline performance of the industry against which future performance will be compared. Secondly, there are insights to be derived from the characterisation of environmental performance at different scales regarding the links between actors and impacts. Thirdly, this information can be used to inform decision making, not only for the present, but for designing preferred future configurations of the minerals and metals value chain. Each of these benefits are further explained and developed.

4.6.1 *Baseline performance of status quo*

Establishing the baseline performance of the status quo is necessary as a point of reference for comparison with alternate futures. However, analysis of status quo environmental performance is useful in its own right. It establishes an environmental performance profile for the industry which is currently lacking. Furthermore, it can demonstrate which steps in the value chain contribute most to environmental burden. Beyond this, with the use of static models for mass and energy flows, it provides the ability to assess the sensitivity of environmental performance to changes in system variables.

4.6.2 *Learning from actor-impact links*

By combining an analysis of impacts and the actors responsible for them can highlight potential collaborations and responsibilities. Establishing a link between actors and impacts also facilitates the drive toward greater accountability and collective responsibility for environmental burden. Linking burdens to particular stages in the value chain highlights responsibility, especially when environmental burdens are manifested at a different scale to that of the actors' domains of interest. Noting the scale of an actor's domain of interest, their domain of influence over system variables (alone or collaboratively) and the scale of the resultant impacts is an important lesson to be drawn from the analysis. Feedback loops to make the behaviour of actors more sustainable will be greater when impacts are not externalised.

Articulating which actors can control key system variables and their potential influence identifies individual actors or potential collaborations which may be required to reduce future impact. This provides an important step in structuring an approach to decision making for a preferred future.

4.6.3 *Status quo analysis as a basis for considering futures*

Looking to the future, the link between the characterisation models developed for the status quo analysis and their use in exploration of paths toward preferred futures is shown in Figure 4-15.

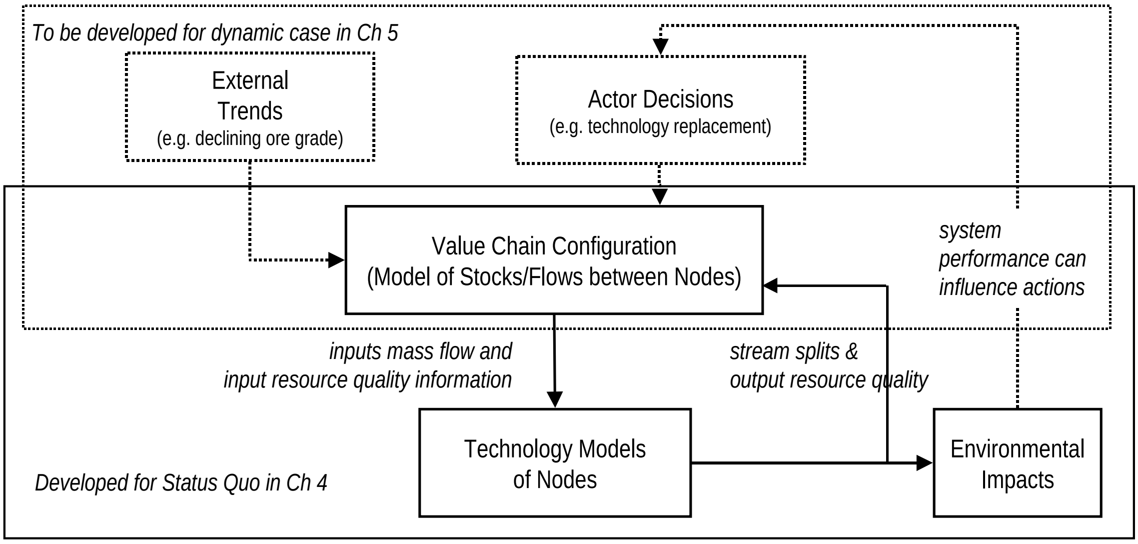


Figure 4-15: Conceptual model of link between value chain flows and technology models

Value chain and technology models which can characterise performance for the status quo have been developed in this chapter. The additional elements which will be included in the dynamic analysis in Chapter 5 are also shown, namely, external trends, system properties and actor decisions will all affect the configuration of flows and technologies in the future value chain. In relation to the characterisation of value chains across scales, information detail and decision making, there are two points to highlight which can be illustrated with reference to Figure 4-15. The first relates to the degree of aggregation and resolution of information used in the analysis. It is important to be aware of the potential for bias when using information from different scales, for example, global averages to describe external trends, with site-specific data for a process under consideration within the system boundary. If the global average has a large bearing on performance, it will be identified in the sensitivity analysis.

The second point is that the ability to use the environmental performance of the system as feedback signal which influences actor decisions, will be compromised if too little information detail (resulting in high uncertainty) is included in the technology models and environmental impacts. This is addressed by effective problem structuring, understanding actor requirements for discerning between options and modelling to a level of detail which can inform appropriate environmental indicators.

4.7 CONCLUSIONS

This chapter has presented an approach for describing the material and energy flows in the value chain for different scales and their associated environmental impact. The reference schema was used to guide information requirement at different scales. A new approach to system characterisation linking system flows to impacts and the actors who control system configuration was developed. This allows a baseline performance assessment of the industry. Additionally it becomes incorporated into the environmental decision making process by providing the basis from which preferred futures can be designed and paths to their implementation explored as discussed in the next chapter.

CHAPTER FIVE

Transitions toward preferred futures

Chapter 4 developed an approach to characterise the status quo of material and energy flows of the value chain and their associated environmental performance at different scales across the reference schema. This included an analysis of system variables over which actors have control, providing the basis in this chapter for establishing preferred futures which actors can achieve individually and collectively. Considering transition paths towards preferred futures is complex, fundamentally because there are limitless possibilities, depending on the timing of changes to flows and infrastructure within the value chain – each of which influences the environmental performance of the system over time.

This chapter makes two contributions to better informed environmental decision making in the minerals industry. Firstly, it develops a new approach to envisioning system states beyond the status quo. Secondly, it develops a transparent approach to evaluating the performance of dynamic transitions toward preferred futures.

Using the link between actor-variable-system-impact, improvements which actors can easily achieve acting alone is contrasted with the potential system improvement possible via collective action between several actors. Considering a path through time, the impacts of external variables beyond the control of actors are also modelled, in order to assess their impact on system performance and resource availability. The approach allows actor behaviour to be modelled as a function of time and system performance, to contrast the effect on cumulative system performance and the timing of transitions to future states. By considering the effort required for actors to take particular decision, the reward-for-effort associated with actor decisions and their effect on system performance can be assessed to make the case for individual or collective action by industry actors. In short, this represents the degree of system improvement which can be achieved acting alone, in concert with others, within existing infrastructure, with new infrastructure and with slow and rapid transitions to future states. The structured approach to understanding the consequences of both action and inaction which can be applied across scales, provides the basis for responsibly selecting a preferred path toward a more sustainable future.

5.1 DIFFERING PERSPECTIVES OF THE FUTURE

Tools developed in Chapter 4 to characterise the status quo for the materials value chain provided the ability to describe 'where we are at' across scales, the first step in environmental decision making outlined by Turner et al. (1997). This section discusses how to deal with the remaining questions of 'where are we headed', 'where do we want to get to' and then 'how might we get there'.

To begin, two approaches to considering the future are examined, namely forecasting and backcasting. They relate in different ways to the questions of 'where are we headed' and 'where do we want to go' and the task is to determine what combination of these approaches is most useful for creating a more sustainable value chain for the minerals and metals industry. To begin this, a brief background discussion is presented on the approach to addressing these questions as part of environmental decision making at different scales.

5.1.1 *Continuing the environmental decision making process*

Having developed an approach to characterise the status quo across scales in Chapter 4, the next stage in the environmental decision making process is to look to the future to ascertain what changes can be made to improve the environmental performance of the value chain.

The proposal by Turner et al. (1997) following an analysis of the status quo is to nominally consider the question of 'where are we headed?', and then 'where do we want to go?', while at the same time acknowledging a significant degree of variety in the way that environmental decision making is carried out – for example, the questions could be addressed in the reverse order. The aim in this section is to briefly examine the importance of each question for the minerals and metals industry, before evaluating how the tools of forecasting and backcasting may be used to answer these questions.

From Chapter 2 and 3 we know that decision contexts vary in scale with respect to geographic and value chain extent, as well as time horizon and 'decision ambitiousness'. From Chapter 4 it was established how to characterise environmental impact, including important variables and the actors who control them. As there are multiple actors controlling important system variables, for any given actor, there will be constraints on the future they can realise, imposed by variables beyond their control. The amount of change they can realise, will also be influenced by the time horizon (Porter et al., 2004). Each of these factors influences the way the future is considered and the importance of the questions 'where are we headed?' and 'where do we want to go?' and the order in which they are addressed.

Contrast these situations: the question of 'where do we want to go?' may be considered without any constraints on the future (envision an ideal state regardless of whether or not it can feasibly be achieved). Alternatively, it may be constrained by where we and others are headed – a case of 'where do we want to go, given that x, y and z are happening'. The actual situation will be dependent on the influence of the actor in the system as a whole, for example, smaller actors will be more constrained by the decisions of bigger players. In this case, first understanding where 'we' and indeed 'other' parts of the system are headed serves to limit 'where we might want to go' – it becomes a case of making the best out of the situation within the given limitations. Regardless of actor influence, this approach is more relevant when considering the short term future. In the longer term, such constraints could be overcome, partnerships could be formed to potentially influence all system variables. In this situation it makes more sense to first consider 'where we want to go' in order to strive for a more sustainable future, and then 'where are we headed' to see if this accords with achieving the ultimate goal, and if not, what needs to be done to change the situation.

In summary, the two questions of 'where are we headed?' and 'where do we want to go?' are closely linked. The way they are addressed depends on the decision context, including the scale, time horizon and level of control which actors have over system variables which can limit their decision ambitiousness. The use of forecasting and backcasting to address these questions is now discussed.

5.1.2 *Forecasting*

Forecasting aims to provide future predictions of system states, based on the existing behaviour of the system and the estimated influence of external factors. Primarily forecasts are concerned with the question of 'what does the future hold?' and in relation to environmental decision making, 'where are we headed?'. Forecasts are termed either absolute or conditional, where a conditional forecast is contingent on a particular action being taken (Helmer, 1983).[1] There is a perception that forecasts are useful for informing resource policy, by providing predictions of the future which are seen as value-neutral, reliable and objective (Robinson, 1988), however such perceptions can be misleading. This section examines the usefulness of forecasting as a tool for assisting strategic decision making in the minerals industry.

Forecasting can be applied at a range of levels within the minerals industry, from qualitative visions of society that will shape the future business operating environment (see, for example, Schwartz and Webber, 1999) to predictions over future developments of individual technologies (Coates et al., 2001). Quantitative forecasts are based on models which may be calibrated with current and historical data. Forecasts may be combined with anticipated changes in key variables to give future predictions of system states for different scenarios, with each scenario reflecting a different combination of key variables. By way of example, Ayres et al. (2001) develops a model to forecast the stocks and flows of copper in different regions of the globe until the year 2100 for eight different scenarios, where each scenario has a different combination of product lifetimes, collection rates and intensity of consumption. While such analyses can provide insight into the effect on the system of changes in system variables, there is great uncertainty associated with using the forecasts as a guide to answering 'what does the future hold?'.

The uncertainties associated with the future mean that forecasts are likely to behave differently than predicted, especially as the time horizon is extended. The inaccuracy of past forecasts has compromised the legitimacy of forecasts in making policy decisions (Robinson, 1988). With no indication of the likelihood of any individual scenario, forecasts should not be considered a constraint on the future, within which a potential future could be envisioned. For forecasts to serve as credible constraints on the future, the system variables must be well understood and likely to behave in a predictable manner for the extent of the forecast. Porter et al. (2004) deem that extrapolative

---

[1] The distinction between absolute and conditional forecasting was made to alert the reader to terminology used in forecasting literature, but the distinction is not important in this thesis.

approaches are only suitable in the short term. I concur with this analysis in concluding that forecasting is most useful for short term predictions. In these cases, the 'certain' forecast becomes a constraint and one can adapt behaviour to what can be considered a 'likely' event based on the forecast.

However, Robinson (1988) points out that 'even if the most likely future was predictable, such information by itself is not particularly useful for making policy decisions, since the crucial question has to do with the range of choices available and their relative impacts and desirability', he cites a need to focus on 'feasibility-testing and desirability rather than prediction'. The predicted mass flows of Ayres et al. (2001) do not include any assessment of environmental impact, which would assist in better informing the desirability of the futures. So how are these long term future predictions useful? In relation to the work of Ayres et al. (2001), the value of the forecasts is that they simply confirm that a problem with the management of the mineral and metals value chain is likely to continue to exist well into the future, regardless of the particular scenario. More importantly, they show the effect on the system flows of changes in specific system variables. They provide some indication of system dynamics, even if it may be unreliable in the long term.

The crucial characteristic of long term planning for resource extraction and use is that, we have the ability to directly intervene and make changes which will bring about a more desirable future. Hence, understanding more about what potential changes could be made and their impacts is of vital importance. In the case of forecasts regarding the minerals and metals value, where trends will take us is not the right starting point to approach the problem, as we wish to directly intervene to design a preferred future which we can work towards. Existing trends must not act as hard constraints on the future we strive for. This suggests that in long term planning, we should initially pay more attention to the question 'where do we want to go?' and less to 'where are we headed?'. However, once having established 'where we want to go' and depending on constraints of 'where we can go', exploring the influence of trends may uncover additional insights that result from modelling the system through time.

In summary, forecasts deal primarily with the question of 'what does the future hold?', not 'where do we want to get to?'. In the short term, forecasts may be reliable, in which case 'what the future holds' can act as a valid constraint on 'where we can get to'. However, in the long term, forecasts cannot be considered reliable, and more than 'where can we get to?' there is an opportunity to consider 'where we want to get to?' and make changes through time that will assist a preferred future to be realised. Backcasting more explicitly considers the question of 'where we want to get to?' and is discussed in the next section.

5.1.3 *Backcasting*

The idea of creating an alternative future and considering how to drive the system of today toward this future is embodied in the approach of backcasting (Robinson, 2003). The useful component of backcasting is that it offers the possibility of envisioning a preferable alternate system state, discontinuous from the unsustainable status quo – in other words 'where do we want to go'. An examination of how the current system can be changed to realise the preferred future can then be undertaken.

Several authors have used backcasting to identify desirable futures and consider what steps are necessary to move toward this goal (Anderson, 2001; Mulder and Biesiot, 1998; Robèrt, 2000; Robinson, 1988). In essence, backcasting is a pro-active look at where we should be aiming to take the system, not merely based on what is currently in place, but also on what could be an alternate system which better meets the desired objective of reducing environmental burden with bringing metal to market. It begins with the perceived future need, rather than extrapolating current operations (Porter et al., 2004). The positive aspect of backcasting is the assumption that the future can be designed through our action, while its weakness is that it may overstate the ability and will of actors to achieve these results (Berkhout et al., 2002).

In what situations is the use of backcasting most favoured? Dreborg (1996) gives a list of five points for decision contexts where backcasting is most useful. These are that:

- the problem is complex
- there is a need for major change
- dominant trends are part of the problem
- externalities are important
- the time horizon is long enough to allow for deliberate choice.

Each of these characteristics fits with the nature of strategic decision contexts to be explored in the minerals and metals value chain, giving an indication that backcasting is likely to be a useful approach. The minerals and metals value chain is complex, the dominant trends incline the system to being unsustainable and hence major change is needed. The industry has traditionally considered the sections of the value chain beyond mining or refining as externalities, but in fact, the entire value chain must be considered when looking to a sustainable alternate future. To do this in a strategic sense explicitly engages with a time horizon long enough to allow deliberate choice in the design of this future. All these elements were identified in Chapter 2. However, due to the lack of constraints on future states, proposed futures may involve radical system change which in itself can be problematic. For the minerals and metals industry, we must be ambitious enough to conceive of a future discontinuous from the status quo, while acknowledging that the existing lifespan of technological infrastructure in place and the industry's inertia, will constrain change in the mid-term. Using an engineering design analogy, the problem is one of 'retrofit', and as proposed by Westerberg (2004) requires further investigation by the research community.

Robinson (1988) also highlights a design analogy, labelling backcasting[2] as design oriented, stating fundamental assumptions explicitly and using them to guide analysis. This contrasts forecasting where assumptions forming part of the predictive model may fall under the black box of the 'model' and not be examined as closely as the outputs of the model, being the forecasts themselves. Furthermore, backcasting does not make claims as to the likelihood of particular futures to be realised as this will depend on the uptake of the recommendations. This is not a disadvantage, as the objective with backcasting is to actively design the future rather than passively reflect on the consequences of a forecast.

The steps involved in backcasting are to specify future goals and objectives within the context of the future operating environment in order to formulate a range of futures (also called scenarios, see Helmer (1983) and Robinson (1988)). The next step is to identify what changes to the current system need to be made to realise this future. In acknowledging that change will be often made incrementally, a practical question to ask of incremental changes, is 'Is this planned change a platform for the next change? (Holmberg and Robèrt, 2000). Backcasting itself is not a fixed method and is open to significant variation in its implementation. The future scenarios may be qualitative or quantitative, concerned with single or multiple issues. Some authors see a role for experts in proposing the future in a more structured way (Helmer, 1983) while others do not seek to formalise the creative process of imagining more preferred future scenarios, as 'getting

[2] The technique commonly referred to as backcasting may also be called 'normative forecasting' – for example see Helmer, 1983. In this case 'forecasting' as described in this thesis in Section 5.1.1 would be termed 'factual forecasting' to differentiate it from 'normative forecasting'. I have chosen to use the terms 'forecasting' and 'backcasting' in this work.

ideas' is a non-logical process (Dreborg, 1996). In summary, backcasting is useful for addressing the question of 'where to we want to go' however, the variability inherent in backcasting approaches will require a specific approach for designing sustainable metal cycles.

5.1.4 *Specific requirements for strategic planning in minerals and metals*

This section considers the unique nature of the minerals and metals value chain and how this shapes the specific approach to backcasting which will be used in this work to envision a future system state. Beyond backcasting an alternate future, one must then consider how this future could be realised. This necessitates that the **actors** can change the **system variables** to realise the alternate **system state** which itself has environmental less **impact** than the status quo. This highlights the importance of understanding the relationship between the constraints resulting from particular actors only being able to control certain decision variables (as discussed in Chapter 4).

Drawing upon previous discussions in Chapter 2 regarding the broad question of sustainability and the minerals industry, the factors which are particularly significant in defining the minerals and metals value chain are:

- large existing infrastructure and high capital costs for new infrastructure
- large inertia to change due to infrastructure and industry culture
- complex recycle patterns and residence times of materials in value chain
- long lead times to new process development
- actors not used to seeking performance improvements for the overall material value chain (limited collaboration between actors).

Each of these points and their implications for the proposed backcasting methodology will now be explained. The industry's inertia to change and the large existing infrastructure with high capital costs for new infrastructure are two factors which are linked. Due to the high capital costs of new infrastructure, economic factors favour risk-averse technology decisions in mining (Peterson et al., 2001). The industry culture of resistance to change which is encouraged by specific examples of huge cost overruns in the implementation of new technology (for example, processing nickel laterite deposits at Murrin Murrin in Western Australia (see Treadgold, 1999). These characteristics typify the operating environment for minerals and metal and serve to limit the ambitiousness of system change often contemplated within the materials value chain. What this means, is that although backcasting can be used to envision a future state discontinuous from the status quo, one must acknowledge the presence of a large enduring infrastructure in the mining industry when backcasting. This suggests a usefulness in first exploring how much improvement could be made by optimising the use of existing infrastructure and then looking with greater vision, to consider improvements arising from more substantial system changes through the introduction of new technology infrastructure.[3]

Metals may have vastly different residence times in use, from months to many decades. The residence time distribution for metals in use also changes as the applications for which the metal is used evolves. While these factors will not influence the configuration of an alternate future, they will affect the dynamics of moving along the path to an alternate future. For example, the quality and availability of scrap will be time dependent. The ability to monitor such influences must be incorporated into the exploration of paths toward future states, which is further discussed in Section 5.5.

Additionally, lead times to develop new technologies in the minerals industry can exceed ten years (Intec, 2003). This means an analysis is required to study the matching through time of technologies with the ability to process the available resource mix which itself is changing as virgin resources move to lower ore grades and secondary resource streams change composition. Consequently, tools are needed to assess the *feasibility*, being the match of resources and technology, of paths toward backcast future system states and to see how external influences beyond the control of actors will affect their implementation of a preferred future.

The final point, is that the minerals industry sits at the beginning of a complex interconnected materials value chain and is currently not used to engaging with the entire materials value chain to better its overall performance. However, it was established in Chapter 2 that a holistic approach is necessary for advancing a more sustainable future. Using the link between actors-variables-system-impact, the contribution of individual actors to improving performance can be compared with which actors would be required to collaborate to bring about greater system improvement. Each minerals industry consideration which has been discussed in this section, will be incorporated into the specific backcasting approach developed for the minerals and metals value chain in Section 5.1.5.

---

[3] Note that consistent with the aims of this thesis 'substantial system changes' does not consider the services currently being provided by metal in society being replaced with another system (e.g. plastic) nor the demand for metal products to be eliminated. A continuing demand for metal is assumed and the aim is to provide this to market with less environmental burden.

5.1.5 *Conceptual approach to alternate futures*

Given the understanding of the needs of future planning across the materials value chain, the task is to develop a method to backcast an alternate system state beyond the status quo as an end-goal to strive for and then consider tools to assess performance of this end-state and make system changes to improve overall performance.

Section 5.1 established that for planning a more sustainable minerals and metals value chain, forecasting 'where are we headed' is not an appropriate starting point. Forecasts are unreliable in the long term and hence cannot act as a constraint on the long term future. Rather, we seek to design a preferred future and hence better understand the desirability of actions we can take, either as a single actor or collectively. Hence, the question to tackle first, is 'where do we want to go'. The conceptual approach of backcasting can be successfully used to generate and assess a preferred future which is not constrained by the present in order to answer the question of 'where do we want to go'. These conclusions are general to long term environmental decision making. However, when considering the specific case of the minerals and metals value chain, it is apparent that practical constraints do exist which can limit the question of 'where we can get to'. A radical change to system functionality is not being proposed – the aim is still to deliver metals to market for useful purposes in society, just in a more sustainable manner. Additionally, the large infrastructure in place supporting the minerals industry and its conservative nature to adopting new technology, means that even its future in several decades will be characterised as a retrofit rather than complete system redesign. Consequently the variables which actors can change and the scale at which they exert influence become important determinants in achievable futures. Furthermore, existing system dynamics do need to be studied subsequent to the question of 'where do we want to go' in order to address the question of 'where are things headed'. This needs to be tackled with forecasting, despite its unreliability, to show what influence external trends may have on actors seeking to implement a more sustainable future.

The elements of a more sustainable metal cycle were discussed in Chapter 2 and include the need to aim for a closed loop system with increased recycling, links to clean energy and reduced environmental impact of system operation.

An alternate system state must be envisioned and then the path through time to this alternate state can be explored. Using the actor-system variable-system-impact link, a two pronged approach is proposed to develop a set of alternate futures. First, the impact end of the actor-variable-system-impact link is targeted. This looks to backcast an alternate future for the entire system (measured by improvement in one or more environmental performance indicators) and resulting from changing all influential decision variables. This is informed by the sensitivity analysis of variables which would require changing to bring about this reduced impact, irrespective of whether actors are in a position to easily effect the changes in variables themselves – collaboration may be required. Secondly, the focus moves to the actor end of the actor-variable-system-impact link. This considers the influence of a particular actor (or actors), the variables they can control within their domain of influence and the change in system impact that this achieves. Following a comparison of alternate futures at a set potion in time and the impact profile achieved, an analysis of the influence of external variables beyond the control of actors is included. This may include factors such as declining resource quality and forecast changes to demand. Finally, the average impact of paths toward the future are assessed, also including the time-dependent nature of actor decisions and possible collaborations. By noting the required changes compared with the status quo, including changes to infrastructure and future collaborations, a preferred future trajectory can be chosen. This process is outlined in Figure 5-1.

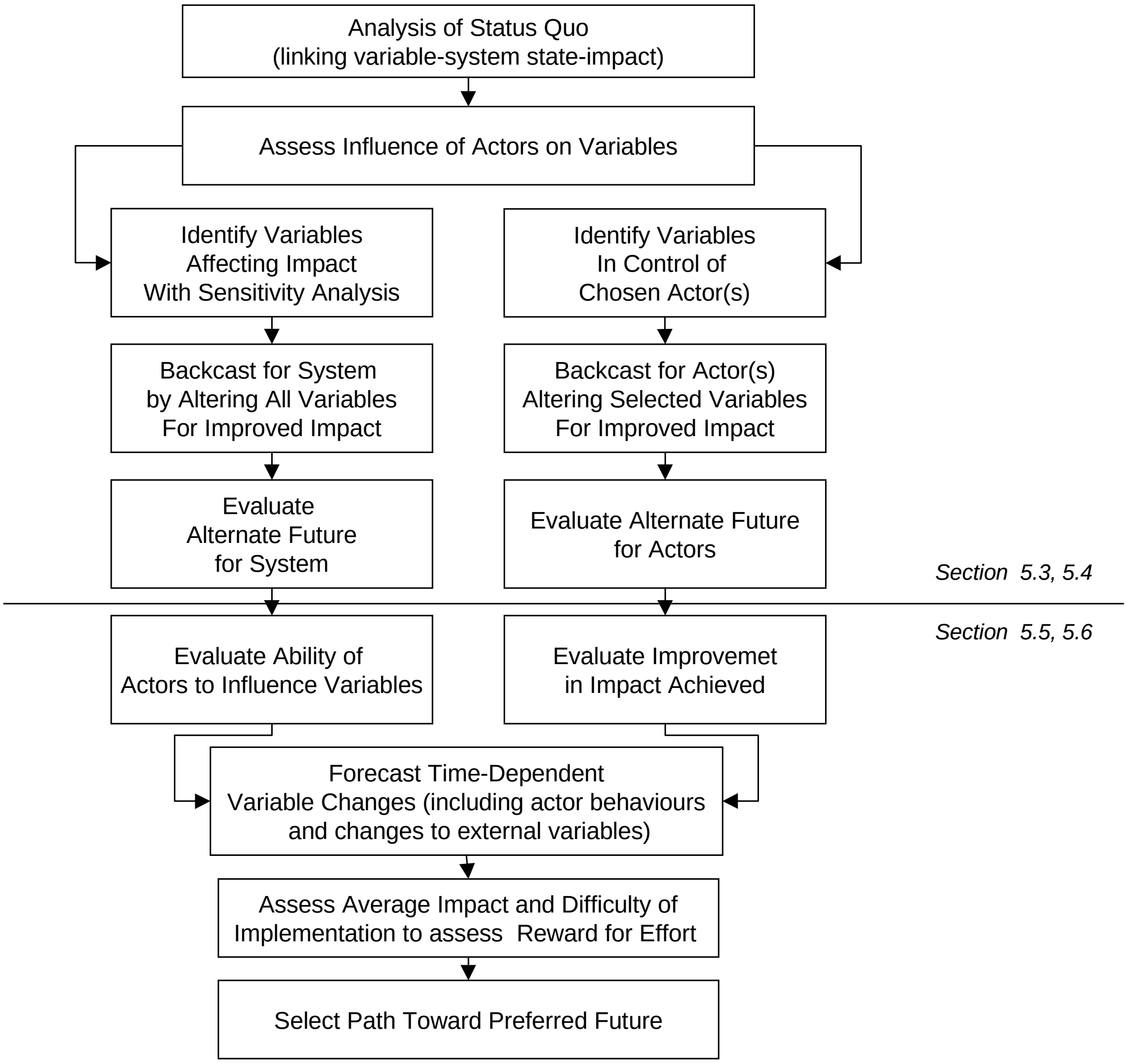


Figure 5-1: Development of concepts in Chapter 5

5.2 GENERATING PREFERRED FUTURE STATES

Having proposed a method to guide the investigation of alternate system states in the previous section, this section will consider step-by-step what information requirements and approaches are required to generate alternate system states from the status quo analysis completed in Chapter 4, and thus proceed with environmental decision making for a preferred future.

5.2.1 *Status quo analysis: actor influence, sensitivity, impact*

The development undertaken in Chapter 4 provides the tools to assess the current performance of the industry at a range of scales. The characterisation of the status quo across scales allows problem structuring for a preferred future by highlighting which impacts are important and who can control them.

The key outcomes from the status quo analysis that link to considering the future of the materials chain are determining:

- the magnitude and location of impacts,
  - including the value chain stages giving rise to the impacts (for example, the impacts from mining, the impacts from refining).
- the system variables to which environmental impact is sensitive,
  - at different scales
  - the actors which control these system variables.

This now means that for any given scale in the reference schema, key actors, system variables and impacts can be identified. Consequently, when approaching the task of envisioning an alternate future, one can do so with a clear understanding of the relationship between actor-variable and impact at the scale of interest. In essence this represents the problem structuring phase of decision making. This will form the basis of understanding which futures are achievable by which actors alone and working collaboratively. Additionally, one understands the relationship between important sensitivities at the scale of interest, with those at adjacent scales. This information alone, represents a significant improvement in the ability of the minerals industry to understand its influence and impacts across spacial scales. However, it becomes even more effective when linked to an analysis of desirable futures.

5.2.2 *Backcasting a sustainable future*

The overall aim is to envision a more sustainable future for the minerals and metals value chain. As noted earlier, backcasting is a creative process (Dreborg, 1996) which implies a requirement background knowledge and experience, in order to deliver meaningful insights. For this reason, a multi-disciplinary approach is useful in backcasting an alternate future in order to capture differing perspectives and experience from different disciplines. Where this is not practicable, the problem structuring approach developed in Chapter 4 provides a comprehensive basis for backcasting to be undertaken.

Additional to the required background understanding of the minerals and metals value chain is an appreciation of desired sustainability objectives. These have been described in Chapter 2 and environmental performance measures were selected in Chapter 4. It is very important that the underlying values inherent in the choice of performance indicators is recognised (Dreborg, 1996) whether they are economic, social or environmental.

The result of the backcasting is a future configuration (or configurations) of the minerals and metals value chain, with new technologies and new system flows through each component of the value chain. The environmental performance of these configurations can then be established, and a path chosen toward a preferred future. [4] The issues of at what scale backcasting should occur, the relationship to variables and the nature of their change is discussed in the following sections.

5.2.3 *Scale, constraints and variables*

At what scale should backcasting occur? Backcasting requires changes in system variables to achieve a new future system configuration. The system variables must be controllable or potentially controllable by actors involved in bringing metal to market. Thus the scale for backcasting occurs at the scale at which the collective actors in the decision problem can exert current or potential future influence.

The variable changes occur within certain constraints. External variables are initially considered as constant when backcasting an alternate future state, as the actors do not

---

[4] At this point it is helpful to draw distinction between backcasting and the related approach of 'scenario analysis'. Scenario analysis conjures an image of prevailing future geo-political circumstances and then determines how the problem of interest is placed or would react under the prevailing scenario (Berkhout et al., 2002). For examples of the range of futures scenarios projected in studies related to the copper industry see Schwartz and Webber, 1999; The Warren Centre, 2004.

have direct or potential control over these variables. The implications of this assumption are explored later (in Section 5.5) when assessing the dynamic transition to alternate future states. Here, the implications of forecast changes to external variables are included in the analysis to determine their effect on environmental performance and the ability of actors to implement preferred futures. This is illustrated by the example in Table 5-1.

Table 5-1: Current and future value of variables in backcast future

Sensitivity	Value of Variable (Status Quo)	Highest Level of Control	Value of Variable (Backcast Future-Actor Focus)	Value of Variable (Backcast Future-Collaborative)
Highest	$\text{Variable}_{\text{a-current value}}$	A	$\text{Variable}_{\text{a-future value}}$	$\text{Variable}_{\text{a-future value}}$
Next highest	$\text{Variable}_{\text{b-current value}}$	P	$\text{Variable}_{\text{b-current value}}$	$\text{Variable}_{\text{b-future value}}$
Next highest	$\text{Variable}_{\text{c-current value}}$	E	$\text{Variable}_{\text{c-current value}}$	$\text{Variable}_{\text{c-current value}}$
Next highest	$\text{Variable}_{\text{d-current value}}$	P	$\text{Variable}_{\text{d-current value}}$	$\text{Variable}_{\text{d-future value}}$
.....	.....	.....	....	....

In relation to Table 5-1, the following points must be explained. It lists the sensitive variables for the particular scale of analysis as identified in Chapter 4. The value of the variables in the second column is their current value from the status quo analysis. The third column reflects the 'highest level of control' from actors included in the analysis. Each variable is classified as either: directly controllable by the actor in question (**A**); partially / potentially **(P)** controllable by the actor (for example, controlled by another actor with whom the actor in question could co-operate in future from the list of those considered); externally controlled (**E**) beyond the potential influence of the actor. Consequently, the rating from greatest to least control is A>P>E. The next two columns reflect the value of each variable for two backcast futures, one with an actor focus and one representing a future driven by collaboration between all actors. The difference is that for the actor-driven future, only variables under the direct control of chosen actors are changed (in Table 5-1 this would be $\text{Variable}_{\text{a}}$). In the collaborative future, all actors work together to change actor controlled variables and those which are potentially or partially actor controlled (in Table 5-1 this would be $\text{Variable}_{\text{a}}$, $\text{Variable}_{\text{b}}$, $\text{Variable}_{\text{d}}$). In both cases, the externally controlled variable does not change its value in the projected future.

With respect to future changes in system variables, we must consider both the type of the change and the extent of the change.

There are two principal types of changes:

- changes to nodes within the value chain,
  - additional nodes or fewer nodes
  - nodes with new properties
- changes to flows within the value chain,
  - magnitude of flows
  - splits of flows between nodes.

Further exploring the types of changes possible and the degree to which these variables could be changed is explored in the next sections.

5.2.4 *New infrastructure nodes*

In a more sustainable future, one envisions both new technology infrastructure (with existing functionality that is used to service increased demand) and new infrastructure which has improved functionality and performance. Understanding the potential for improved functionality of technologies allows a more realistic picture of the future to be depicted. However, it is wise to remember that what different people consider feasible is guided by their beliefs and imagination. Porter et al. (2004) cite the examples that while birth control and space travel were predicted well before becoming available, wireless voice communication wasn't imagined even shortly before becoming reality. Information regarding sector-specific technology developments can be used to guide this process. General trends to consider include the following:

- greater recoveries
- reduced energy demands
- reduced emissions
- multi product recoveries (e.g. precious metals)
- decisions by actors guided by environmental performance.

For the case of copper Young (1999) also proposes consideration of a future with greater use of *in situ* leaching (possibly through biotechnology) and no open pits; nobody working underground; no waste dumps; smaller processing facilities. The approach to considering future technology improvements can also consider today's best practice being more widely implemented or potential improvements, based on current distance from thermodynamic limits providing an indication of how far from ideal current practice is.

The important task is to provide a way to describe the performance of future value chain nodes, so that their inclusion in the value chain can be evaluated alongside existing infrastructure. It is important that an equivalent level of information detail is used to describe new and existing technology so that the comparison is not biased. Including too much information can prejudice the result just as much as including too little information. Hence, the technology modelling approach outlined in Chapter 4 should be used to also describe future technologies.

5.2.5 *New splits between infrastructure flows*

A reconfiguration of flows in the future value chain is also possible, both with respect to the magnitude of flows and with respect to the split of flows between technology nodes. From a backcasting perspective, this does not require any additional environmental characterisation information, the magnitude and split of flows through the nodes themselves will determine the overall performance of the value chain. The only requirement is to set the final splits between technologies. The splits which can be altered will differ for the actor-driven and collaborative futures. Only splits controlled by the actor in question can be changed in the actor-driven future while in the collaborative future all splits between technologies can be changed. The final value chosen for the future will be informed by consideration of mass balance constraints within the system and reasonable future values.

5.3 COMPARISON OF FUTURE STATES

The next stage in the process of environmental decision making is the problem analysis or evaluation of the alternatives. Assessing the performance of the end-state is the first part of this process which is described in this section. Subsequent analysis considers the performance of the transition path through time from status quo to alternate future.

5.3.1 *Evaluating actor-driven versus collaborative futures*

The range of alternatives has been structured deliberately around the comparison between an actor driven future and a collaborative future. The motivation for this approach is to clearly illustrate the difference between the improvement possible when actors choose to only exert action within their existing domain of influence and compare this with the improvement possible through wider collaboration. If a large improvement can result from a straightforward collaboration between two actors, then this analysis can be used to make the case for change. If not, then the actor can be confident that the improvement potential under their control represents a significant component of overall potential improvement and is justified in acting alone.

It is possible to generate more than two future states for evaluation. For example, in addition to the collaborative future, and a single actor-led future, different actor-led futures could be backcast. These additional futures could be from the perspective of the same actor taking a different set of actions. Alternatively, they could be from the perspective of a second actor, whose backcast future could then be compared both with the collaborative future and with that implementable by the first actor.

The comparison of the performance of the backcast future configurations, then serves as a screening exercise to select which future states to extend further consideration in the dynamic analysis through time. Of the alternatives proposed, the highest performing (two or three is a useful guide) configurations are retained for further analysis.

Additional to the environmental performance of the alternate futures, consideration at this point in the decision making process must be given to two other factors: the degree of change from the status quo with respect to alternative infrastructure and the required partnerships to realise the alternate future. These considerations will later be used to determine which courses of action are worthwhile for actors to pursue, however a final decision cannot be made prior to consideration of a dynamic transition path between status quo and alternate future.

5.3.2 *Need for dynamic analysis: system complexity*

It is the assertion in this work that is there significant additional insight to be derived from a dynamic analysis of the path toward a preferred future. The need for a dynamic analysis derives from the fact that it is not only the environmental performance of the final configuration of the backcast future, but also of the path toward this future which affects the cumulative performance of the value chain over the course of the projected time horizon of 50 years. Could it be that a single actor immediately implementing a simple improvement to the value chain, returns greater benefit over the time horizon considered than waiting for the implementation of a greater improvement either through increased collaboration or the advent of an innovative technology? This is the possibility illustrated in Figure 5-2 where the cumulative benefit is depicted by the area under the curve.

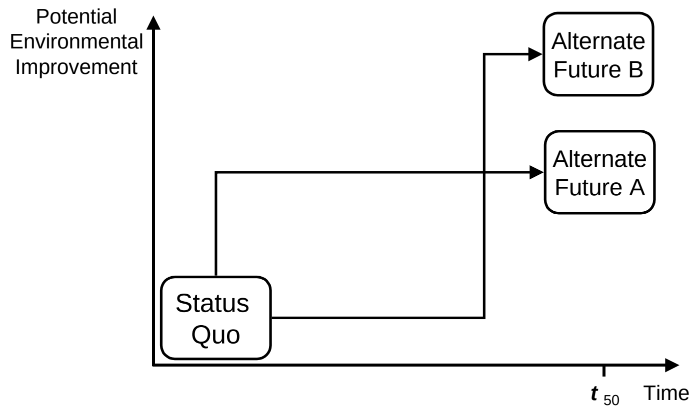


Figure 5-2: Importance of path toward alternate futures in overall impact

Importantly the discussion illustrates the need to link the timing of actions by actors with their impact on system performance. This will allow more informed decision making to take place. Furthermore, the influence through time of forecast changes in external variables must be understood and this can only occur with a dynamic analysis. The complexity of the dynamic cycles present in the minerals and metals value chain is vast – from cyclical demand cycles of several years to ore grade declines over hundreds of years and impacts manifested immediately or delayed. The focus for this thesis is to capture they dynamics of changes to infrastructure and flow patterns over the next fifty years.

5.4 DYNAMIC PATH TOWARD PREFERRED FUTURES

The exploration of paths toward alternate future states considers the time dependency of system components and behavioural components for actors. The system components refer to influences on the system configuration driven by external factors (e.g. demand, residence times of products in use, resource availability). The behavioural components refer to the decisions taken by actors (e.g. choice of infrastructure and distribution of flows) and what guides these decisions.

5.4.1 *Dynamic value chain models*

This section reviews the way in which dynamic models have been used in modelling material flows to develop a generalised approach to dynamic modelling which can be coupled to the status quo analysis and be applicable across scales.

Dynamic models are increasingly being used to model material flows (see (McLaren et al., 2000; Zeltner et al., 1999)) and product flows (Binder et al., 2001; Kandelaars, 1999) thorough the value chain. Firstly, what constitutes a dynamic model? As defined by McLaren et al. (2000), a dynamic model differs from snapshot and static models in that values of variables are dependent not only on inputs (as for static model) but will depend on inputs and the time at which the inputs occur. In addition, the functional relationships between variables within the models themselves also change, depending on the system configuration and variable values at a point in time. In its simplest form

$$f'(t)=f(t,x_n)$$

where the value of the function at time t is dependent on both time and the value of the decision variables x_n (whose relationship to influencing the value of the function may also change with time). The relevant situations in which dynamic models have been used in the literature are now reviewed.

The work of Zeltner et al. (1999) considers material flows through the value chain in the USA. It models the quantity of material flows through each node in the value chain and calibrates system variables against historical data. The modelling is undertaken using MATLAB software. Future scenarios consider the magnitude of material flows with different values for key parameters. There is no consideration of environmental performance, nor on the ability of actors to control the key parameters which are being changed.

Similar work is undertaken by Ayres et al. (2001) who extends the USA model globally. Other works modelling future resource flows include van Vuuren et al. (1999) who use a system dynamics model which considers future metal usage under three different 'worldview' scenarios, Hierarcist, Egalitarian, Individualistic and also Legarth (1996) who explores alternate demand and recycling scenarios and resource depletion and use. Collectively, the usefulness of these works is in their approach to modelling material flows. However, the approach lacks consideration of actor-controlled and external variables which is required for understanding the performance of paths toward preferred futures. Furthermore, beyond the approach itself, in the detail of performance indicators used and system variables included, the aforementioned studies do not include consideration of environmental performance, nor the quality of material cycling through the value chain. Understanding both the quantity and quality of material is important, as the same flow of material through in identical technology will have a greater environmental burden associated with its processing if it is of a lower quality.

The work of McLaren has its main focus on contrasting the conceptual differences between, static and dynamic models for modelling material flows using the STELLA modelling environment. The illustrative case study for the iron and steel sector demonstrates the potential to couple material flows to environmental performance, with energy used as a first-pass indicator of environmental performance. Again, no distinction is made between actor-controlled and external variables.

Moving from the dynamic modelling of materials to now consider product flows, Kandelaars, (1999) constructs a dynamic model for the demand for different types of window frames in the STELLA modelling environment. Both economic and environmental performance is measured. Scenarios considering the effects of levies on the resultant product flows are explored. The imposition of levies begins to address the question of modelling the results of actor controlled and external variables, but is not incorporated explicitly into the approach.

Based on the review of the literature, the representation of Zeltner (itself originally based on the work of Baccini and Bader, 1996) is used as the basis for representing the dynamic models in this work. It is consistent with a mass balance approach to modelling system flows, and can be extended to include the influence of actor decisions, as well as specific environmental performance associated with material flows of different qualities.

5.4.2 *Generic model formulation*

Using the same example as in Chapter 4 the following equations for mass flows through the value chain are given.

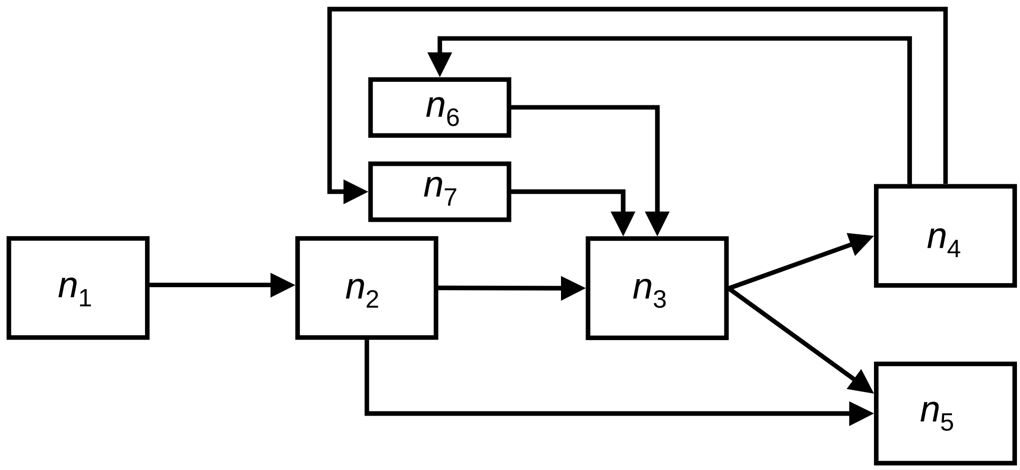


Figure 5-3: Example of value chain to illustrate dynamic model

This illustrative model has:

- three stocks: $n_1(t)$ primary resources, $n_5(t)$ dissipated resources and $n_4(t)$ secondary resources – both high grade and low grade[5]
- four process: $n_2(t)$ primary processing, $n_6(t)$ high grade secondary scrap processing, $n_7(t)$ low grade secondary scrap processing and $n_3(t)$ manufacture and use of goods
- nine flows: $m_{12}(t)$, $m_{23}(t)$, $m_{25}(t)$, $m_{34}(t)$, $m_{35}(t)$, $m_{46}(t)$, $m_{47}(t)$, $m_{63}(t)$, $m_{73}(t)$.

Mass balance equations are as follows:

$$F_1 = \dot{n}_1(t) + m_{12}(t) = 0$$ Equation 5-1

$$F_2 = \dot{n}_2(t) + m_{23}(t) + m_{25}(t) - m_{12}(t) = 0$$ Equation 5-2

$$F_3 = \dot{n}_3(t) + m_{34}(t) + m_{35}(t) - m_{23}(t) - m_{63}(t) - m_{73}(t) = 0$$ Equation 5-3

$$F_4 = \dot{n}_4(t) + m_{46}(t) - m_{34}(t) = 0$$ Equation 5-4

$$F_5 = \dot{n}_5(t) - m_{25}(t) - m_{35}(t) = 0$$ Equation 5-5

$$F_6 = \dot{n}_6(t) + m_{63}(t) - m_{46}(t) = 0$$ Equation 5-6

$$F_7 = \dot{n}_7(t) + m_{73}(t) - m_{47}(t) = 0$$ Equation 5-7

[5] Node n_4 in fact comprises two separate stocks, one for high grade scrap and one for low grade scrap, with a 50:50 split coming in from use, but it has been represented as a single unit for the illustrative example.

Demand

$$F_8 = m_{23}(t) + m_{63}(t) + m_{73}(t) - D(t) = 0$$ Equation 5-8

Null Stocks (processes)

$$F_9 = \dot{n}_2(t) = 0$$ Equation 5-9

$$F_{10} = \dot{n}_6(t) = 0$$ Equation 5-10

$$F_{11} = \dot{n}_7(t) = 0$$ Equation 5-11

Splits/Recoveries/Time Delay Parameters

$$F_{12} = [m_{34}(t) + m_{35}(t)] - [m_{63}(t - R_1(t)) + m_{23}(t - R_1(t))] = 0$$ Equation 5-12

$$F_{13} = \frac{m_{63}(t) + m_{73}(t)}{m_{63}(t) + m_{73}(t) + m_{23}(t)} - R_2(t) = 0$$ Equation 5-13

$$F_{14} = \frac{m_{23}(t)}{m_{25}(t) + m_{23}(t)} - R_3(t) = 0$$ Equation 5-14

$$F_{15} = \frac{m_{34}(t)}{m_{35}(t) + m_{34}(t)} - R_4(t) = 0$$ Equation 5-15

$$F_{16} = \frac{m_{46}(t)}{m_{46}(t) + m_{47}(t)} - R_5(t) = 0$$ Equation 5-16

The specification of the model is shown in Table 5-2 and Table 5-3.

Table 5-2: Illustrative model parameters

Parameter	Value	Comment
$R_1(t)$	5 years (low grade scrap) 10 years (high grade scrap)	Lifetimes of goods in use. Modelled that goods entering are all tied up until end of useful life, then all proceed to scrap (not modelled with distribution). Actual lifetimes of copper in use can be 30–50+ years for some products.
$R_2(t)$	30%	Fraction of demand met by secondary scrap
$R_3(t)$	85%	Recovery to product from primary[6]
$R_4(t)$	99%	Goods that proceed to scrap (i.e. only 1% are dissipated and unrecoverable)
$R_5(t)$	60%	Fraction of secondary processing that is high grade
$D(t)$	1,000,000 + 0.006D(*t*–1)	Annual growth of 0.6% per year from a base demand of 1,000,000 tonnes (illustrative only) This total demand goes to manufacturing high grade goods and low grade goods in equal quantities for this illustrative example

[6] A similar recovery would be included for secondary processing, but has been omitted to simplify the illustrative example.

Table 5-3: Illustrative initial stocks for model

Initial Stock	Value (t)	Comment
$n_1(0)$	10 000 000	Stock of primary copper (copper content)
$n_3(0)$	0	Stock in use (taken as zero to more clearly illustrate model behaviour)
$n_4(0)$	1 000 000 (high grade scrap) 1 000 000 (low grade scrap)	Stock of secondary scrap
$n_5(0)$	0	Stock of dissipated copper (unrecoverable)

Initial stocks must be specified $n_1(0)$, $n_3(0)$ $n_4(0)$ and $n_5(0)$ and then the functions for the demand $D(t)$ and recoveries $R_n(t)$. The form of the functions for the demand and splits/recoveries determines the nature of the model.

The functions may be constant, functions of time and/or functions of system configuration and actor behaviour. For the illustrative example, only demand is a function of time, while the other parameters are constant through time.[7] When using the model to represent a transition between the current and a defined future state, the parameter functions should be specified such that the initial and final states are reflected in the model.

Section 5.4.3 details the model output for the illustrative example. Further discussion on appropriate functions for actor-controlled and external system variables in transitions between current and future material chain configurations are then discussed in sections 5.4.4 and 5.4.5 in relation to their spatial scale within the reference schema.

5.4.3 *Illustrative example of mass flows through material chain*

Using the example outlined in Section 5.4.2, this section illustrates the operation of the model. The mass flows are shown for the important stocks and processes within the model in Figure 5-4. The model illustrates the transition from the status quo to a future with a small annual increase in demand.[8]

[7] With this configuration, the model is more accurately described as time-dependent steady state, rather than dynamic. A dynamic model would have, for example, the recycling rate dependent on the quality and quantity of secondary resources compared to primary resources.

[8] The increase in demand is included to illustrate model behaviour through time, however, the illustrative example does not yet include changes to actor-controlled variables as would be the case in exploring the transition between current and preferred future material chian configuration. Actor-controlled changes to system variables are discussed in Section 5.4.4. Non-linear increases to demand are also possible.

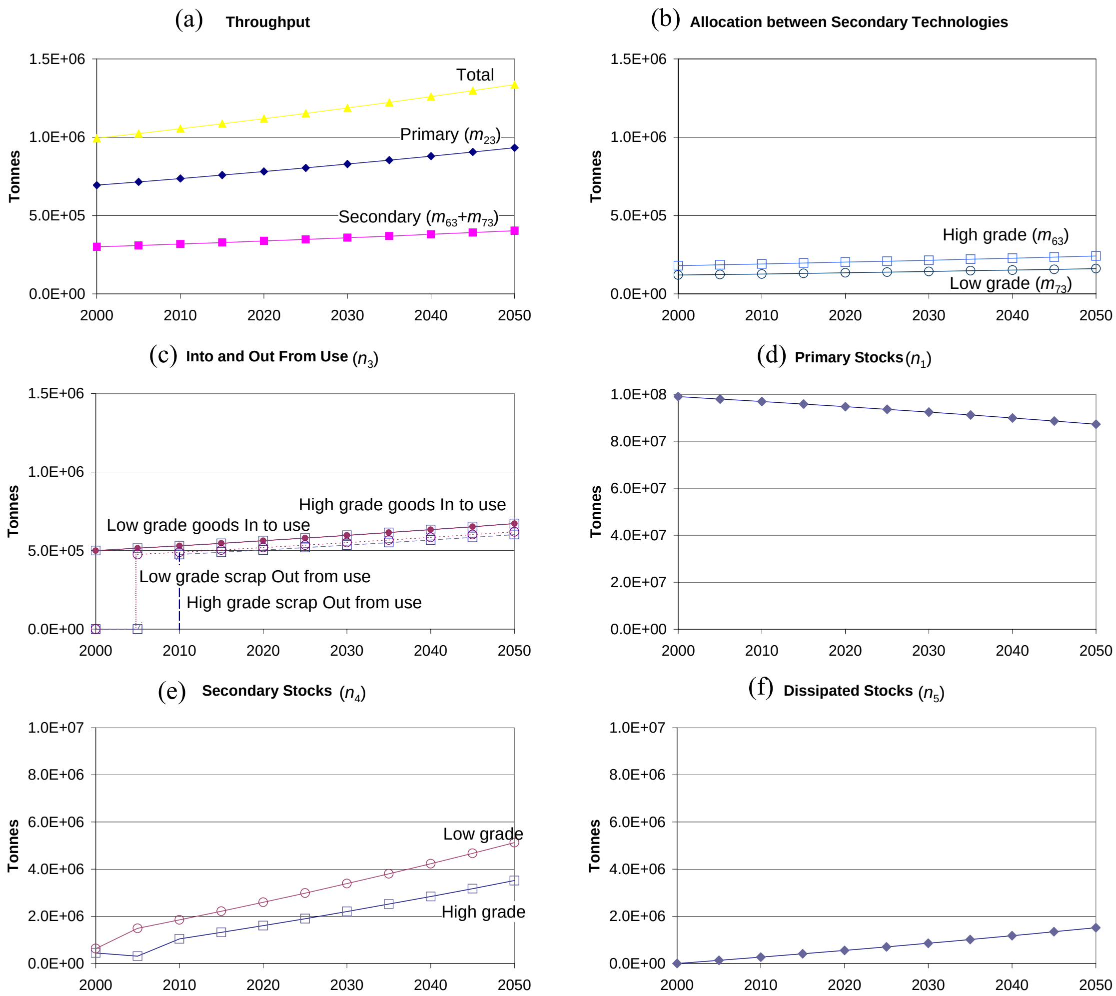


Figure 5-4: Principal mass flows for illustrative model

Figure 5-4(a) shows the relative amount of total demand which is met by processing primary and secondary resources. The percentage of demand met by processing secondary resources is constant as specified by $R_2(t)$ at 30%. In a more comprehensive dynamic model, this could be modelled with a range of relations, for example:

- the rate could be changed as a function of time to reflect actor choices by either incremental or step-changes to the recycling rate, consistent with the transition to a preferred future material chain configuration that has increased recycling
- the rate could be a function of available primary and secondary resource quality and quantity which would change in time, subject to declining ore grades and reserves and the types and lifetimes of products in which the metal was used

- ♦ the rate could be a function of the environmental performance of material chain, such that changes to increase the recycling rate occur in response exceeding regulatory thresholds

Figure 5-4(b) shows the amounts of secondary metal produced, with respect to the quality of secondary scrap used as a feed: either high grade or low grade. Both increase with increasing demand. Again, this parameter is fixed for the illustrative example, but could be modelled as a more complex function of available scrap and/or available processing infrastructure.

Flows associated with the manufacture and use node n_3 are shown in Figure 5-4(c). The total initial demand of 1,000,000 tonnes is manufactured into high grade goods and low grade goods in even quantities (500,000 tonnes each). These values increase in time with demand and are represented by the solid lines in the graph. The dotted lines show the outflow from the use phase. Outflow of low grade scrap only occurs after its lifetime in use of 5 years (e.g. such as in electronic goods, mobile telephones), while outflow of high grade scrap occurs only after 10 years (e.g. wires, pipes – note, actual lifetimes of high grade scrap can be up to 30–50 or more years). The result of the delayed outflow is a decrease in the initial stocks of secondary goods for high grade scrap, until supplemented by the outflow after 10 years as shown in Figure 5-4(d). In practice, the economy has an existing stock of goods in use, which the illustrative model can be adapted to reflect.

Figure 5-4(e) and Figure 5-4(f) show decreasing primary stocks and increasing dissipative stocks respectively. For the illustrative example, it is assumed that no new primary stocks are discovered through the 50 year time horizon, however the model can easily be adapted to incorporate this consideration.

This section gave an overview of the operation of the generic dynamic material flow model. Additional nodes and flow streams can be added according to the decision problem. The mass flows were presented here and the environmental performance associated with these mass flows through the material chain configuration is presented in Section 5.5.1.

5.4.4 *Models for actor-controlled variables and behaviour*

In the generic representation of a dynamic value chain, the split variables R_n may be actor-controlled or externally-controlled. For those which are actor controlled, an approach is required to clearly represent the decisions and choices of actors through time. The aim of the dynamic model overall is not to predict actor behaviour, but to show the consequences of different decisions and behaviours on the environmental performance of the system.

There are two main cases to be considered for actor-controlled variables: pre-determined changes to actor-controlled variables, and changes to actor-controlled variables where decisions made by actors are subject to feedback regarding the current state of the system as an input to deterring their future behaviour.

First, we consider the model for split variables when there is no feedback mechanism for actor-controlled decisions. In these cases, the value of the variable at each point in time for the transition between status quo and alternate future must be specified. The function could be for an evenly spaced transition through time, for example as shown in Equation 5–17.

$$R_n(t) = R_n(t_0) + \frac{t - t_0}{t_{final} - t_0}\left(R_n(t_{final}) - R_n(t_0)\right) \quad \text{where} \quad t_0 \le t \le t_{final} \qquad \text{Equation 5-17}$$

or another function of time, for example, based on step-wise transitions at specific points in time as shown in Equation 5–18

$$R_n(t) = \begin{cases} R_n(t_0) & \text{for } 0 \le t < t_{change\_a} \\ R_n(t_0) + a\left(R_n(t_{final}) - R_n(t_0)\right) & \text{for } t_{change\_a} \le t < t_{final} \\ R_n(t_{final}) & \text{for } t = t_{final} \end{cases} \qquad \text{Equation 5-18}$$
$$\text{and } 0 < a < 1$$

The function is selected to represent a potential actor behaviour pattern for which environmental performance is to be evaluated. It need not necessarily be the most probable actor behaviour, which may be to take no action. Rather, the aim is to provide actors with insight into the consequences of their actions as input to guiding their behaviour, including the timing of their actions and the rate at which they implement change. To do this, specific courses of action are explored to describe the nature of the transition between status quo and preferred future. This provides no guarantee that the chosen transition path is 'optimal' in the sense of representing the lowest environmental burden. However, charting performance of all possible combinations, is computationally intensive and wrongly shifts focus away from consequences of actions by actors to determining a hypothetical environmentally preferred behaviour pattern. This is an unhelpful approach for several additional reasons. Seeking a transition path with least environmental burden can lead to trivial results, such as 'implement all improvements immediately'. To avoid this case, 'plausible' constraints are placed on the system. For example, a maximum rate of change of system configuration within a given time period for a given actor. If these constraints are deemed plausible, an 'optimal' solution can be calculated. The risk with this approach is that the focus falls to the configuration of the optimal solution and the plausibility of the constraints – or indeed the use of proposing such constraints with respect to long term futures for which there is significant uncertainty and trade-offs – is overlooked.

A better approach is to agree to investigating plausible actor decisions, (rather than plausible constraints) and to maintain the focus on actors understanding the consequences of their actions, including trade-offs between environmental objectives associated with their choices. This information is more helpful in allowing actors to make better informed decisions. Furthermore, it is consistent with IChemE president Robin Batterham's approach which highlights that 'engineers should provide options rather than solutions' (Mackley, 2004). The proposed methodology allows a transparent approach for the evaluation of options.

Additionally, the methodology supports actor behaviour being modelled as responsive to the system configuration and performance. In this situation, actor decisions are modelled as conforming to a set of behavioural rules, rather than a specific pre-determined set of actions. The analysis becomes more complex, because a set of rules for performance must be developed, in effect a codification of 'behavioural constraints'. There will remain uncertainty in the long term future as to whether modelled behaviours will reflect true behaviours, but it allows the impacts of responsive behaviour to be modelled in a simulation exercise, the process of which itself can reveal useful insights. For example, if the environmental performance at time t is under a legislative limit, then actors could be modelled to continue to use existing infrastructure, otherwise when the legislative limit is exceeded, choices could be then made by actors to implement newer technology.

The degree of influence actors have over system variables within the value chain and the relationship they have with other actors will vary according to the scale of the decision problem within the reference schema. This is shown in Figure 5-5 and acts as a guide to the way actor behaviour is modelled across scales.

	MEGA: MORE THAN ONE MC	**MACRO**: ONE MC	**MICRO**: PART OF MC
GLOBAL	Multiple Actors • Actors have competeing objectives • Difficult to co-ordinate action across material chains	Multiple Actors • Actors have competing objectives • Few single actors have control over multiple material chain stages globally	Single or Multiple Actors • Technology vendors or multinationals may promote like-technologies throughout their operatiosn worldwide
REGIONAL *Continent* *Country* *State*	Multiple Actors • Collaborative along single material chain where large actor has key control • Less collaborative if material chain is poorly integrated • Competitive between material chains (e.g. copper competing with aluminium)	Multiple Actors • Collaboration required for co-ordinated action across the material chain • Single actor may control flows and infrastrucutre in a single region or for singe material chain stage	Single or Multiple Actors • Actors have greater direct influence, but only over limited stages of the material chain
LOCAL *City* *Plant* *Site Specific Plant*	Multiple Actors • Collaborative along single material chain • Competitive between material chains	Multiple Actors • May be collaboration within and between stages (in newly formed material chain while becoming established or eco-industrial park) • May be competition within and between stages (in extablished material chain)	Single (or Multiple Actors) • Single actor are common • Direct control over limited stages of material chain • External influences likely to be very important

Figure 5-5: Actor influence and inter-relationships at different scales

Two broad trends are identified from Figure 5-5. First, moving toward the global-mega scale (top left), many actors are present, which collectively have a large potential influence over the configuration of flows and infrastructure in the material chain. However, the potential to co-ordinate collective influence toward a common sustainability objective is limited – due to the complexity of the interactions between material chains and numerous actors across the globe. Modelling actor behaviour at these scales is difficult and an aggregated, top-down approach is most practicable. Second, moving toward the local-micro scale (bottom right) the number of actors is reduced. This facilitates modelling actor behaviour, but their domain of influence is limited to one or two stages in the material chain only which means the remaining variables must be modelled as external, which limits the analysis.

Several approaches to describing behavioural patterns both within and between organisations in a network drawn from fields as diverse as economics, ecology and psychology. The aim is not to summarise them here (see Bousquet and Le Page, 2004; Conti et al., 1995; Costanza et al., 2001 for helpful background), but rather to demonstrate the ability of the approach developed in this thesis to link with more detailed models of actor and system behaviour. This is demonstrated in the case study in Chapter 9.

5.4.5 *Models for external variables*

External variables are beyond actor control, but a better understanding of their behaviour contributes to the question of 'where are things going' (in relation to forces beyond control) and at the same time impacts on 'how will we get to where we want to go'. They can be modelled as dependent on time, or additionally on the behaviour of the system (as for actor behaviour) or as radical changes to new states through scenario analyses. The types of variables which are considered 'external' depends on the scale of analysis as shown in Figure 5-6 which can be used as a general guide.

	MEGA: MORE THAN ONE MC	**MACRO**: ONE MC	**MICRO**: PART OF MC
GLOBAL	• Requirements of new product trends and their influece on production and consumption	• Material substitution (e.g. copper for plastic in pipes or copper for aluminium in overhead electrical transmission wires)	• Demand and use patterns (e.g. linear, logistic, intensity of use hypothesis) • Resource quality • Technology (may be fixed)
REGIONAL *Continent* *Country* *State*	• Control over Imports and Exports will vary • Available resources within region	• Available quantity and quality of resources within region (primary and secondary) • Demand and use patterns may be dictated external to the region (which then go on to affect secondary resource quality and quantity)	• Demand and use patterns (which then go on to affect secondary resource availability and quality) • Resource quality • Technology (may be fixed)
LOCAL *City* *Plant* *Site Specific Plant*	• Demand external to region • Available primary and secondary resources within region	• All stages of the material chain may not exist in a local area • Demand external to region • Locally available resource quality	• Demand • Resource quality and availability • Technology quality and availability of infrastructure

Figure 5-6: External variables at different scales

Precisely modelling the behaviour of external variables is not the focus of this thesis. The principal aim in this work is to understand the consequences of actor-decisions in the transition from status quo to alternate future, in light of changes to external variables. Modelling changes to external variables and whether they act synergistically or antagonistically toward the transition from status quo to preferred future, places the relative influence of changes to actor-controlled variables in context.

The specific form of the functions which can be used to model specific external variables (for example, exponential decay, linear or logistic growth, scenario analysis) are discussed in the case study in Chapter 9. Similar to those used for forecasting can be applied, but with a focus on testing the results of actor decisions in an externally changing environment, rather than predicting futures.

5.4.6 *Implementation of dynamic modelling using visual basic*

A modelling platform is required to implement dynamic modelling. The programming environments of STELLA, MATLAB and Microsoft Excel are environments which have found use in the literature. The Visual Basic environmental in Microsoft Excel is chosen for the task in this thesis. The decision is based on the need to combine the static process models for individual technologies in the value chain from Chapter 4 (which were already created in Excel), with dynamic aspects associated with the performance of the value chain through time. The most accessible solution was to continue using Excel, but to incorporate dynamic capabilities through the use of the Visual Basic programming environment.

A description of the dynamic programming approach capability is as follows:

1. Specify number of time steps from status quo to alternate future
2. Detail initial assumptions of actor behaviour
3. Paste assumptions at time *t* into value chain model
4. Update value chain model a node at time *t*
5. Value chain model determines flows to process model j. calculate performance for node j
6. Update available stocks (inflow minus outflow)
7. Return to step 4 until all nodes have been updated and total system performance calculated for time *t*
8. Paste impacts and values of stocks and flows into summary sheet
9. Update assumptions of actor behaviour (for the case where they are modelled as dependent on system performance)
10. t=t+1, return to 3 up to max number of iterations
11. End

This conceptual approach is demonstrated for case studies in Chapter 9.

5.5 ASSESSING PERFORMANCE OF TRANSITION PATHS

Section 5.4 outlined the process for dynamically modelling material and energy flows through the transition from status quo to alternate future. This section addresses two key points:

- illustrating how to measure system performance for the transition between status quo and alternate future, including the use of an average performance score
- additional considerations for performance evaluation through time using multiple criteria.

5.5.1 *Illustrative example: environmental performance*

Figure 5-7 describes the environmental performance of the mass flows through the material chain for the illustrative example described in Section 5.4.3.

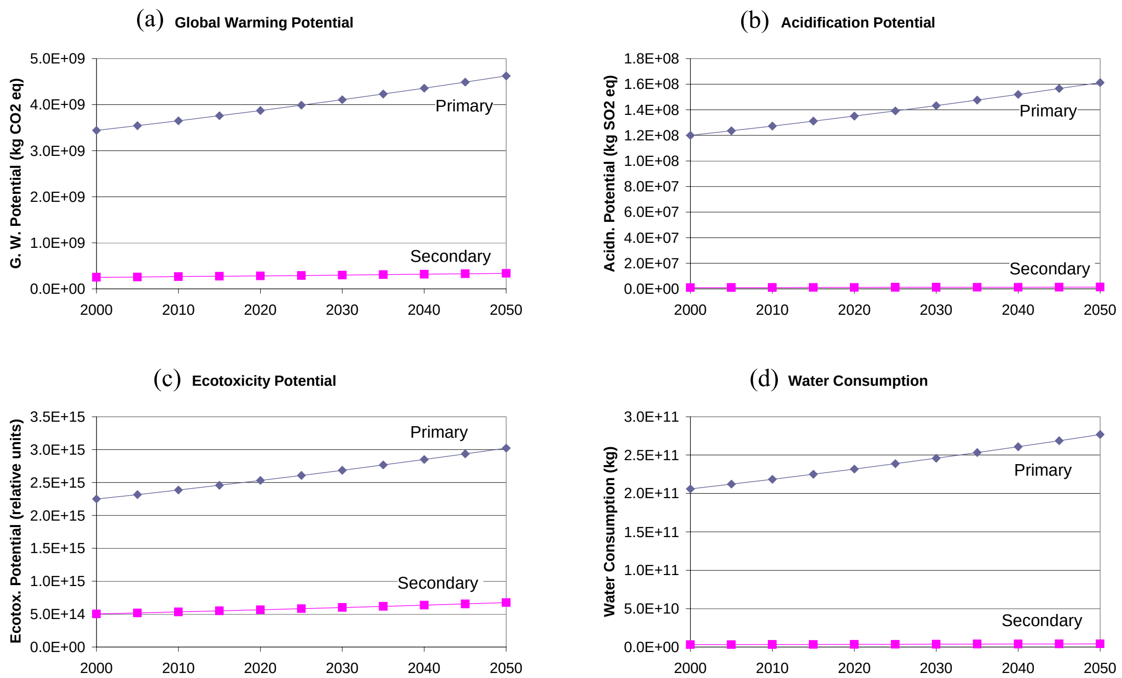


Figure 5-7: Illustrative example of environmental performance through time

A similar performance pattern through time is observed for each performance category as the relative configuration of the splits between technologies stays the same through time, only demand increases. A greater potential impact is attributed to primary processing for each category. With an actual transition from status quo to alternate future involving new technologies and new configurations of flows through the material chain, there may be trade-offs where improvement in one category comes at the expense of deterioration in another.

Consequently, there is a need within the generic methodology development to handle comparison between:

- differing transition paths toward alternate futures, and

- across multiple impact categories.

The first point of comparing multiple transition paths toward alternate futures (for a single impact category) is explored in Section 5.5.2 then issues associated with consideration of multiple impact categories are explored in Sections 5.5.3 and 5.5.4.

5.5.2 *Average performance of transition paths using LCA-type indicators*

LCA indicators were successfully used to assess performance of specific value chain configurations for a specific point in time, both for the status quo and for preferred future configurations. They do this by aggregating potential performance across space and time; performance scores are not site-specific and do not predict time-dependent impact profiles. In the literature, LCA indicators have been applied to evaluating products and processes, but not to the design and implementation of industrial ecologies through realising preferred value chain configurations, as is proposed in this work. Consequently, an approach is required which can couple LCA-type performance measures with an assessment of transition paths between status quo and alternate future. This is necessary to reflect the impact on performance of the timing of changes to the value chain configuration as highlighted in Figure 5-2.

The conceptual approach to evaluating the performance of different value chain configurations through time is illustrated in Figure 5-8. It illustrates the concept of an evolving value chain whose configuration changes thought time as the result of particular actor-interventions at t_a and t_b.

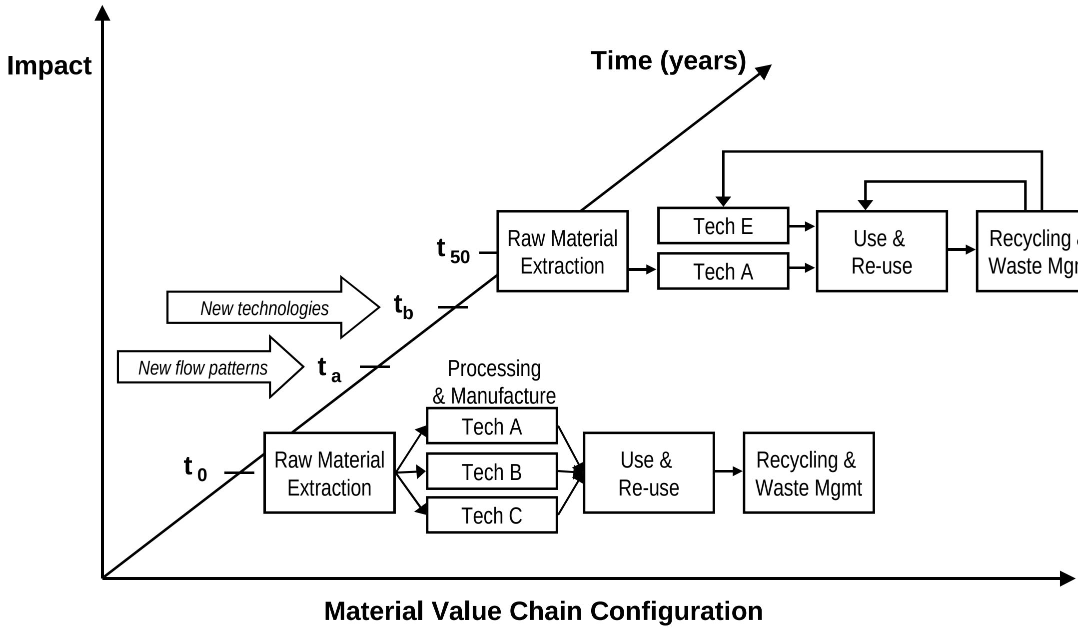


Figure 5-8: Assessing performance of changing value chain configurations which include new flow patterns between nodes and new technology infrastructure

It is proposed to adapt the use of LCA-type indicators, to evaluate the series of configurations which occur during the transition from status quo to alternative future, rather than just for a single configuration at a point in time. To this end, it is proposed that the environmental performance of system configurations at discrete intervals (e.g. annually) be assessed using LCA-type indicators. The output would be an impact potential for each system configuration at each time step. This would allow the performance of different transition paths between status quo and preferred future to be differentiated. An overall average performance assessment for the transition path from status quo to alternate future, for each impact category, can then be expressed as shown below:

$$Avg_i = \frac{\sum_{t=1}^{t_{final}} E_i(t) \cdot \Delta t_{int}}{\Delta t_{int} \cdot n_{int}} \qquad \text{Equation 5-19}$$

where Avg_i is the average performance score for the ith impact.

E_i is the performance score for impact category i at time t.

Δt_{int} is the width of the time interval, n_{int} is the number of time intervals from 1 to t_{final}.

Time intervals at which performance is measured should be equally spaced to ensure that the summation approximates the area under the curve.

The use of LCA-type indicators to calculate an average impact potential – for the range of transition states from status quo to preferred future – diverges from the standard application of LCA methodology as outlined in the ISO 14040 series of standards. The ISO method seeks to generate an impact potential which reflects the potential burden of a product across its life cycle, not a networked configuration of processes in the material chain. The purpose of using LCA-type indicators as proposed in this thesis, is to differentiate between the potential impact of alternate transition paths toward preferred futures, to promote actors pursuing lower impact trajectories. In doing so, it is important to recall the limitations of LCA-type indicators.

LCA-type indicators do not address the spatial and temporal aspects of its impact potentials (Finnveden et al., 2003; Olsen et al., 2001). This leads to an inability to represent exposure and ambient concentrations and in turn, thresholds and dose-response characteristics (Hansen, 2004). For example, a series of small emissions each year which can be absorbed in the environment may have a lesser effect than a large release at a single point in time, yet the total emission is the same. Considering impact potentials for system configurations at each year does not overcome these limitations. Furthermore, impact potentials are not realised impacts. Real impacts will themselves be time-dependent, affecting the duration and magnitude of exposure – this has not been included in the approach. The aim of using an average indicator in this analysis is to measure the effect which the timing of actions that bring about system changes have on the collective performance of the system in the time period considered. For this, the average indicator provides a useful guide which is easily applied.

There are additional considerations to highlight, including the normalisation, weighting and discounting regimes used which are discussed in Section 5.5.3.

5.5.3 *Influence of normalisation, weighting and discounting*

There are three additional issues which require consideration, in order to evaluate the performance through time of transitions between current and future system configurations: normalisation, weighting and discounting. Normalisation refers to the approach taken to determine whether the environmental performance score for an impact category is considered 'large' or 'small'. Weighting refers to the relative importance of one performance measure to another in the evaluation (for example, is a large score in 'global warming impact potential' more or less important than a large score in 'water usage'). Discounting refers to the change in value of a particular performance score in the present, compared with the value at a future point in time. Each consideration is now explored in more detail.

Normalisation as defined by the International Standards Organisation (2000) refers to 'calculating the magnitude of the category indicator results relative to reference values'. The role of normalisation and the approach and reference values used varies considerably. Norris (2001) makes a distinction between internal and external normalisation. For internal normalisation, the purpose is to make the units of the various impact categories comparable (as a prelude to weighting). This can be achieved in different ways, for example by:

- comparing alternatives against a 'base case', with the base case performance set to 100% and the performance of the alternatives can be expressed relative to this for each category
- for each category, making the best and worst performance of the alternatives in each category equivalent to the values of 0 (zero) and 1 (one) respectively.

External normalisation seeks to place the performance scores against an external reference, such as the total global warming potential from all industries. In this case one can say that industry or product X, contributes Y% to the total global warming potential of the region. For this thesis, normalisation relative to a baseline is undertaken to assess the performance improvement possible with changes to flows and infrastructure. A relative measure of improvement is useful to assess future states as compared against the status quo.

Subsequent to normalisation, when comparing trade-offs between impact categories a weighting can be applied. Weighting is a qualitative or quantitative step (Jensen et al., 1997). This recognises that for the LCA practitioner, decision maker or stakeholder, some impacts will be of greater importance than others. The relative importance attributed to each impact category may also change with time. Performance for each normalised impact category can be weighted and summed to give a single figure performance score. The act of giving a single aggregated performance score hides insight into tradeoffs and may not always be desirable. When used, it is important to obtain agreement about the approach to weighting used (Finnveden, 2000). This is discussed further in Section 5.5.4.

Discounting considers the change in the value attributed to a particular performance score with time. It is commonly used in respect of economic performance scores, (i.e. profit), to reflect that $100 is worth more now than in 20 years, due to inflation. The concept of discounting is commonly used in evaluating alternative project proposals using economic performance measures through the use of Net Present Value, which applies a chosen discount rate for money to enable calculations of money flows to be evaluated in today's dollars.

The problematic role of discounting in economic-environmental analyses is the subject of continuing debate (see Hepburn, 2002; Lumley, 1997; Pearce et al., 2003). Discounting heavily diminishes the unrealised burden which may come at the end of a plant's operating life (as the future value is discounted away to nothing). This will underestimate future environmental costs. Through the use of a cumulative environmental indicator which is being used in this work, a policy of zero discounting (with respect to environmental performance now and in future) is applied. According to Olson and Bailey (1981), the policy of zero discounting impoverishes the current generation because exploiting resources in the present becomes very costly, due to the high costs (in present dollars) of all future burdens. However, a strong argument can be presented to support that the environment is different to money and should not be discounted in the same way (Hamilton, 1995). Consequently, in this thesis which is concerned with environmental performance, discounting is not applied.

A compromise for economic-environmental analyses may be the use of a dual-rate approach with one discount rate for economic and one for environmental performance (Yang, 2003). The important point is to be aware the value given individually or collectively to performance measures through time can change and that this can affect the analysis, hence it is necessary to be clear about the approach to discounting used.

5.5.4 *Evaluating environmental performance using multi-criteria analysis*

The environmental performance of transitions toward alternate futures is assessed for multiple criteria, using LCA-type indicators. As such, configurations of the material chain which improve performance in one criteria, may offer reduced performance in another. This complicates the selection of the path toward a preferred future, as a 'clear winner' in terms of improved performance may not emerge.

Multi-criteria analysis is useful for evaluating options to assist decision making in such cases by providing a structured approach to link (Resource Assessment Commission, 1992):

i) the discrete alternatives to be evaluated

ii) the performance criteria by which they are assessed

iii) a method to rank the alternatives based on how well they meet each criteria.

This thesis has already addressed points (i) and (ii) of alternatives and their assessment using LCA-type indicators, but point (iii) was only discussed briefly in relation to weighting in Section 5.5.3 and further discussion is provided here. The implementation of multi-criteria analysis is flexible and techniques range from graphical methods to compare the performance of each alternative, to mathematical programming techniques to incorporate ranking preferences for each criteria and calculate the preferred alternative (see Bana e Costa, 1990; Belton and Stewart, 2002; Janssen, 1994; Pohekar and Ramachadnran, 2004) for a comprehensive discussion of multi-criteria methods).

In evaluating a preferred course of action, it is important to understand trade offs between each criteria. This is best achieved by viewing the 'raw' performance scores for each criteria plotted for the transition from the status quo material chain configuration to that for the alternate future. However, multi-criteria methods become useful where the number of performance criteria becomes large –making comparison by eye difficult – and where there is a desire to explicitly incorporate the preferences of relative importance of each criteria (weights) from a number of diverse actors or stakeholders in a structured way.

First, the performance scores in each criteria are normalised (standardised). Normalisation eliminates the effect associated with the varying magnitude of performance scores in different units for different criteria (LCA-type impact categories). To do this, one assigns a performance score of 1 to best performance in that criteria and 0 to worst performance amongst the alternatives being compared. The 'importance weighting' – specified by the decision maker or actors for each criteria – is then multiplied by a normalised performance score in each criteria and then summed to calculate the preferred alternative. A sensitivity analysis should be performed to assess the effects of different relative weightings on the calculation of a preferred alternative.

As mentioned earlier, a multi-criteria approach will not be necessary when the decision maker can readily comprehend the performance scores across categories associated with alternatives. Multi-criteria analysis suffers the drawback that providing explicit weights to accurately reflect preferences of actors can be difficult and may lead to a false sense of objectivity and either excessive faith or mistrust regarding the remaining analysis (Resource Assessment Commission, 1992). Multi-criteria methods are of value in analyses underpinned by rigorous information detail with limited uncertainty, from where decision makers feel comfortable with the quality of the raw data and not that the final alternative is recommended via a 'black box' process.[9] Multi criteria analysis can then be used to explore the impact of differing stakeholder preferences on preferred alternatives. This is important in making the case for collaborative action along the material chain and is discussed further in Section 5.6.1. Regarding the use of multi-criteria methods in relation to the scale of analysis within the reference schema, they are less useful for aggregated analyses at a larger scale where the resolution of the material chain representation aggregates the influence of individual actors. In these decision problems, basic trends should be identified then more detailed analyses conducted.

5.6 INFORMING SUSTAINABLE CHOICES

This section develops approaches to using the performance assessments in Section 5.6 to promote more sustainable choices, thus overcoming the naïvety associated with the current practice of making choices in the absence of the consequences for the value chain as a whole. Suggestions for extending the evaluation of options to include an assessment of 'sustainable scale' is also proposed.

5.6.1 *Reward for effort of individual and collaborative actor choices*

Section 5.5 showed how to measure improved performance through time for transition paths from the status quo to an alternative future; describing the improvement possible in material chain performance through both individual and collaborative action. By reflecting on the degree of improvement achieved in light of the required collaboration and new infrastructure required, a strategy for promoting more sustainable choices along the materials chain can be proposed.

This thesis has concentrated on evaluating the environment performance of future value chain configurations and the link back to actor decisions. For industrial and

---

[9] To address this challenge, recent work by Basson (2004) has developed techniques facilitating the use of multi-criteria methods for environmental decision making under uncertainty.

governmental decision makers to implement changes to the configurations of flows and infrastructure in the value chain, performance against other criteria will also need to be evaluated. This will include economic performance, social costs and benefits and how future value chain configurations will change relationships between actors, their relative influence to direct flows toward their benefit, versus the benefit of the value chain as a whole. With this understanding, barriers can be identified and strategies developed to promote improvement of the value chain as a whole. This could include benchmarking current best-practice and a preferred future value chain configuration against which the performance of individual companies are assessed to promote improved performance.

The strategies used to promote a more sustainable value chain, will depend on whether significantly improved performance can come from a single actor, or only through collaboration. Where collaboration is required, the benefits of collaboration must be made clear to all parties, as well as how they will be shared. Some interventions may always be beneficial to actors individually and to the performance of the value chain as a whole. These should be implemented as a matter of priority, win-win situations can be used to build trust amongst actors to tackle the more difficult issues requiring larger structural change. Other interventions may benefit some actors at the expense of others if enacted individually. This highlights the importance of changing the mindset of actors to embrace a material chain focus – namely, seeking improved performance within a larger domain of interest.

5.6.2 *Aligning scales of interest, influence and impact*

This work provides the basis to develop future evaluations to better reflect the sustainability of actor choices for the system configuration. This can be represented with reference to the relationship between the Domain of Interest, Domain of Impact and Domain of Influence. For any activity taking place within the value chain, there is value to be gained by enlarging the domain of interest of actors within the value chain – this provides the opportunity to implement inter-nodal links and shared benefits. Current practice has the true cost of many environmental effects being externalised. This introduces a delay in time or space to appropriate feedback signal to the actor within their domain of interest to adopt more sustainable behaviour. Furthermore, the influence of actors individually and collectively on the performance of the value chain must be better understood to enable more efficient metal cycles.

Table 5-4 outlines the potential problems and benefits associated with different alignments between the domain of interest, influence and impact. In addition to the action-impact link from Chapter 4 and reward-for-effort evaluation of paths to preferred futures, the information in this table will assist actors in developing effective strategies to implement their chosen paths toward preferred futures.

Table 5-4: Alignment of domains of interest, influence and impact

Domain of Interest	Domain of Influence	Domain of Impact	Comments with reference to potential sustainability
Internal to domain of activity	Internal	Internal	Good feedback control, but potentially naïve to improvements that could come collaboration *e.g. if consumers discarded waste in their own home*
		External	Poor, impacts are external, little feedback to alter behaviour to be more sustainable *e.g. metal refining company who operates process in way that gives large global warming burden*
	External	Internal	Feel helpless ,main influences beyond control *e.g. metal recycler who cannot process new scrap with more complex alloys using the existing infrastructure, scrap quality beyond control*
		External	Need widen focus, be aware of effect on others and collaborate to control effects *e.g. metal refining company whose main environmental burden comes from the energy supply which they buy*
External to domain of activity	Internal	Internal	Aware of bigger picture *e.g. reducing impact of on-site solid waste disposal with an understanding of other impacts across supply chain*
		External	Requires co-ordination across value chain *e.g. design of product for recycling*
	External	Internal	Feel helpless, requires co-ordination and sharing burden along value chain
		External	Largely unaffected, but still requires sharing burden along value chain
Internal & External	Internal & External via collaboration	Internal & External with feedback	Encourages sustainable system operation when configured around sustainable targets

5.7 CONCLUSIONS

Characterisation of the status quo configuration of the value chain was undertaken in Chapter 4. This chapter concluded that to envision an alternate future configuration for the value chain, backcasting should be used. Using the actor-system variable-system state-impact link from Chapter 4, and understanding of sensitive variables affecting performance and the actors which control them, preferred future value chain configurations are generated. Different future states are generated which can be implemented by single actors, or actors in the primary and secondary resources sector collectively. It is concluded that comparing future states alone, is inadequate. Value chain performance can take differing transition paths to alternate futures, based on the timing of actor decisions; performance will also be affected by trends in external variables. These futures are tested in a dynamic system model which provides insight into how the implementation of these futures by actors is affected by external trends beyond the control of the actors. Understanding the environmental performance improvement achieved by actors individually and collectively, in light of the effort associated with establishing new infrastructure and collaborations, enables better informed decision making to promote strategies that lead to more sustainable futures.

CHAPTER SIX

Demonstrating approach via case studies

Chapter 6 is divided into three parts: the first section provides a brief summary of the methodology developed in the previous chapters. The second section outlines a background to the copper industry and its operation. Finally the third section describes how the copper case studies in Chapters 7, 8 and 9 will be used to demonstrate the key features of the developed methodology.

6.1 SUMMARY OF THE NEW METHODOLOGY

The methodology developed in this thesis offers a new approach to tackling the problem of improving the performance of the minerals and metals value chain across spatial scales from global to local.

The minerals industry consists of material and energy flows through globally distributed nodes in the value chain. These activities give rise to both local and global environmental impacts. Seeking to reduce these impacts is the driver for the development of a new approach to addressing the problem. As highlighted in Chapter 2, attempts at impact reduction have been hindered by an inability to characterise performance across scales and link it with the different abilities of individual actors within the value chain to realise system improvements.

A reference schema is developed in Chapter 3 with two key benefits. First, it provides a guide for classifying the current tools and indicators used at different spatial scales in the value chain. Second, it provides the basis for structuring a more complex multi-scale study of industrial ecologies.

The development of new tools for characterising flows and impacts for the value chain, which can be applied across scales, is undertaken in Chapter 4. Snapshot and static models are used to characterise current value chain configurations and establish baseline performance against which future value chain configurations can be evaluated.

A new approach to envisioning and evaluating paths toward preferred futures is developed in Chapter 5, using dynamic models of value chain flows and configurations. The approach allows the resultant impacts from actor-initiated changes to the value chain and the effect of external influences to be assessed and to inform the pursuit of preferred paths toward more sustainable futures.

The approach is demonstrated with case studies in copper. Section 6.2 provides a background to the copper industry and is followed by an outline of the case studies in Section 6.3.

6.2 BACKGROUND TO COPPER INDUSTRY

6.2.1 *History*

Copper has been critical to the development of our current civilisation. Its first recorded use dates to around 8500 BC in Northern Iraq and the earliest copper smelters were operating around 3500 BC in Israel and other parts of the Middle East. It was widely used by the Egyptians and by the Roman Empire. In the middle of the sixteenth century smelting operations began in Mansfield, Germany and Swansea, Wales employing successive oxidations and reductions to eliminate iron and sulfur in a process similar to modern methods. In 1877 the mines of Rio Tinto in Spain produced 24,000 t/year making them the largest copper producer at that time (George, 1998). Chile is currently the world's largest copper producer due to its state owned company, Codelco, and the United Stated is the second largest producer. World production in 1999 exceeded 14,000,000 tonnes (International Copper Study Group, 1999), which is the third largest annual production behind aluminium (30 million tonnes in 2004) and steel (1,000 million tonnes in 2004).

6.2.2 *Resources*

6.2.2.1 *Primary resources*

Copper deposits are found throughout the world, but are heavily concentrated in specific areas. These abundant copper zones are in Chile and the west coast of North America (Kesler, 1994). Copper is the twenty-eighth most abundant metal in the earth's continental crust at a concentration of 25 ppm (Wedepohl, 1995).

Copper occurs in a number of mineralogical forms and may be classified as sulfide, oxidised and native. Primary sulfide minerals include bornite (Cu_5FeS_4), chalcopyrite ($CuFeS_2$) and are concentrated in ore bodies by hydrothermal processes. Covellite (CuS) and chalcocite (Cu_2S) are important secondary sulfide minerals and occur when exposed primary copper sulfide deposits were leached by weathering and groundwater followed by re-precipitation of the copper near the water table. Oxidised minerals were formed by oxidation of surface sulfides; they include cuprite (Cu_2O), malachite ($CuCO_3.Cu(OH)_2$) and atacamite ($Cu_2Cl(OH)_3$). Native copper is copper occurring in its elemental form and generally occurs in the same zone as where oxidised copper is found (George, 1998). Approximately 80–95% of mined copper is from sulfide deposits (Ayres et al., 2001; Davenport et al., 2002). The remainder of mined copper is from oxide ores, which are not readily amenable to flotation required to concentrate them for further smelting, but may be processed by hydrometallurgical processes. The proportion of oxide ores being processed by hydrometallurgy is increasing.

The average ore grade for copper ores has been steadily declining throughout the 20th century, for example in the USA the average ore grade was 3.5% in 1900 and 0.5% in 2000 (Ayres et al., 2001). The consequences of this trend are that greater environmental impact is associated with sourcing copper from primary ores, and, increasing levels of contaminants are associated with sourcing copper from low grade ores which may favour processing via different technologies which are better able to handle contaminants. In particular, flash smelting, which is the mainstay of pyrometallurgical processing has a limited ability to handle ore concentrates with high levels of impurities. On the other hand, the hydrometallurgical route of heap leach, solvent extraction, electrowinning (SX/EW) is able to better cope with the impurities. A brief overview of technologies currently in place for processing copper is given in Section 6.2.3.

6.2.2.2 *Secondary resources*

Secondary resources comprise copper-containing products, landfills and waste or slag dumps from existing mining operations. They constitute a significant fraction of available resources, for example in the USA, compared with 90 million tonnes of copper remaining in ore reserves, the stock of copper containing products in use amounts to 70 million tonnes, while that in landfills amounts to 40 million tonnes (Zeltner et al., 1999).

Together with the stock of primary ores declining, the utilisation of secondary ores has the potential to become an increasingly important source to provide copper to society. Secondary resources have different compositions than primary resources and are often processed via dedicated secondary processing technologies, however, some secondary scrap may also be fed directly to suitable primary smelters (e.g. at Noranda in Canada, Sippel and Roos, 2001). Furthermore, the composition of the secondary resource stock is also changing through time as the use of pure copper in wires and pipes decreases relative to the use of specific copper alloys and copper with other metals in electronic circuitry, which yields a mixed scrap with copper and other metals.

In addition to the differences in composition of primary and secondary ores, the location of secondary resources is generally in the consumption-intensive northern hemisphere economies while the extraction of primary ores is more prevalent in the South (although extraction also takes place in the North).

The quality, location and technology requirements for using secondary resources in the production of copper are different from those for primary resources and these factors will need to be incorporated into any analysis of future changes to technology infrastructure.

6.2.3 *Technology*

The processing of copper ores occurs mostly by pyrometallurgy (over 80%) with the remainder occurring by hydrometallurgy.

Pyrometallurgy involves mining the ore, crushing and purifying it via flotation to make a concentrate or 20-30% copper. The concentrate is then smelted and then refined to give a copper product. Flash smelting (and its derivatives) are the dominant forms of smelting, although older reverberatory smelters are still in operation and are described further in Chapter 7.

Currently, hydrometallurgical processing of copper involves trickling an acid leach solution over a crushed heap of ore. After passing over the ore heap, the acid solution becomes copper-rich. The solution is purified via solvent extraction and then copper is electroplated from the solution ('electrowinning') to give a final copper product. This process is known as the heap leach solvent extraction electrowinning route (often abbreviated as SX/EW).

Low grade scrap is processed much like copper ore, by being crushed and smelted in dedicated secondary blast furnaces. Some scrap is also recycled in furnaces processing primary ore. Higher grades of scrap (>95% Cu) are just re-refined, while very high grade scrap (>99%) is simply remelted.

6.2.4 *Use*

Copper is used in a variety of applications from wiring and piping, to roofing and coinage. It is largely exploited for its electrical conductivity, but also for its corrosion resistance and thermal conductivity (Davenport et al., 2002). An approximate breakdown of the applications in which copper finds use is given in Table 6-1. The emerging trends of using copper extensively in electronic products complicates recycling efforts as the copper is mixed with many other metals. This contrasts traditional uses in pipes and wires where copper was used in a more pure form in the product.

Table 6-1: Breakdown of copper end uses (Noranda, 2003)

Use	Percentage
Construction (wires, plumbing, heating, air conditioning)	40%
Electric & electronic products (telecommunications, lighting, electronics)	25%
Industrial machinery and equipment (machinery, valves, heat exchangers)	14%
Transportation equipment (automotive, marine, aircraft)	11%
Consumer and general products (appliances, coinage, military ordinances)	10%

6.2.5 *Future overview*

Regarding technology, the use of hydrometallurgy is increasing (Davenport, 1999) and is likely to continue doing so in future. It can process ores with more impurities than flash smelters and is economic from small to large scale operations (whereas smelters must process large tonnages to be economic). Hydrometallurgy is not currently used for processing scrap resources, but may do so in future. Currently, scrap recycling is via the pyrometallurgical route.

The actors in the copper industry are generally less vertically integrated than other metal industries such as aluminium, where single companies are involved in mining, refining, producing a metal product and also recycling. This limits the control individual actors have over system variables in the absence of collaboration. However, the trend toward industry consolidation generally in the minerals industry may reverse this. Increased industry consolidation, whilst offering the potential for companies to effect greater system change, also puts them in a position of power where they could be less inclined to pursue sustainable practices in the absence of competition.

Improved environmental performance of the copper material chain requires an understanding of the improvements that can be achieved when targeting the material chain as a whole, rather than within narrower boundaries. The following case studies show how these potential improvements can be quantified and used to inform a preferred future for the material chain.

6.3 OUTLINE OF CASE STUDIES

This section describes the case studies to be undertaken in Chapters 7, 8 and 9. Case studies in Chapter 7 evaluate the status quo at several locations within the reference schema and serves to demonstrate the linking of actor to system variables, system state and impact. This information is then used to determine the minimum environmental impact possible using current technology in place for the region of Europe. Chapter 8 explores the assessment of an innovative technology, the factors within and beyond control of the technology vendor and their relative impact. This study highlights issues that will need to be addressed in the development of future technologies and develops specific indicators for performance assessment of emerging technologies, with particular regard to solid waste. Guided by the insight from previous case studies and modelling capacity developed, the case study in Chapter 9 explores alternate system states and potential paths toward these states. These alternate states involve the retrofit of existing infrastructure with new technology and the methodology of assessing performance through time from the status quo to alternate system states is demonstrated. This allows the reward for effort for different actors to be clearly articulated by following easier and more difficult paths toward preferred futures. Each chapter of case studies is now described in more detail.

6.3.1 *Chapter 7: Status quo characterisation and improvement*

The first case study (7a in Figure 6-1) in group one is undertaken at an aggregated global level and seeks to determine the major stocks and flows within the materials value chain. This will allow a first-pass assessment of where potential impacts arise and the operation of the system. Of interest is whether the usage of copper leads to largely dissipative or intact uses which leaves it available for further recycling, and the amounts of available resources and their current rate of use. This case study provides a first-pass characterisation of *flows between nodes* (where nodes represent aggregated stages within the value chain) and builds an initial system-impact link.

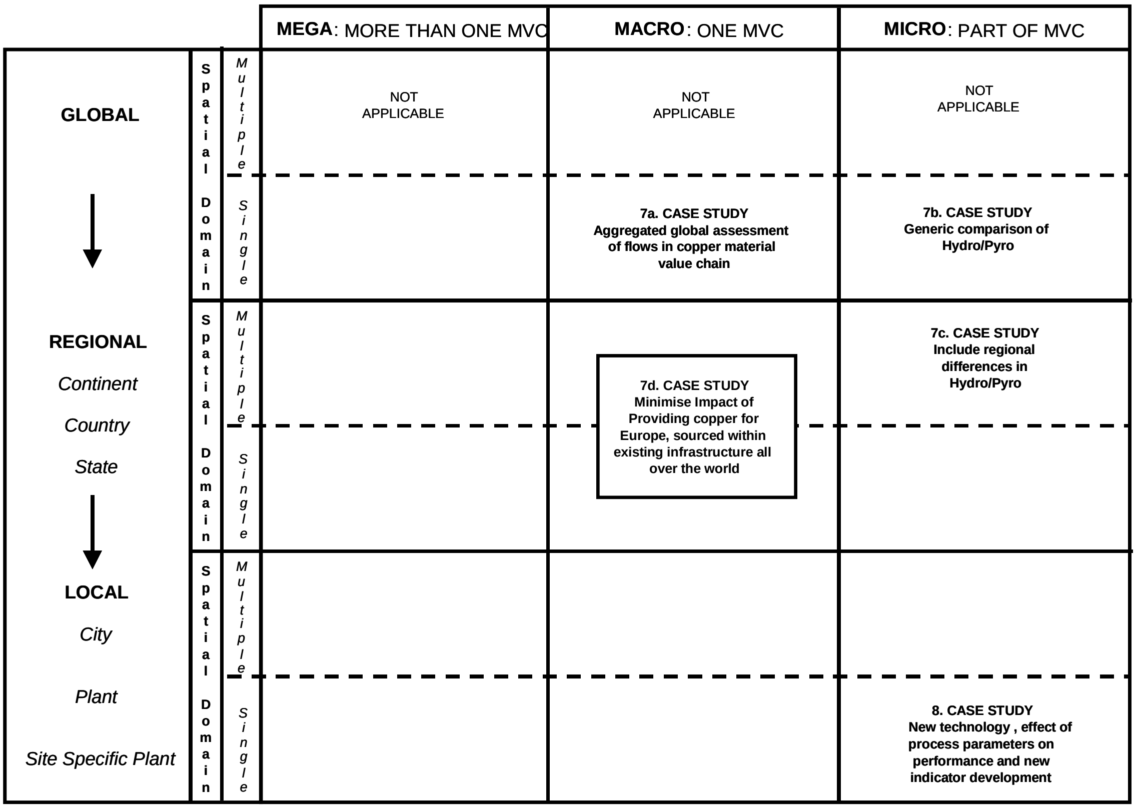


Figure 6-1: Case studies explored for current time-frame and current infrastructure

To understand more about the system variables within nodes, the second case study in Chapter 7 (7b in Figure 6-1) compares hydrometallurgical and pyrometallurgical technologies currently in place for primary and secondary refining at a globally aggregated level. This aims to determine the difference in impacts associated with processing low and high grade primary ore, and the various grades of secondary copper (namely No1, No2, Low and Brass). Average global values for the resource quality and other inputs are used to highlight the *difference between the technologies* themselves rather than these region / site specific factors at this stage. The differentiation between technologies and relative amounts of primary / secondary processing are important system variables and this case study demonstrates the quantification of the system variable-system-impact link.

The second case study is extended (7c in Figure 6-1) with *region specific information* regarding such factors as ore grade and energy mix. The desire to move to more information detail is to give a more realistic assessment of the materials value chain at a level consistent with that at which actors can exert influence, and to test the relative magnitude of impact which these factors exert. It would be ineffectual to suggest the selection of one technology over another from the second group of case studies, without validating – through this third set of case studies – that the factors assumed to be 'average' at the global level of analysis, did not in fact have a greater effect when included (namely ore grade and electricity mix) than the differences between the technologies themselves. The third case study includes these regional differences in impact associated with processing different ore grades in order to produce copper and with different energy mixes on different continents. This allows a baseline performance map to be created for each region across the globe and shows how a regional actor-system variable-system-impact link can be established.

Case three (7d in Figure 6-1) places these individual components in the context of the materials value chain network to consider where a single region actor, for example the European Union, could source its primary copper with least environmental burden, including the impact of transport as well as regional differences in the technology mixes used and ore grade and energy. This case constitutes a demonstrated example of improving environmental performance within the existing network infrastructure, which is important to understand, given the slow turnover time of infrastructure.

6.3.2 *Chapter 8: Emerging technology considerations*

Bridging the analysis of material chain configurations using existing infrastructure in Chapter 7 and future configurations with new technology in Chapter 9, the case study in Chapter 8 evaluates the environmental performance of a novel hydrometallurgical process using pilot plant data which has yet to begin commercial operation (labelled 8 in Figure 6-1) . This case study has two objectives. First, technology operating parameters are assessed to determine their impact on overall environmental performance which demonstrates that the newly developed methodology can be applied down to the level of operating process parameters and links company-internal and company-external system variables to overall environmental impact. Secondly, it provides insight into the drivers such as decreasing ore grade which are behind new technology development, that lead-times to new technology implementation can be lengthy and that additional indicators are required to discern potential environmental performance at a process-specific level of detail. To this end, a modified indicator for the stability of solid waste is also developed, given that the stability of solid waste is a major point of difference between hydrometallurgy and pyrometallurgy and that hydrometallurgical technology developments are being driven by their ability to process lower grade ores with more contaminants than pyrometallurgical technologies. This process is also of interest to study as it may develop into a process capable of using both primary and secondary resources, to produce copper and other metal products such as gold and zinc. This case study provides performance information which can be used to create potential technology combinations possible in the future.

6.3.3 *Chapter 9: Evaluating paths toward alternate futures*

The culmination of all tools developed in the thesis are applied in Chapter 9; to determine the baseline performance for the current material chain in the USA, to envision preferred future states for the matinal chain and to evaluate transition paths toward these states. The USA is of particular interest as it is both a large producer of copper (from declining ore grades) and large consumer of copper, giving rise to abundant secondary resources. Changes to flows and infrastructure for primary and secondary processing are assessed in the context of external drivers including declining ore grades, changes in the quality of scrap, lead time to technology development, changing demand, in order to find the transition path with least environmental burden through time. The resultant information makes it possible for actors to assess their preferred roadmap to the future, based on the improved performance possible by changing system variables within their control and by collaborating with other actors in the system to effect greater change.

With reference to Figure 6-2, cases are divided into three parts for Chapter 9: case (9a) examining the alternate future achievable by collaboration between actors; case (9b) considering the alternate future achievable by an individual actor in control of primary technology selection; and case (9c) the evaluation of dynamic transition paths toward both these futures.

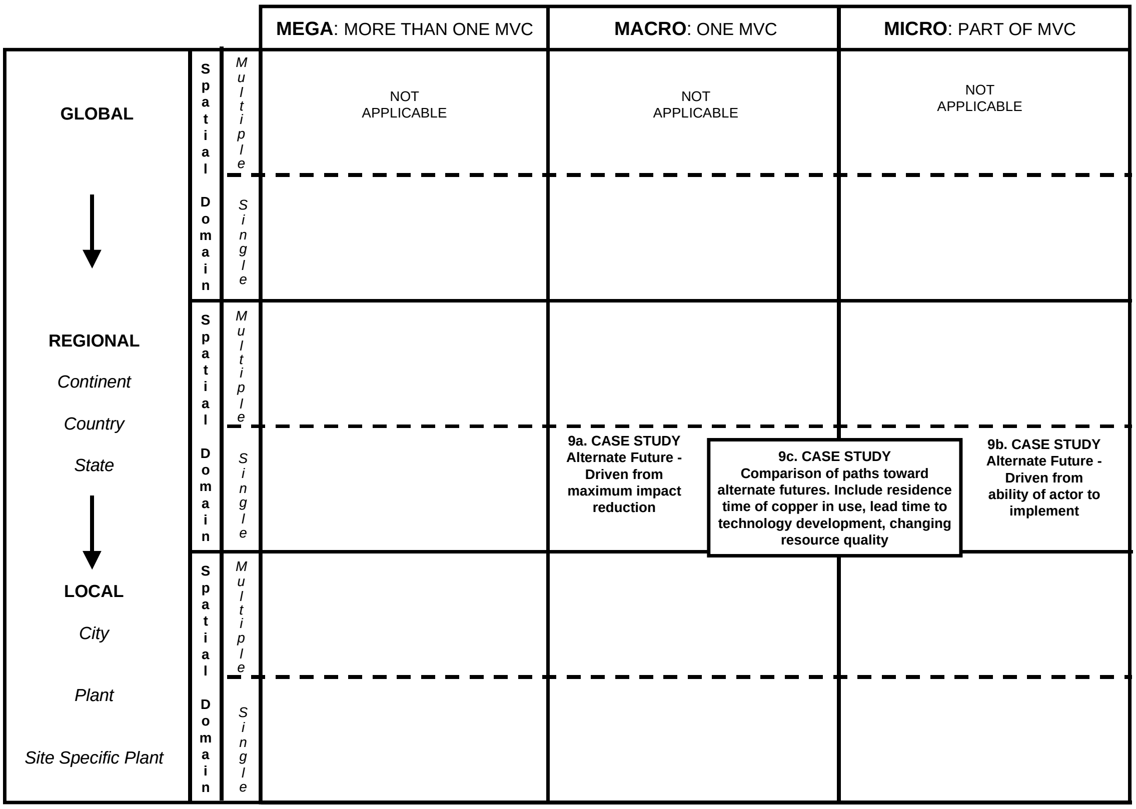


Figure 6-2: Case studies explored with increasing vision (future time domain and changes to infrastructure)

CHAPTER SEVEN

Assessing existing material chains across scales

The case studies in this chapter characterise the status quo at different scopes and with different levels of information detail and then assess the potential for performance improvements within the existing infrastructure. To begin, a focus on the materials value chain at an aggregated global level provides a first-pass assessment of dominant material and energy *flows* between nodes in the value chain and highlights areas for further investigation. Then, looking in more detail at the refining of copper from primary ore, representative *technology infrastructure* options are compared and evaluated. The technology assessments are then tailored to include *region-specific* information providing a baseline of environmental performance for regions across the globe. Informed by region-specific sensitivities to impacts, a case study of Europe examines the changes to environmental performance that can be achieved by changing the sourcing of primary copper from different continents.

7.1 AGGREGATED GLOBAL ASSESSMENT

7.1.1 *Aims and scope*

The first case study begins with an assessment of the copper value chain at a global level, where processing activities along the value chain are highly aggregated. The aim is to demonstrate an approach for preliminary system characterisation in the minerals and metals industry which can then also be used to identify relevant areas in which to focus more detailed investigations. As such, it is useful to industry and government policy makers.

Which aspects should be addressed in a preliminary characterisation of the value chain? Methods of preliminary characterisation in the literature are not uniform. Graedel and Klee (2002) consider the ability to continue supply – drawing upon both primary and secondary resources – in seeking to establish *sustainable rates of consumption* across the next fifty years. Current usage rates can then be compared with sustainable rates to provide an initial measure of system sustainability. Alone, this analysis is useful when comparing different value chains (for example comparing the value chains for copper, zinc, vanadium etc) for establishing the 'immediacy' of the potential lack of resource availability. The elemental nature of metals has led them to be described as indefinitely recyclable (Five Winds International, 2001) which can suggest that resource scarcity is not a problem. However, it has already been noted that contamination with other metals is a practical inhibition to infinite recycling – in addition to the increasing energy requirements for recovery from more dilute sources. Hence, resource availability must still be considered, given the aforementioned considerations and that availability may be limited if primary stocks are low and if secondary sources are largely tied up in use. Establishing the lack of resource availability gives an indication of when new infrastructure pathways to supply metal will require development – part of a measure of the 'immediacy' with which the problem should be further investigated.

Resource availability is not the only important issue and additional indicators are needed to support a more informed view of the 'immediacy' with which the problem is further investigated, based not only on resource scarcity, but potential environmental impact.

Frosch and co-workers (1997) go part way to addressing the 'immediacy' of required action within a value chain, based on two conditions for material sustainability failure:

1. Non-renewable resource depletion
2. Resource leakage into the environment resulting in poisoning of the environment as a useful system for supporting life.

They soundly regard 'running out' as unlikely for metals, given that they are not destroyable in the same way that combustible organics (such as oil or other hydrocarbons) are. Consequently, leakage into the environment is viewed as the main problem for metals, given their potential toxicity which poisons the environment as a useful system for supporting life. However, an important consideration not discussed by Frosch et al. (1997) is that in addition to toxicity resulting from the leakage of metals from the materials chain, significant impact is also associated with the energy resources used to drive the materials value chain. These energy resources are often non-renewable and also give rise to the poisoning of our environment as a useful system for supporting life.

For this reason, it is proposed that the approaches of both Frosch et al. (1997) and Graedel and Klee (2002) are extended to answer a third useful question at the level of an initial system characterisation – namely, what are the approximate mass and energy flows for the system? Noting principal mass flows will give a preliminary estimation of the magnitude of the potential resource scarcity and resource leakage. Additionally, it will highlight the split between primary and secondary resource utilisation. Energy is used as a first pass proxy-indicator for environmental performance, to assess the potential magnitude of environmental performance and to discern the difference between energy usage between primary and secondary refining, to see whether at a first assessment the increased utilisation of secondary resources may offer environmental benefits.

In summary, for an initial characterisation of a materials value chain at a macro-global level, the following themes need to be addressed:

1. Resource scarcity (how immediately concerned do we need to be about the lack of available resource)
2. Dissipative uses (how efficient is the system, i.e. how much is being lost to dissipative uses and how potentially toxic are these losses)
3. Mass and energy flows for system (how big a system are we dealing with, within the materials value chain are there possibilities for energy savings by changing flows).

This represents an extended approach to initial system characterisation at an aggregated global level and will be used to direct focus in more detail to sections of the materials value chain where significant improvement appears possible, based on the initial characterisation. The tools to enable this assessment are described in Section 7.1.2.

7.1.2 *Models and indicators*

A snapshot stocks and flows model is used here to describe the status quo for the materials value chain aggregated at a global level. The approach used in constructing this status quo analysis is to reconcile data from various sources (Ayres et al., 2001; Edelstein, 1999; Edelstein, 2001; ICSG, 1999; Graedel et al., 2004) into a consistent set which provide a first-pass approximation to global material flows as presented in Figure 7-1 where figures are rounded to the nearest million tonnes (Mt) unless otherwise indicated and are likely to have an accuracy of ±50%. It is noted that more data were found for production than for disposal.

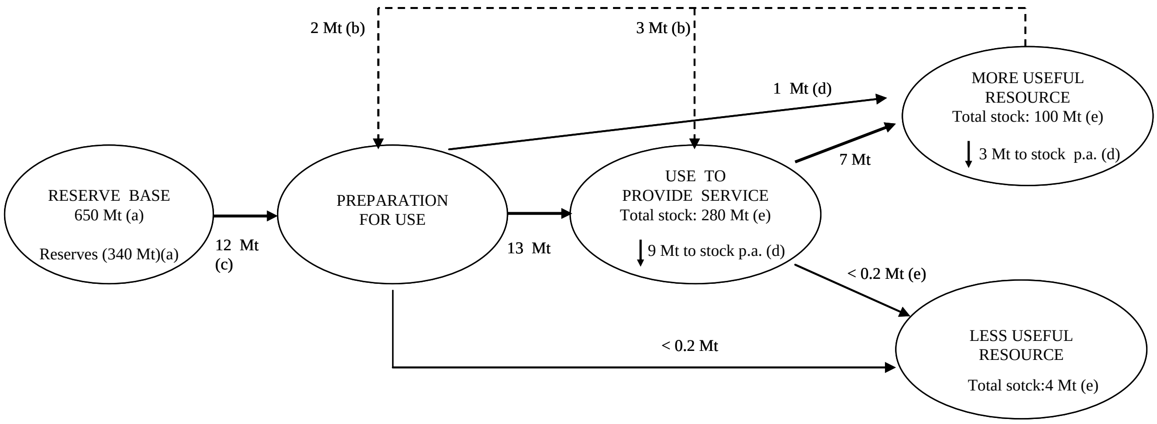


Figure 7-1: Global material value chain for copper. Approx. flows indicated are for 1999. Stocks are absolute. Figures are in million tonnes (Mt). References from (a) Edelstein (2001), (b) Edelstein (1999), (c) ICSG (1999), (d) derived estimates from Graedel et al. (2004) who used 1994 figures, (e) Ayres et al. (2001).

Primary resources are shown as 650 Mt 'Reserve Base' and 340 Mt 'Reserves'. The United States Geological Survey makes the following distinction between the two:

- Reserve Base: That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth.
- Reserve: that part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative.

'Preparation for use' covers mining and refining with inputs from primary ores (12 Mt) and secondary sources (2 Mt) which constitutes old scrap which is recycled. A 'working inventory' may be present, increasing or declining in relation to business cycles in industry, but essentially inputs equal outputs for this node. Leaving the 'preparation for use' node are 1Mt[1] of copper contained in tailings and smelting slags which are deemed here to be 'More useful resources' as in future they may be re-mined as this becomes economic and technology improvements make this more cost effective. A limited flow of

[1] The actual figure from Graedel et al. (2004) is 1.55 Mt

copper is assumed to dissipate. This allows for airborne emissions in particulates and the limited operations (e.g. Ok Tedi, Papua New Guinea) where riverine disposal of tailings occurs, dispersing the copper more widely and making re-mining in future less likely. By contrast, in the 'use to provide service' comprising the manufacturing and use phases, approximately 9 Mt is added to the global stock of copper annually in cables, wires, pipes and electronic goods. Approximately 7 Mt is discarded each year from manufacture and use (including new scrap which is directly re-melted (3 Mt)), from which only 5 Mt is recovered, meaning there is a net addition of 3 Mt to the potentially recoverable stocks of secondary resources. Copper flows to dissipative uses (the 'less useful resources' node from which recovery is not practicable) are limited.

The results of this snapshot model can be used to first understand resource scarcity issues. Using the method of (Graedel and Klee, 2002), the copper reserve base of 650 million tonnes (1999) is divided by 50 years to give a sustainable primary supply of 13 Mt per year. Including the current recycling rate of 2 Mt per year gives a sustainable supply of 15Mt per year.[2] This can be compared with the current total refining of 14Mt per year showing that at first glance the usage of copper is close to exceeding its sustainable supply. An alternative calculation which divides the current annual consumption from virgin ore of 12 Mt per year into the current reserves of 340Mt shows an availability to utilise current reserves for 28 years while using the reserve base figure of 650Mt gives a timeline of 54 years. This estimates that known primary copper ore bodies will be exploited in 54 years. Consequently, with regard to resource supply, there is a medium term issue of resource supply constraints.

The second assessment criteria regards material dissipation which can be defined as:

Annual dissipated flow / Annual resource extraction rate * 100%

From Figure 7-1 it is observed that the rate of dissipation for copper is

$(< 0.2 + <0.2\ )\ /\ 12 * 100\% = < 3\%$

Other estimates of dissipative uses are in the order of 1% or less (Ayres et al., 2001), mainly in chemicals, herbicides and brake-pad linings for cars. In the case of copper this is a reasonably low figure compared with other metals (cf. approximately 20% for zinc Annema and Ros, 1994). It is not easy to set a limit at which a metal system would 'categorically fail' a test for sustainability at the level of system dissipation. However, if a

[2] This is done on a total mass basis rather than per capita as in Graedel and Klee (2002).

significant portion of the system throughput is being lost, it directs closer attention to the causes of the dissipative uses and whether they can be reduced or avoided. The classification of a use as dissipative is a function of the metal and available recovery technology (Stewart and Weidema, 2004).

With the use of a mass flow indicator alone (used to inform the first and second of the three initial characterisation criteria), it is noted that:

(a) there is currently accumulation of copper in the stock of 'More useful resources' which is potentially available for recycling

(b) the majority of copper extracted from the earth is currently in use

(c) the majority of current demand in met by the extraction of primary resources

(d) the stock of less useful resources (dissipated copper) is relatively small.

The final test for initial system sustainability is to assess the impact associated with running the system from the perspective of energy usage. This is included to give some indication of the impacts associated with maintaining system function.

As a useful first indicator for assessing the impacts of the system, energy usage correlates well with overall environmental performance (Haberl, 2001).[3] Furthermore, it is the most readily available source of information for processing from primary and secondary materials. The approximate energy required to make copper available for useful service in 1999 is shown in Figure 7-2.

[3] It was already discussed in Chapter 4 that there is a large difference in the impact of 1kWh of electricity, depending on its source. This is investigated when the energy mix is studied in more detail. At the initial first pass assessment, the idea is simply to determine the difference in energy usage between primary and secondary refining.

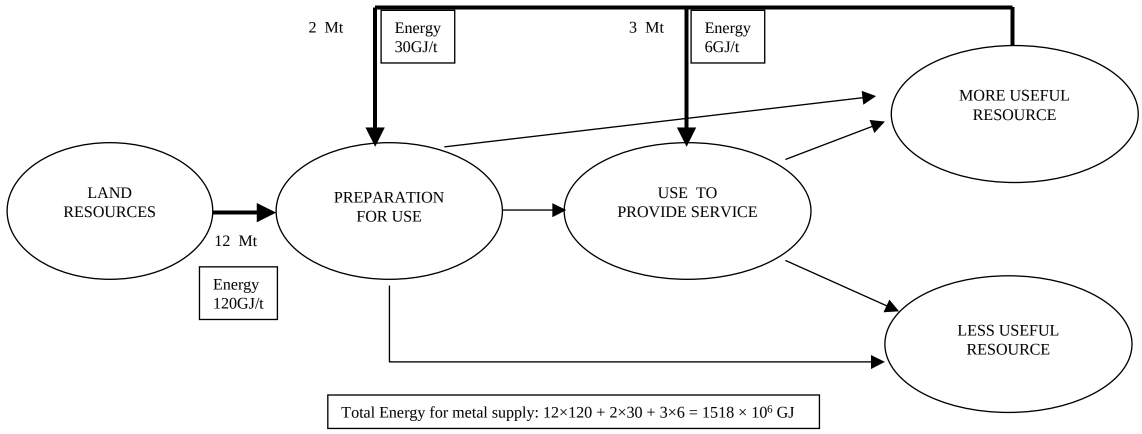


Figure 7-2: Energy consumption for metal supply (Henstock, 1996): Base case of 1999 production

This information allows a first comparison of the impact associated with metal supply from primary and secondary sources and reveals that significant reductions in energy use may be possible with increased metal sourcing from secondary resources. Secondary processing requires one quarter of the energy required for primary processing (30 GJ/t compared to 120 GJ/t). The figure of 6 GJ/t refers to direct re-melting of scrap.

Together, Figure 7-1 and Figure 7-2 provide the baseline assessment of the status quo. As can be seen from Figure 7-2 there is a significant difference in the energy requirements for copper production from primary ore and for recycling secondary scrap, with even less energy required for remelting.

7.1.3 *Actors, system variables and assumptions*

Beyond the analysis of the mass and energy flows to establish baseline environmental performance for the status quo, consideration is now undertaken to assess which system variables may be changed to bring about an alternate future and how these system variables correspond to those which current actors can control. Given the high level of aggregation of the macro-global decision context, the analysis is primarily of use to direct areas for further analysis at a more detailed level, as no actors can realistically exert influence at this aggregated level.

The main system variables in the depiction of the materials value chain as shown in Figure 7-2 which could be changed to improve environmental performance include:

- decreasing the rate of metal use (beyond control of minerals industry actors),
- increasing the rate of recycling (consider),

- decrease dissipative uses (only a relatively small mass flow to begin with),
- use less energy in preparation for use (consider, however, a greater level of information detail is required to understand this further).

This directs a focus in more detail on the mining and refining section of the materials value chain to unpack the preparation for use and see what variability can be exploited in these approximate figures and to bring it closer to the level at which an actor actually operates (no actor controls the entirety of the 'preparation for use' node, minerals and metals companies may control an individual plant or series of technologies).

7.1.4 *Discussion*

This case study has established an initial estimate of the baseline performance for the status quo of the copper value chain at the macro-global level using the extended 3-criteria approach as the basis for an initial assessment of the value chain. It concluded that resource availability will be constrained in 28–54 years, that <1–3% of copper is dissipated (and unrecoverable using current technology) in the value chain and an energy usage per tonne of copper produced ranging from 20GJ/t to 140GJ/t depending on the nature of the resource (secondary or primary).[4] The demand for copper in 1999 is approximately 14Mt/yr.

An additional purpose of the initial assessment at this aggregated level is to focus attention at an area within the value chain for further consideration in more detail. Given the potential for energy savings, Section 7.2 will focus in more detail on the 'preparation for use' node in the next case study, detailing the technologies used to bring copper to market from primary ore which currently represents the main source of copper supply.

7.2 TECHNOLOGY-SPECIFIC DETAIL

7.2.1 *Aims and scope*

The motivation for this second case study in this chapter is to quantify the difference in environmental performance associated with the main classes of primary processing technologies. This will quantify the difference in performance which can be explained by increasing the resolution at which the materials value chain is described. With the desire to better understand the relationship between domains of influence, interest and impact

[4] This compares with 19–40GJ/t for steel and 108–270GJ/t for aluminium (Yoshiki-Gravelsins et al., 1993)

(with the actor-variable-system-impact link of Chapter 4) – this increase in resolution also serves to describe the system at a level closer to which 'real' actors can exert influence. In other words, actors such as mining companies operate existing technologies and can purchase new technologies, thus changing a particular node in the material chain when represented as a specific or representative technology, but actors such as mining companies cannot easily exert influence over the aggregated 'preparation for use' node as was described in the previous case study.

In addition to highlighting differences between environmental performance, this analysis comprises an important step in establishing a baseline of environmental performance for the industry with technology-specific detail, which will be used in the exploration of future states in Chapter 9.

7.2.2 *Background to technologies used in primary production*

This section disaggregates the 'preparation for use' node into greater process steps. Disaggregation is both linear (into a greater number of process steps) and parallel (where more than one possibility exists for a process step) as shown in Figure 7-3. Each node is explained in more detail as a background to its function and to justify its representation at the level of detail specified.

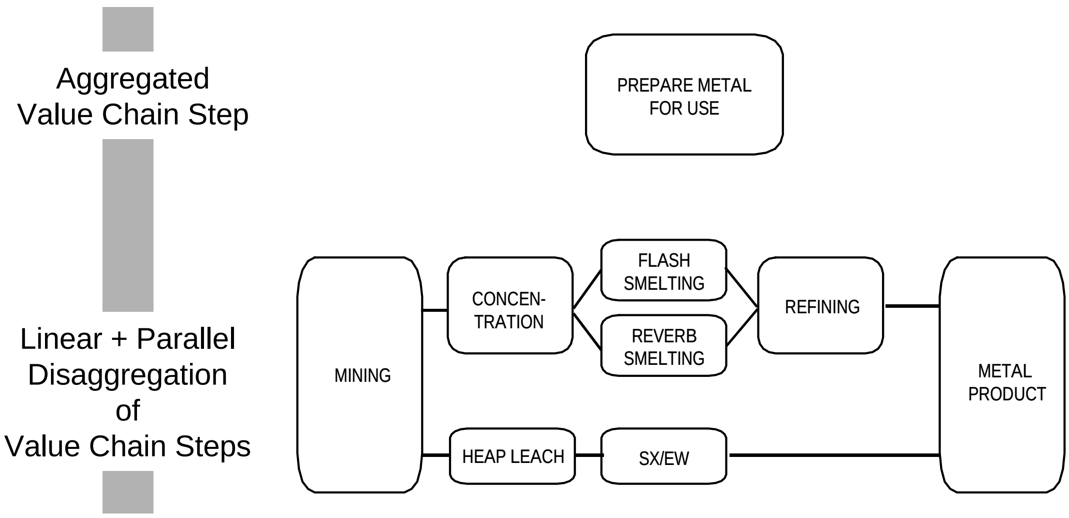


Figure 7-3: Disaggregation of process steps within 'preparation for use' node. Linear disaggregation is the separation of the generic process steps such as 'mining, concentration, smelting....' while parallel disaggregation is the specification of 'flash and reverberatory smelting' in place of the generic smelting step.

7.2.2.1 *Mining and concentration*

Before the 20th century, copper was primarily sourced from underground mines (Ayres et al., 2001) with ore grades in excess of 8% copper. Progressively through the 20th century, large scale equipment made the mining of lower grade ores (less than 1%) from above ground deposits more profitable and combined with the decline in available higher grade ore bodies, open cut mining accounts for over 80–95% of copper currently mined at an average ore grade of 0.5%. The implication of mining lower and lower ore grades is a significant increase in the environmental burden associated with the mining process.

While underground mining is more energy intensive than open cut mining, both processes require more energy to process copper from lower grade ores – for example, the global warming burden increases three to fourfold when mining a 0.5% copper ore compared to a 2% copper ore (Norgate and Rankin, 2000). The mined ore is then processed into a 'concentrate' of approximately 30% copper which can then be fed into a smelter (generally either a variant of a flash smelter or a reverberatory smelter). Alternatively, the mined ore can be processed hydrometallurgically by the Heap Leach/ Solvent Extraction (SX)/ Electrowinning (EW) method. These three classes of technology are representative of over 90% of copper processing undertaken around the world in 1999 (Riekkola-Vanhanen, 1999). Having described the mining and concentration steps in the disaggregated value chain representation, Sections 7.2.2.2 to 7.2.2.4 consider the background to the operation of the three principal copper refining technologies. This establishes the background information for subsequent modelling of these technologies in Section 7.2.3. For a more extensive description of these copper processing technologies see Biswas and Davenport (1994).

7.2.2.2 *Pyrometallurgy I: Reverberatory Smelting & Electric Smelting*

Reverberatory smelting was once the mainstay of smelting operations, but the last new reverberatory furnace was commissioned in 1976 (Biswas and Davenport, 1994). Essentially, reverberatory smelters burn hydrocarbons to create a hot furnace which acts as a large melting unit for copper concentrate to make molten copper matte and a slag. Large quantities of SO_2 are generated in the process from the oxidation of sulfur which is also contained (together with iron) in the copper concentrate. The matte is further refined to give a final copper product and the iron-rich slag is discarded. Since then, flash smelting technology has superseded reverberatory smelting due to decreased operating costs and better gaseous SO_2 management such that it can be subsequently used for sulfuric acid production. An environmental concern with reverberatory furnaces is the large quantities of SO_2 they to the atmosphere which in turn contributes to the formation of acid rain. Reverberatory furnaces have been classed as a separate technology class in this comparison as they still represent a significant (approximately 15%) proportion of worldwide processing capacity. Electric smelting has been included with reverberatory smelting as it is has similar energy requirements to reverberatory smelting. There are very few electric smelters (only 3 or 4) being used for primary production worldwide, so the environmental performance in this class will be dominated by reverberatory smelting operations.

7.2.2.3 *Pyrometallurgy II: Flash Smelting & similar technologies*

Flash smelting is the dominant technology currently utilised in the copper industry and in particular, the Outokumpu flash smelting technology. Approximately half of all smelters currently operating use the technology, which continues to be installed in new operations (Davenport, 1999; Hanniala et al., 1999). Consequently, Outokumpu technology is the basis for environmental performance modelling in the flash smelting class in this case study. For this study, other high intensity oxygen enriched smelting technologies such as Inco flash smelting, Noranda, El Teniente, Mitsubishi and IsaSmelt are included in the same class as they have similar feed and energy requirements and approximately comparable emissions. Essentially, the flash smelters (and similar) burn the feed concentrates in an oxygen-rich environment to produce a matte and slag. The slag is often reprocessed to recover copper contained in it. The matte is further refined to give a pure copper product.

7.2.2.4 *Hydrometallurgy: Acid Heap Leach, Solvent Extraction Electrowinning*

Hydrometallurgical copper processing based largely on the heap leach/solvent extraction /electrowinning combination (SX/EW) considered here, represents the most rapidly expanding class of technologies under development (Davenport, 1999). This is in part driven by a decline in the availability of higher grade ores (e.g. >2% copper) necessitating increased mining of lower grade ores (e.g. 0.5% copper). When lower grade ores are processed into concentrates, they can contain high impurity levels which prevent flash smelter processing. In these cases, hydrometallurgical processing of the ore may be a viable option, as it can better handle contaminated feeds. Furthermore, hydrometallurgy is practised with both copper oxide ores as well as sulfide ores. Oxide ores are not processed in flash smelters as they lack sulfur in the feed, which is needed for the oxidation reaction which supplies heat to the furnace. Oxides are also less amenable to froth flotation which is required to make the concentrate used in smelters. However, SX/EW uses more energy per tonne of metal produced (Alvardo et al., 2002; Norgate and Rankin, 2000) which can carry an increased environmental burden, lixiviants may be toxic in hydrometallurgical processing (Ritchie, 1998) and the solid waste from SX/EW operations can contain more mobile metal species than from pyrometallurgy representing an increased toxicity potential which is not well quantified.

In hydrometallurgical copper processing, the majority of operations are an acid heap leach followed by solvent extraction and electrowinning, although other processes based on bio-leaching and chloride leaching are gaining interest. An innovate hydrometallurgical technology based on a bromine-chlorine leach is evaluated in Chapter 8, after the current environmental profile of the industry is established in this chapter.

7.2.3 *Flowsheets and models*

Flowsheets for flash and reverberatory smelting and heap leach, solvent extraction electrowinning (SX/EW) are presented in Figure 7-4, Figure 7-5, Figure 7-6.

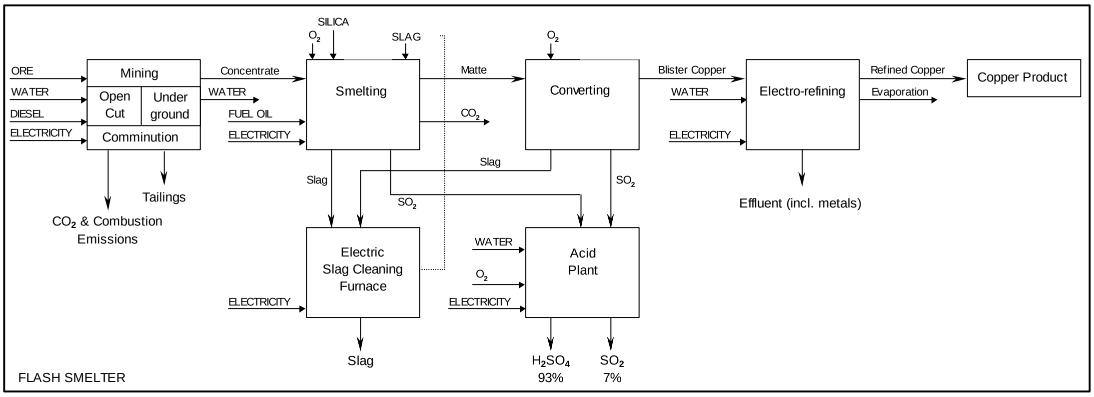


Figure 7-4: Flowsheet of Flash Smelter

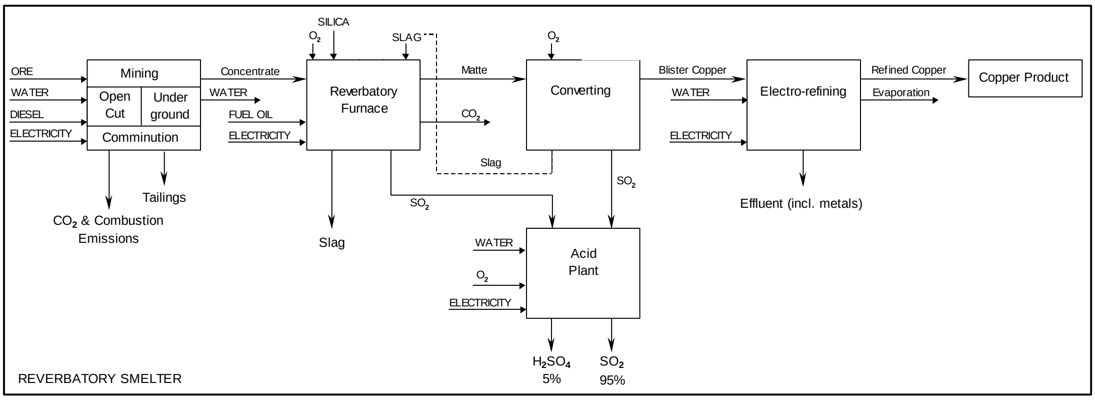


Figure 7-5: Flowsheet of Reverberatory Smelter

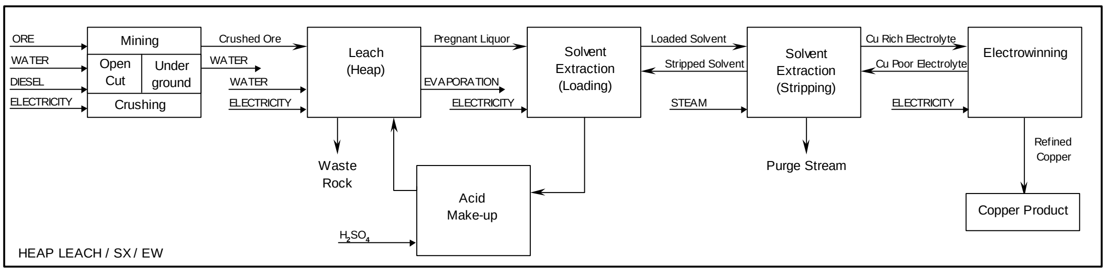


Figure 7-6: Flowsheet of Heap Leach / Solvent Extraction / Electrowinning

In line with the methodology outlined in Chapter 4, these models are designed to track principal mass and energy flows. A copper recovery is specified for each node and inputs (such as diesel and electricity) and emissions (such as CO_2 and SO_2) from each node are linked to mass throughput through the node. This information used to construct average technology performance was taken from the literature and is described in Section 7.2.4.

From these flowsheets, the level of detail of inputs and outputs included in the models and the system boundary for each technology can be seen. Consistent information detail has been ensured for each model. This allows valid comparisons to be made between technologies. In LCA terms, the system boundary applied to these technologies can be termed 'cradle-to-gate', that is, from initial extraction of the ore (cradle) to the processing of refined copper, out the 'gate' of the processing plant.

Mass flow models were developed in Microsoft Excel using the approach described in Chapter 4. Sulfide ore was modelled for the feed to each technology, as this accounts for over 80% of copper mined worldwide. In addition to the inputs shown in Figure 7-4, Figure 7-5, Figure 7-6, the elements of Cu, Fe and S (which are the principal components by mass in a copper sulfide ore) were tracked through the process. All heavy metals/contaminants and the remaining gangue/waste rock were also monitored.

The models can easily accommodate changes in ore grade, mining method (above ground/underground) fuel and electricity consumption and total throughput for each process. By using the goal seek function for a desired throughput, the required quantity of feed (depending on the ore quality) and all other inputs and outputs are calculated for a specified demand.

7.2.4 *Principal model assumptions*

Table 7-1 lists the principal assumptions used to define the performance of unit processes within the system boundary. The reference year is 1999. The ore grade, mining method and electricity supply are consistent across process options in order to assist comparison between the performance of the individual technologies themselves. All other assumptions are detailed in Appendix A.[5] An equivalent ore grade was used for each technology to highlight the technology-specific differences in performance.

[5] Descriptions of secondary processing technologies and assumptions are also given in Appendix A for comparison and later use in the case study in Chapter 9.

Table 7-1: Principal modelling assumptions (Biswas and Davenport, 1994; Norgate and Rankin, 2000; Riekkola-Vanhanen, 1999)

	Reverberatory Smelter	Flash Smelter	Heap Leach SX / EW
Ore type	Sulfide	Sulfide	Sulfide
Ore grade	0.5% Cu	0.5% Cu	0.5% Cu
Mining method	Open cut	Open cut	Open cut
Overall Recovery	88%	88%	62%
Total Electricity (kWh / t Cu)	5 700	6 000	9 350
Electricity supply	Coal Based Power	Coal Based Power	Coal Based Power
Fuel Oil (t / t Cu)	0.48	0.15	0
Diesel (t / t Cu)	0.46	0.46	0.65
SO_2 capture for H_2SO_4 production	5%	93%	—
H_2SO_4 acid make up (t / t Cu)	—	—	1.7

7.2.5 *Selection of performance indicators*

In this case study, the aim is to be able to characterise the average performance of a technology without knowledge of site-specific conditions. As mentioned in Chapter 4, LCA has the flexibility to be used without site-specific information. LCA establishes the system-impact link by providing information on the performance of a process relative to its potential to contribute to recognised local and global environmental problems: for example, global warming, ozone depletion, acidification, eutrophication, human toxicity, ecotoxicity and smog.

To briefly recapitulate LCA involves: defining a boundary for the system under investigation; creating an inventory of inputs and outputs for this system; assessing the environmental impacts (global warming, ecotoxicity etc.) attributable to these inputs and outputs, based on standard characterisation factors. The results may then be used in an improvement analysis, targeting areas of the process causing the most environmental impact.

This investigation considers how improvements in environmental performance could be made through technology choices; each technology makes the same refined copper product and there is no need to consider the use of this refined copper beyond manufacture, as this is independent of the metals' production method.[6] LCA studies

[6] The issue of impact allocation arising for flash smelting which produces a copper product and a sulfuric acid product is not considered in this work. It is assumed that the production of copper is the primary reason for operating the smelter and similarly for copper smelters producing other metal by-products.

which include the effects of copper consumption by further tracking its manufacture, use and final disposal would be termed 'cradle-to-grave'. No such studies are available in the published literature at this time.

For a detailed description of LCA refer to SETAC (SETAC, 1992). Stewart & Petrie (1996) more specifically outline the use of LCA in minerals processing.

In this current case study, a first-order LCA is performed on three main classes of copper refining technologies: flash smelting, reverberatory & electric smelting and heap leach, SX/EW. The following LCA impact categories were selected for inclusion in the comparison:

- global warming
- acidification
- ecotoxicity
- smog.

Further information regarding these impact categories is given in Table 7-2. The categories were chosen to reflect a breadth of effects which manifest both locally (e.g. ecotoxicity) and globally (e.g. global warming) and which may arise directly from the copper processing (e.g. acidification from smelter SO_2 emissions) or indirectly (e.g. smog, from the burning of coal to provide electricity for the process). This representative selection highlights the usefulness of the LCA approach for describing both local and global effects, and with its wide system boundary, both direct and indirect effects.

Table 7-2: Description of LCA impact categories significant in this study

Table impact category	Description	Impact manifested
Global Warming	Contribution to global warming due to the Greenhouse Effect.	Globally
Acidification	Decreasing the pH of natural systems through mechanisms such as acid rain.	Regionally
Ecotoxicity	In this paper, Ecotoxicity means toxicity to aquatic ecosystems. It is reasoned that any terrestrial toxicity will eventually appear in groundwater and is covered under aquatic toxicity.	Locally
Smog	Atmospheric pollution in the form of smog.	Locally

Norgate & Rankin (2000) undertook an LCA of copper processing, but considering only Global Warming and Acidification effects. This case study extends this approach to include ecotoxicity and smog, with the ecotoxicity of solid waste from minerals processing being a significant impact from the industry (Hansen, 2004). This work also compares a greater number of technologies by including reverberatory smelting in addition to flash smelting and heap leach SX/EW.

7.2.6 *Results of Technology-Specific Performance Assessment*

As a result of coupling LCA indicators to the models of material and linked flows which provided an inventory for each technology, Figure 7-7 describes the environmental performance of each technology in four impact categories: global warming, acidification, ecotoxicity and smog. Each category has one substance as a reference. For global warming, CO_2 is the reference and other compounds contributing to global warming are scaled accordingly, for example CH_4 has 21 times the greenhouse forcing potential of CO_2.

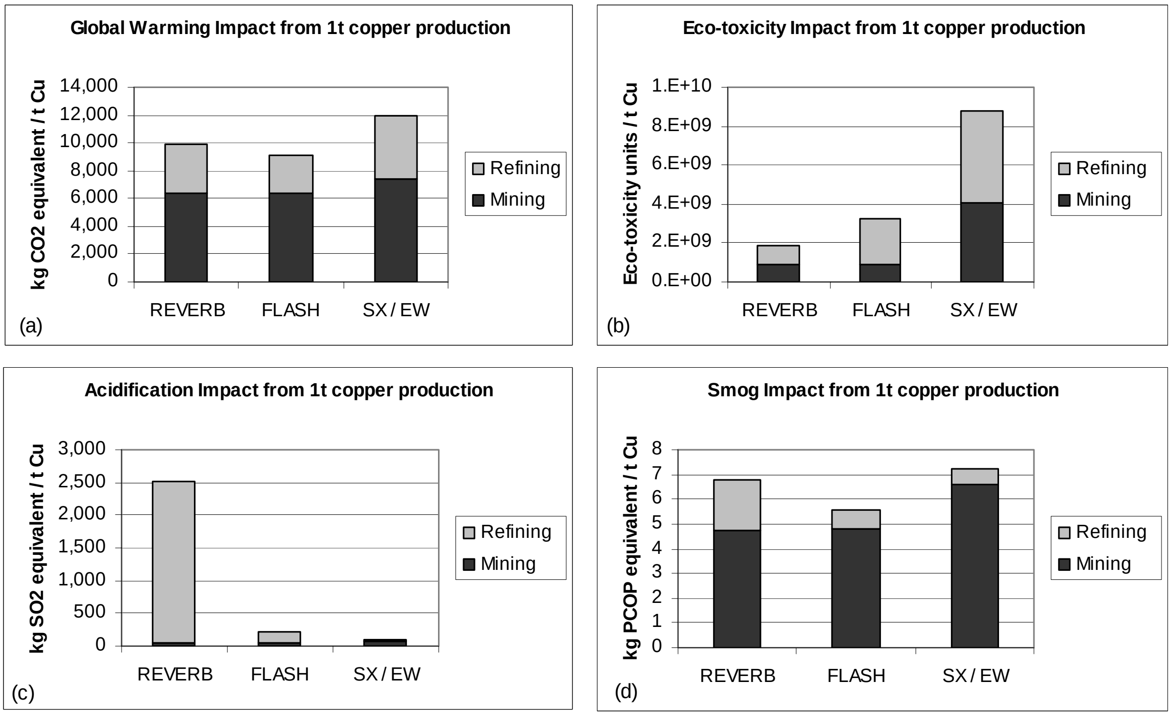


Figure 7-7: Principal environmental impacts for production of 1 tonne refined copper

The representation in Figure 7-7(a) is hence a depiction of the global warming potential in equivalent kilograms of carbon dioxide per tonne of refined copper (kg CO_2 eq. / t Cu). The reference substance for acidification is sulfur dioxide (SO_2). For smog, POCP is the abbreviation for photochemical oxidation potential, and the reference substance is ethene. Ecotoxicity is expressed relative to the ecotoxicity of the reference substance, chromium (VI).

7.2.6.1 *Global Warming*

Figure 7-7(a) shows that flash smelting and reverberatory smelting have a similar global warming impact. Reverberatory smelting does not obtain energy from the burning of sulfides and consequently has a significant fossil fuel requirement to maintain high temperatures in the furnace. Flash smelting harnesses energy from the burning of the copper sulfide concentrates by adding oxygen to the furnace and requires only a small fossil fuel input for temperature control. However, pure oxygen manufacture requires considerable electricity, which using coal based power, results in an approximately equivalent overall global warming contribution. SX/EW has the highest global warming impact due to its high electricity requirement. Electricity consumption is much higher for electrowinning (in SX/EW) than for electro-refining due to electrowinning's high voltage requirement (~3 V) compared with electro-refining (~0.2 V) (Biswas and Davenport, 1994).

7.2.6.2 *Acidification*

The acidification potential is significantly higher for the reverberatory furnace, due to its lack of adequate SO_2 capture, meaning that SO_2 is vented directly to atmosphere. While no SO_2 is produced at the SX/EW plant, the associated acidification effect arises from the burning of coal for electricity generation.

7.2.6.3 *Ecotoxicity*

The ecotoxicity for the SX/EW process is higher due to its lower overall recovery of copper (65%) compared with that of the other processes (88%).

7.2.6.4 *Smog*

Smog arises mainly through the burning of diesel associated with mining, meaning it is an indirect effect not occurring within the smelter/refinery boundary.

Having established the environmental performance per tonne of copper using average data, the sensitivity of this analysis to changes in system variables underlying the modelling is now investigated.

7.2.7 *Identifying key variables via sensitivity analyses*

The identification of key sensitivities to environmental performance enables more accurate and functional models to be developed. Accuracy is increased by including additional information detail with respect to sensitive variables. Functionality will be increased, by treating all other variables (for which environmental performance is not sensitive) as constants in future analyses. This will be of particular importance when using the technology models developed in this chapter to envision paths toward alternate futures in Chapter 9.

7.2.7.1 *Technology sensitivity*

The effect of changes in technology model variables is assessed through a sensitivity analysis where each variable is changed by ±20% and the resultant change in impact is observed. The results of the sensitivity analysis for flash smelting are summarised in Table 7-3.

Table 7-3: Sensitivity of variables in Flash Smelting

	Variable Change	Greenhouse	Acidification	Eco-toxicity	S.Smog	Water
MineUnderGnd_Elec_Rate_kWh_per_t ore	+	●				
MineOpenCut_Elec_Rate_kWh_per_t ore	+	●				
MineOpenCut_Water_Rate_t_per_t ore	+					●
MineOpenCut_Diesel_Rate_t_per_t ore	+				●	
Percent Open Cut Mining	+	◯			●	◯
Ore_Cu_Rate_percent	+	○			○	○
Overall_Cu_Recovery_percent	–	⬤	●	⬤	⬤	⬤
Smelt_SO2_Rate_t_per_t Cu_in_conc	+		●			
Converter_O2_Rate_t_per_t conc	+		●			
Converert_SO2_Rate_t_per_t O2	+		●			
BlisterCopperQuality_Cu_Rate_percent	–			⬤		
SlagCleaning_Slag_Fe_Rate_percent	+			●		
GasTreatment_SO2_to_acid_Rate_percent	–		⬤			
Electricity Mix (North America)	+	⬤				●

A solid dot indicates that the impact moves in the same direction as the change in variable and for a hollow dot, the impact moves in the opposite direction. For example, as the ore grade increases (indicated by a +), greenhouse emissions decrease (indicated by ○), whereas for a decrease in copper recovery (indicated by a –), greenhouse emissions increase (indicated by ●). Small, medium and large sensitivities are represented by increasingly sized dots. The full results for all technologies are given in Appendix A.

The sensitivity analysis reveals the greatest sensitivity with respect to global warming potential for the percentage of ore mined underground versus open cut, overall copper recovery and energy mix. Ore grade and the amount of energy used in mining were also sensitive.

The identification of key system variables affecting environmental performance is important. When considering alternate futures, the actors who control these variables can be the particular focus of investigation. For better describing the status quo, region-specific information detail (rather than average global data) can be used to provide a more accurate representation, while minimising additional information gathering.

7.2.7.2 *Further discussion of sensitivity to electricity mix*

Given that electricity mix is a key sensitivity, it is important to understand more about the range of variation between electricity generation types and the combination of sources used around the world. The difference in impact between electricity from different sources is shown in Table 7-4. Water usage has been substituted in place of the smog impact category here.

Table 7-4: Characterisation impact factors used in this study (Simapro, 1999)

	Global Warming (kg CO_2 eq.)	Acidification (kg SO_2 eq.)	Water Usage (L)	Ecotoxicity (Relative units)
Electricity: Natural gas (per kWh)	0.772	0.00138	2.46	929
Electricity: Coal (per kWh)	1.02	0.00608	37.8	6910
Electricity: Nuclear (per kWh)	0.00858	0.0000859	9.04	233
Electricity Hydro (per kWh)	0.00412	0.000022	0.09	22.5
Electricity Oil (per kWh)	0.889	0.0105	70.9	9260

This data set shows orders of magnitude differences associated with each impact category for different forms of electricity generation. Clearly the type of electricity is a significant influence on environmental performance.

Table 7-5 shows the composition of regional electricity sources across the globe.

Table 7-5: World electricity mixes (U.S. Department of Energy, 1999)

	North America	Latin America	East Asia	Central Asia	Africa	Oceania	Europe	World Avg.
Natural Gas	13%	11%	15%	36%	0%	10%	14%	15%
Coal	45%	10%	41%	24%	80%	80%	23%	39%
Nuclear	19%	1%	15%	8%	10%	0%	35%	16%
Hydro/Renew	19%	76%	17%	20%	10%	10%	22%	20%
Oil	4%	2%	12%	12%	0%	0%	6%	10%

The combination of the regional electricity impact profiles is compared with that used for coal in Figure 7-8. It shows that except for smog impacts in China / South East Asia and Russia / Mid East / India, using models based on coal based power represents a worst case scenario, as actual regional impacts from electricity generation are between 20% to 80% less.

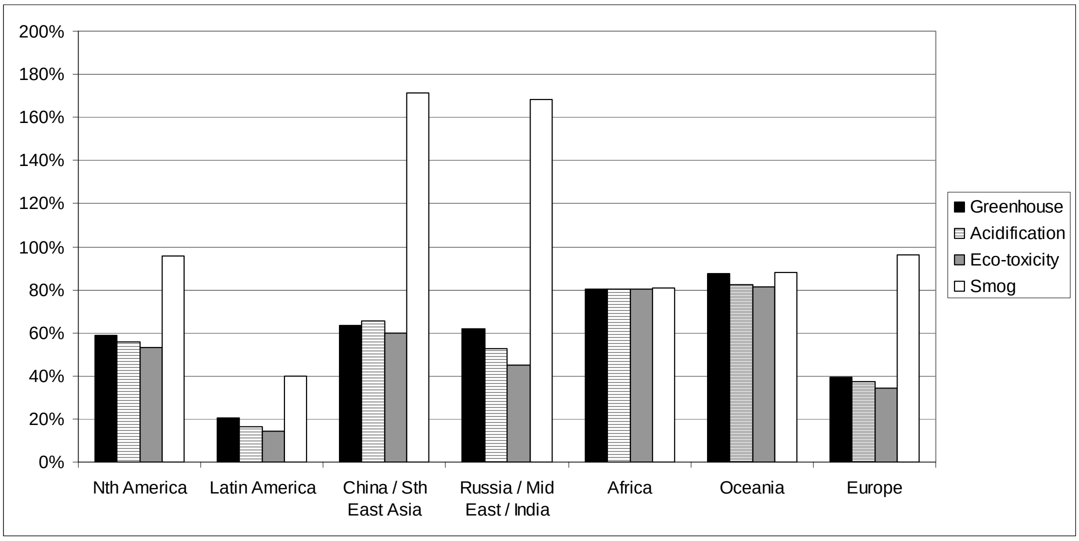


Figure 7-8: Relative environmental burdens of regional electricity mixes relative to coal-based power

7.2.8 *Demonstration of sensitivities to ore grade and electricity mix*

This section explores a more detailed analysis of the technologies in two specific countries: Australia, and Chile – the world's largest copper producer. In response to the Kyoto Protocol, there is increasing pressure on countries to examine their contribution to global warming. The case study presented here considers the actual ore grade and electricity mix for each technology in both countries. These are two of the most important factors affecting global warming, which, in addition to the copper processing technology itself, have a significant impact on the overall environmental performance of the process.

Table 7-6 lists the principal assumptions for the models in this case study. The results of the environmental performance modelling are presented in Table 7-7.

Table 7-6: Principal assumptions for Chile / Australia comparison

	Ore Grade (% Cu)	Electricity Mix	
		Hydro	Coal
Reverb Smelter (Chile)	1.4	70%	30%
Flash Smelter (Chile)	1.4	70%	30%
Flash Smelter (Australia)	1.3	–	100%
Heap Leach SX/EW (Chile)	0.7	70%	30%
Heap Leach SX/EW (Australia)	2.6	–	100%

Table 7-7: Environmental impacts for the production of 1 tonne refined copper product

	Water (m^3)	Energy (MJ)	Global Warming (kg CO_2 eq)	Acid-ification (kg SO_2 eq)	Eco-toxicity (Rel. units)	Smog (kg POCP equiv.)
Reverb Smelter (Chile)	100	59 000	4 300	2 500	240 000	3.4
Flash Smelter (Chile)	100	44 000	3 300	160	89 000	2.2
Flash Smelter (Australia)	110	70 000	8 400	180	97 000	2.4
Heap Leach SX/EW (Chile)	190	82 000	6 200	40	48 000	4.7
Heap Leach SX/EW (Aust)	30	81 000	10 600	40	26 000	1.5

The results of the case study highlight a number of significant points arising from the difference in ore grade and electricity mix between the two countries. Energy use in SX/EW processes is much higher than for reverberatory and flash smelting. Chile's energy use per tonne of copper is the highest of all processes due to it utilising the lowest grade ore. However, the global warming effect of Chile's SX/EW process is still less than for both the SX/EW and flash processes in Australia. This is due to Chile's high percentage of electricity sourced from hydropower.

While the use of hydropower in Chile reduces the global warming burden of its SX/EW process, one impact which it does not assist in reducing is smog. As a direct result of the low ore grade used for SX/EW in Chile – which requires more diesel for mining and ore transport – the smog effect is much higher than for SX/EW in Australia. Water consumption for SX/EW in Australia is lowest due to its high ore grade.

This analysis, highlights the usefulness of integrating regional circumstances into the assessment. Technology choices can then be supported with an understanding of local conditions and region-specific concerns for particular environmental effects. These figures were calculated on a per tonne of copper produced, but did not take account of the tonnages produced by different technologies in different regions.

7.2.9 *Regional Technology Distribution*

The analysis of comparative performance between individual technologies on a per tonne basis was undertaken in Section 7.2.6. In order to better represent the spatial distribution of impacts, the split between technologies used in each world region and the total throughput of each region. Both pieces of information are represented in Figure 7-9.

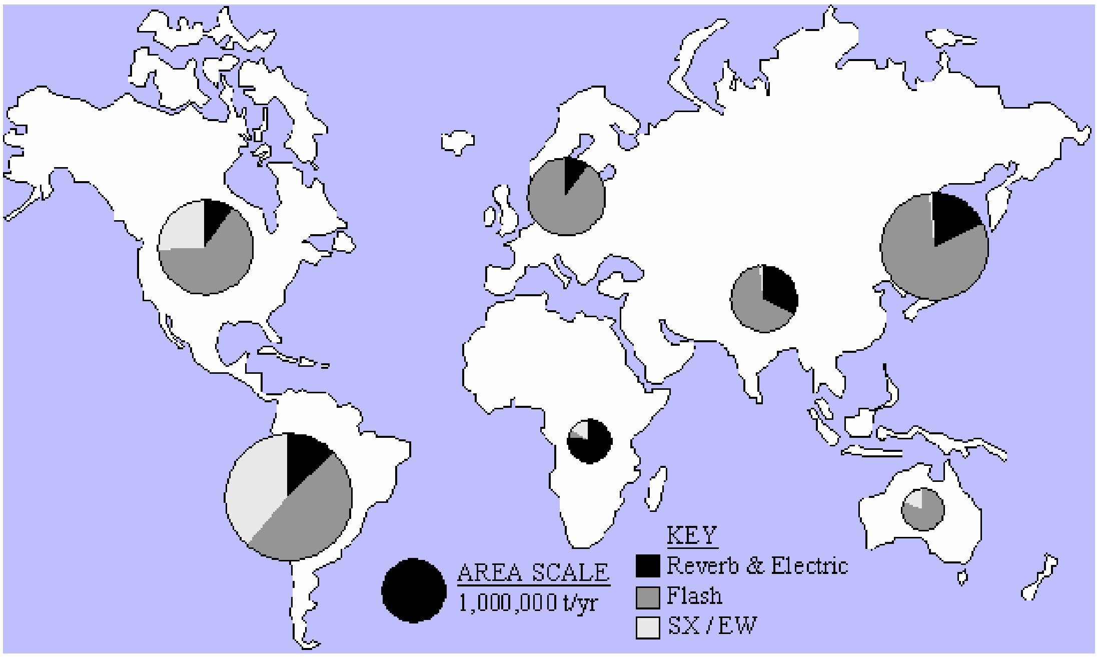


Figure 7-9: Technologies used for copper refining across the world- size of circle relative to 1999 production (compiled with data from (Biswas and Davenport, 1994; Edelstein, 1999; Moreno, 1999))

From this representation, the significant points are:

- More than one technology type is used in each region
- Flash smelting is the dominant technology in use today
- SX/EW is most utilised in North and Latin America
- Reverberatory smelting still accounts for 10–15% of world production, and the only region without continued reverberatory smelting is Oceania.

The countries represented in the regions depicted in Figure 7-9 are detailed in Table 7-8.

Table 7-8: Description of countries falling within regional classifications

Region	Countries
North America	Canada, United States of America
Latin America	Mexico and Central America, South America
Europe	Western Europe, Bulgaria, Cyprus, Macedonia, Poland, Romania, Serbia, Slovakia
Central Asia	Russia, India, Armenia, Georgia, Iran, Kazakhstan, Oman, S. Arabia, Turkey, Uzbekistan
East Asia	China, Mongolia, Nepal, Japan, South East Asian and Pacific Rim countries
Africa	All of Africa
Oceania	Australia, Papua New Guinea, New Zealand

This information can now be coupled with the impact profiles from Figure 7-7 to provide a baseline characterisation of impacts for regions across the globe incorporating technology-specific detail.

The region-specific ore grades are given in Table 7-9 which additionally affects the environmental performance. Regional data for the recoveries of technologies were unavailable and not included.

Table 7-9: Average regional copper ore grades

Region	Copper Ore Grade
North America	0.47%
Latin America	1.00%
Europe	1.50%
Central Asia	1.51%
East Asia	1.13%
Africa	3.00%
Oceania	1.56%

7.2.10 *Regional impact profile for baseline environmental performance*

By combining technology models with region-specific information a distribution of impacts for regions across the globe is presented in Figure 7-10. Each column represents the percentage of the total impact for that category which is noted in the legend.

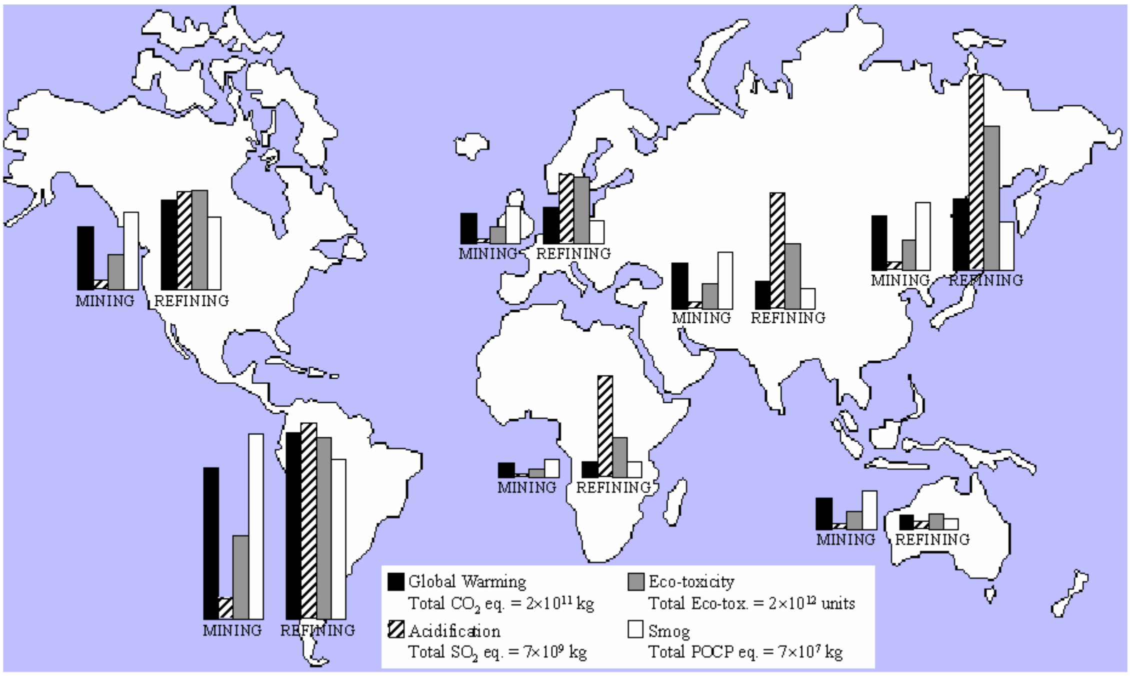


Figure 7-10: Distribution of Global Warming, Acidification, Ecotoxicity, Smog Impacts for mining and refining

The importance of Figure 7-10 is that it presents an overview of the distribution of environmental impacts from copper processing worldwide, from which changes to the status quo can be compared. Linking the impact distribution back to copper consumption for regions across the globe initially presented in Figure 2–2, it prompts the further need for large consuming regions such as Europe – who only have a small burden associated with copper mining and refining – to assume more responsibility for the copper used in its economy which is extracted and refined elsewhere and seek to improve the performance of the value chain which services its demand.

7.2.11 *Discussion*

This case study has characterised flows and impacts to give a baseline environmental performance of the status quo. Variability to changes in ore grade, recovery and electricity mix were highlighted in the sensitivity analysis as having a significant influence on environmental performance. Consequently, these factors can be specified using region-specific data to give a more accurate representation of environmental performance which is used in the next case study. It seeks to understand the impact which regional differences could have to the impact associated with imported copper in Europe.

7.3 REGIONAL SENSITIVITIES: REDUCING THE IMPACT OF COPPER IMPORTS TO EUROPE

7.3.1 *Aims and scope*

The technology modelling in Section 7.2 showed the impacts for the status quo and sensitive system variables of ore grade and electricity mix. In response to these identified sensitivities, this case study uses technology models with greater information detail, to explore the improvement in environmental performance for supplying copper to market in Europe by importing copper from different regions to meet demand. This potential improvement is possible in the short term without any change to processing infrastructure in Europe. More ambitious system changes introducing new technology infrastructure to the value chain are explored in (Chapters 8 and 9).

In order to demonstrate this approach, the baseline performance is mapped for the region of Europe using region-specific data. The region of Europe was chosen for analysis as it is has a developed economy with a large per-capita consumption of copper, with a mixture of local processing and imported copper being used to meet demand. Within this context, the European Union as a collective actor, is actively seeking to improve environmental performance – for example, through their support for the Kyoto protocol on greenhouse gas induced climate change (Christen, 2002). Quantifying the magnitude of improvement possible by changing material chain configurations within existing infrastructure, provides insight into whether more radical system changes (e.g. new processing technologies, increased recycling) are needed to improve performance to desired targets. Additionally, the trade-offs between potential environmental impacts associated with different configurations are made explicit together with their location outside Europe. Extending this analysis with data describing the financial performance of each configuration would highlight externalities not reflected in prices and could be used to guide policy development to balance these externalities.

7.3.2 *Status quo for Europe*

To begin the analysis, this section maps the status quo of material flows and environmental impact for Europe. It uses region-specific information detail as a more accurate baseline (than that using global averages) for comparison of future states in this case study.

The current network structure in place for supplying copper to Europe is represented in Figure 7-11.

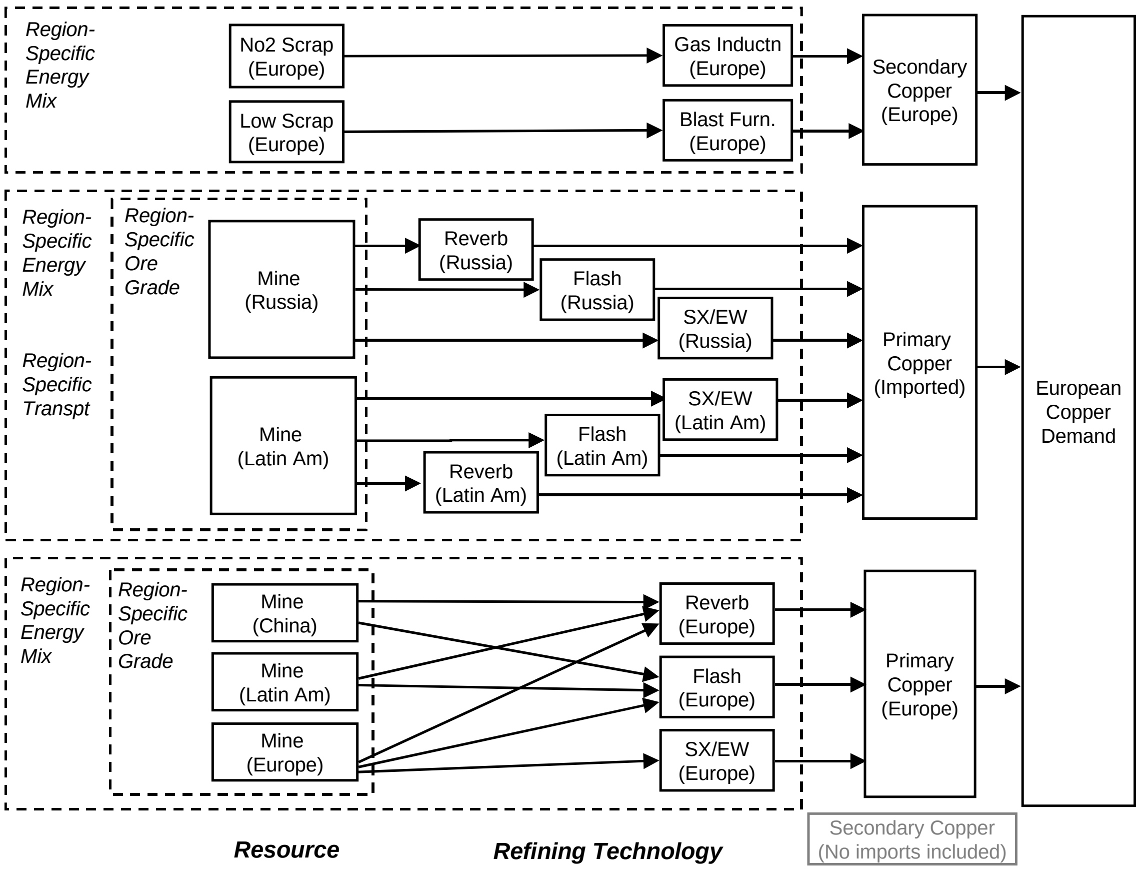


Figure 7-11: Material chain structure supplying copper to Europe

As shown in Figure 7-11, to meet the demand for copper in Europe, there are three principal sources of copper: primary copper refined in Europe (either mined in Europe or elsewhere), primary copper imported into Europe and secondary copper re-refined in Europe.[7]

[7] Secondary copper which is imported into Europe provides a small contribution to impact and is not considered.

Using the technology models developed in Chapter 7 with the region-specific data, the equivalent global warming impact associated with each principal source of copper for Europe is shown together with tonnages supplied by each source in Figure 7-12.[8]

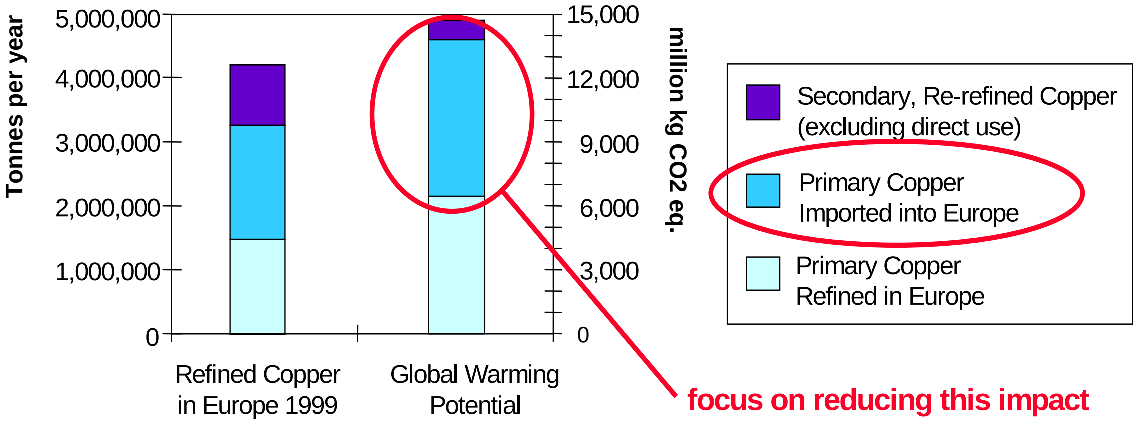


Figure 7-12: Global warming potential associated with refined copper used in Europe

The representation in Figure 7-12 allows a focus area for variables allowing system improvement within the existing infrastructure to be easily identified. Of the three impact profiles, primary copper refined in Europe and imported into Europe are the most impacting and represent a focus for improvement. This case study seeks improvements using existing infrastructure within Europe and does not change the structure of copper refining in Europe. Consequently, the circled region relating to the importation of copper to Europe from regions with different technology mixes, ore grades, electricity mixes and transport distances are evaluated to demonstrate the approach of performance improvement within existing infrastructure.

7.3.3 *Actor influence of system variables*

In this case study targeting a shorter term 'vision', the actor-system variable link is assessed and changes proposed which are deemed possible in the near future. This requires an initial analysis of the actors represented in this case study.

[8] The ability to track multiple environmental impacts was demonstrated in Chapter 7, here the initial focus regards global warming. The performance for other impacts is highlighted later in this chapter.

Table 7-10 highlights the actors linked to the supply of copper to market in the European value chain.

Table 7-10: Actors in the system

Actor	Intervention	Level of Control - Short Term	Level of Control - Long Term
Mining / Refining Company	Technology Change	Low	High
Importers	Change raw material suppliers	Medium	High
Manufacturers	Change suppliers of metal	Medium	High
EU Government	Promote use of copper in Europe with less CO_2 burden associated with its manufacture	Medium / High	High

The principal actors with the ability to control system variables identified in this case study are European Policy Makers who through their encouragement of buying strategies, such as those reducing greenhouse burdens, could alter the types of imports into Europe. While these changes to do not involve changes to infrastructure, they will involve a change to supplier contracts and partnerships.

7.3.4 *System model*

The variable to be the focus of this case study is the origin of primary copper imports into Europe. This variable has been identified as the source of significant impact and under the potential control of European Union policy makers and Europe's imports constituting a large proportion of the global warming impact as identified in the baseline environmental assessment in Figure 7-12. Changing the source of imports does not require any changes to infrastructure on the part of the European industry.

The ability to reduce impacts will come from the difference in impacts associated with sourcing from different regions around the world (based on different ore grades and electricity mixes and transport distances). This is represented in the diagram of the current network structure in Figure 7-13 (overleaf).

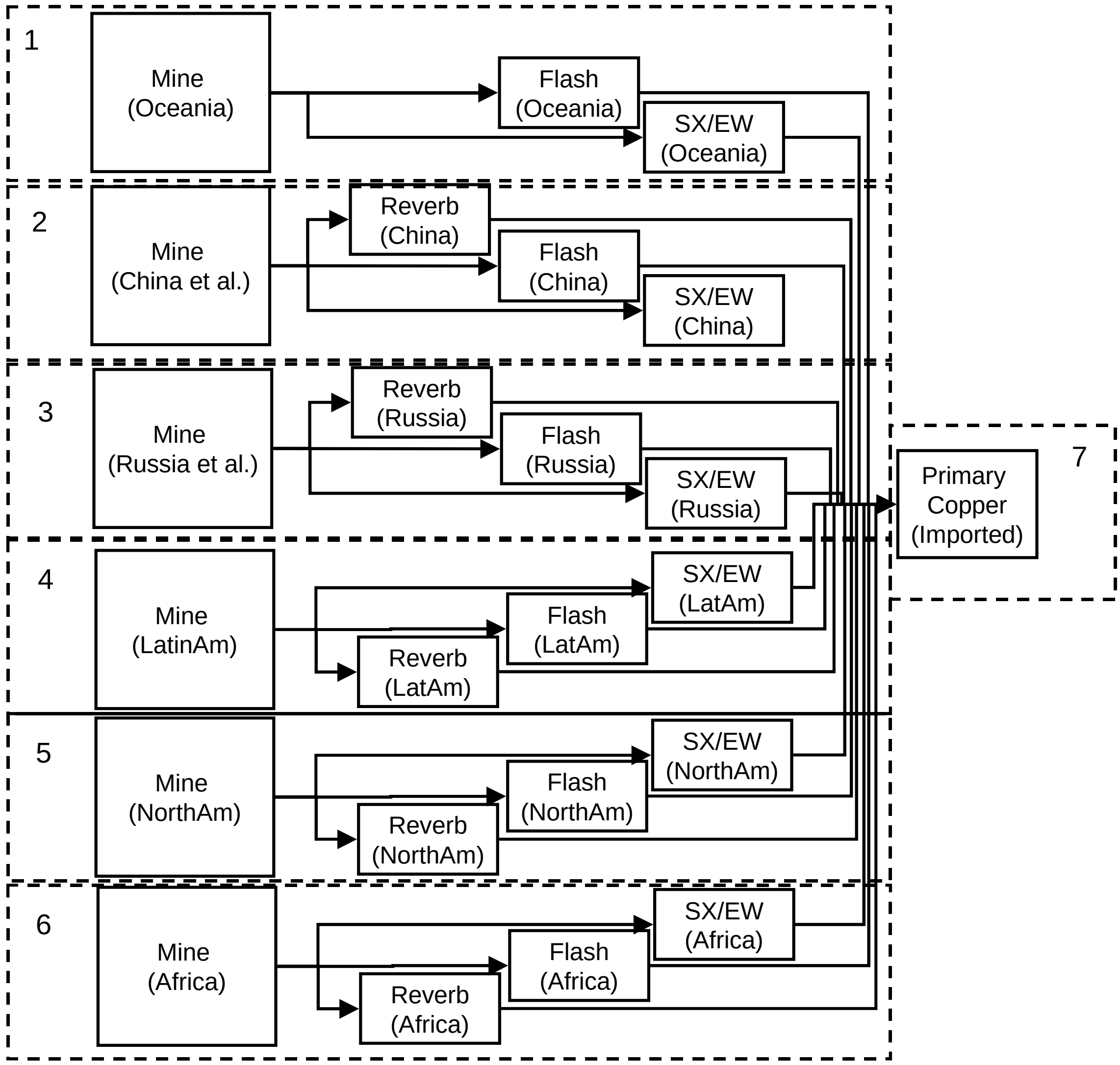


Figure 7-13: Configuration of material chain to be optimised, with each dotted box (1-6) representing a potential source of imported copper to meet demand (7)

7.3.5 *Assessing improvement potential*

To assess improvement potential, a model is required to link system configuration and environmental performance which can then be optimised within the capacity constraints of current production in each region.

To consider improvement arising from sourcing imported or from alternative locations, each of the potential paths must be described in the network and then linear programming techniques used to determine optimal allocation of flows between potential sources, based on relative impacts of each source and constraints on availability of supply from each region.

Consequently for this system, the configuration may be simplified to a series of linear equations for flows through each node to meet the demand.

$m_{17} + m_{27} + m_{37} + m_{47} + m_{57} + m_{67} = m_7$ (Demand of 1,500,000 tpa) Equation 7-1

Based on the previous modelling work in Chapter 7 modelling linked flows and impacts for each technology and the relative proportions of flash, reverb and SX/EW in each region, the local ore grade, electricity mix and transport distance to Europe – a final average impact profile vector for sourcing copper from each region can be created. This is presented in Table 7-11. The splits between technologies used in each region are fixed and are taken from Figure 7-9.

Table 7-11: Impact vectors per tonne of copper product for regions outside Europe

	Global Warming kg CO_2 eq	Acidification kg SO_2 eq	Ecotoxicity Relative units
Avg Africa	5.4×10^3	19.8×10^2	3.0×10^9
Avg China et al. (East Asia)	5.5×10^3	6.3×10^2	3.0×10^9
Avg Russia et al. (Central Asia)	4.3×10^3	9.3×10^2	2.8×10^9
Avg Oceania	6.4×10^3	1.9×10^2	4.3×10^9
Avg Latin	4.0×10^3	4.4×10^2	5.1×10^9
Avg Nth Am	8.1×10^3	4.2×10^2	4.5×10^9

The form of the optimisation will be an allocation of flows between streams in order to minimise impact for a single performance indicator. The allocation is performed to minimise impact while complying with imposed constraints based on availability. The availability for each region is shown in Table 7-12.

Table 7-12: Constraints of available primary ore in each world region (1999 figures)

	Availability (t.p.a)
Africa	439 000
China et al. (East Asia)	2 848 612
Russia et al. (Central Asia)	1 066 634
Oceania	417 100
Latin America	3 906 769
North America	2 217 500

The optimisation problem can be represented as

$$\text{Minimise GWP} = P_1 m_{17} + P_2 m_{27} + P_3 m_{37} + P_4 m_{47} + P_5 m_{57} + P_6 m_{67} \quad \text{Equation 7-2}$$

where P_n are the GWP performance scores for each region and all mass flows must be between zero and their upper constraint.

The Solver in Microsoft Excel was used as the platform for determining the results. A similar objective function can be created to optimise for minimum impact in any performance category.

Beyond optimising for a single criterion at a time, a multiple criteria analysis can be performed as suggested in Chapter 5 which would allow equal preference to be given to each of the three performance criteria or another desired relative weighting between each category that is consistent with stakeholder and decision maker preferences.

A value function, is created which incorporates importance weightings for each criteria and standardised performance scores in each criteria.

$$V = \sum_{c=1}^{n} w_c \cdot \hat{P}_{alt,c} \cdot m_{alt} \quad \text{Equation 7-3}$$

where w_c is the weighting given to criteria / impact category c (for each category from 1 to n) and $\hat{P}_{alt,c}$ is the standardised performance score for each alternative in criteria c and m_{alt} is the mass flow through that alternative.

Standardised performance scores are calculated as shown in Equation 7-4 in order to position the performance of each alternative on a linear scale from best to worst performance[9] with 0 as best performance and 1 as worst.

$$\hat{P}_{alt,c} = \frac{P_{alt,c} - \text{minimum } P_{alt,c}}{\text{maximum } P_{alt,c} - \text{minimum } P_{alt,c}} \quad \text{Equation 7-4}$$

[9] Another common standardisation approach is to divide each raw score by the maximum in that category

The results of standardising values given in Table 7-11 are shown in Table 7-13.

Table 7-13: Standardised effects table and overall value per tonne of copper product for each world region

	G.Warming kg CO_2 eq	Acidification kg SO_2 eq	Eco-toxicity Relative units	Value *V* using equal weightings of one-third for each category
Avg Africa	0.34	1.00	0.08	0.47*
Avg China et al.	0.37	0.24	0.08	0.23
Avg Russia et al.	0.07	0.41	0.00	0.16
Avg Oceania	0.59	0.00	0.63	0.41
Avg Latin Am.	0.00	0.14	1.00	0.38
Avg Nth Am.	1.00	0.13	0.73	0.62

*Sample calculation: (0.34×0.33)+(1.00×0.33)+(0.08×0.33)=0.47

The figures in Table 7-13 show that when each of the three categories is afforded equal weighting, then Russia et al. is first preferred (lowest score for *V*) as a source of imported copper to Europe and then China et al., then Latin America, Oceania, Africa and North America last.

7.3.6 *Indicators and results*

The indicators of performance chosen for this case study are impact categories from Life Cycle Assessment CML[10] methodology and CML 'impact factors' were sourced from Simapro LCA software (PRè, 2000). It is recognised that data quality for such impact factors in LCA is questionable (Bretz, 1998), in particular for minerals and metals (Stewart, 2001) as discussed in Chapter 4. The first principal concern regards the aggregation of potential impacts in LCA over space and time. Actual emissions and resultant impacts will depend on how the process is operated through time and local factors that will affect dose-response characteristics from the emissions are not considered – this is of particular relevance to the exploration phase of mining and to the post-closure plans of mines (Stewart, 2001). Secondly, current practice for calculating the potential ecotoxicity impacts of solid waste emissions does not take account of the stability of the metal in the waste, which will in turn affect the potential toxicity. The case study in Chapter 8 considers this aspect in greater detail.

[10] 'CML' is the 'Centrum Milieukunde Leiden' also known as the 'Institute of Environmental Sciences' at Leiden University, The Netherlands who developed the LCA characterisation factors.

While global warming was selected as the primary impact of concern for which the objective function was optimised, material chain configurations were also optimised for acidification, ecotoxicity and the multiple-criteria case where each was given an equal weighting. The results of the mass flows in each case and their associated environmental impacts are shown in Table 7-14 and in Figure 7-14 overleaf.

Table 7-14: Origin of European imports when optimised per environmental impact

	Origin for 1999 Base Case	Origin for best GWP	Origin for best Acidification	Origin for best Ecotoxicity	Origin for multi-criteria equal weight
Imported Copper (tonnes)	1,500,000	1,500,000	1,500,000	1,500,000	1,500,000
Africa	–	–	–	29 %	–
China et al.	–	–	–	–	29%
Russia et al.	50 %	–	–	71 %	71%
Oceania	–	–	28 %	–	–
Latin America	50 %	100 %	–	–	–
North America	–	–	72 %	–	–

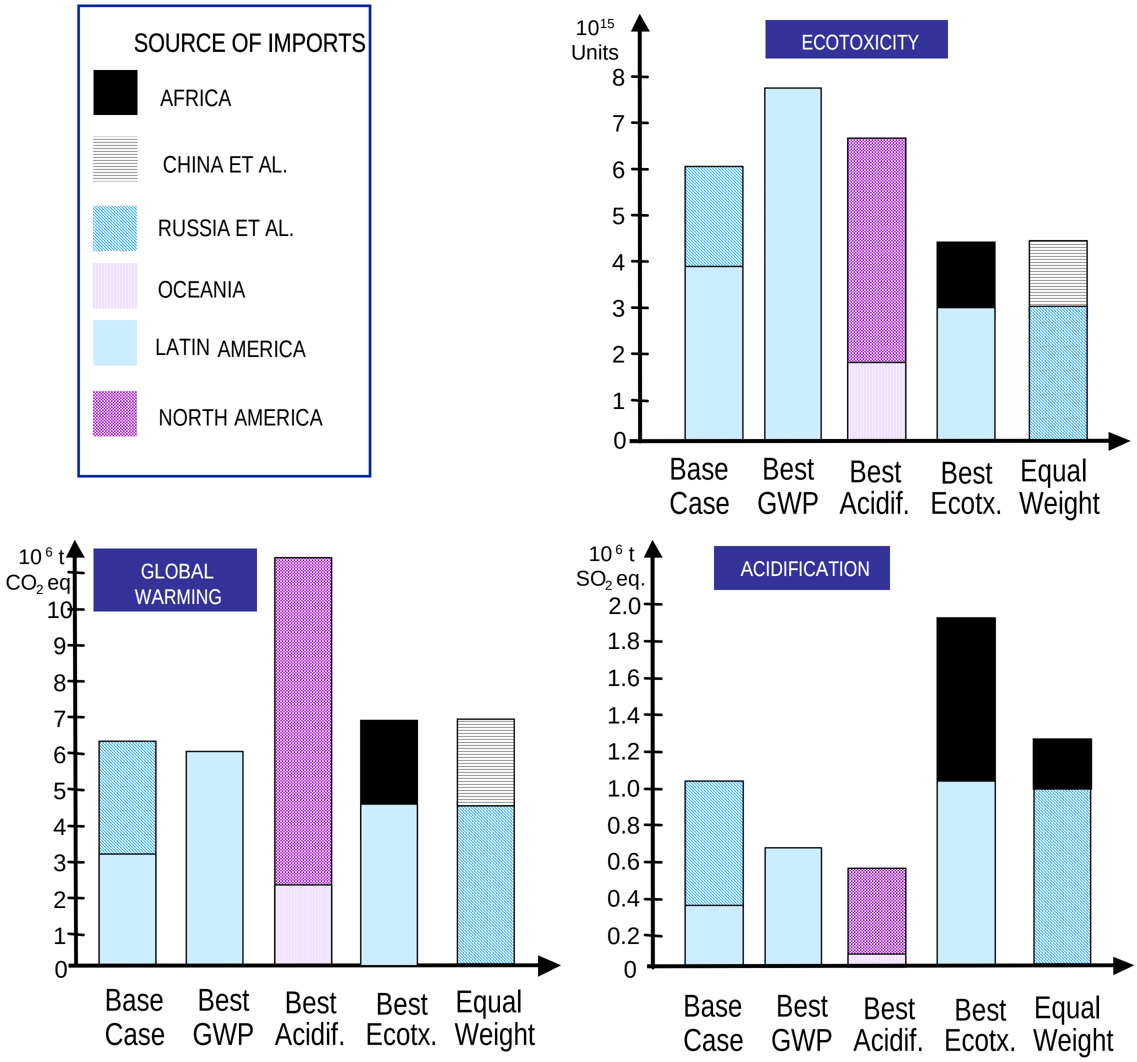


Figure 7-14: Impacts from imported copper to Europe when optimised for minimum greenhouse effect, minimum acidification, minimum ecotoxicity and equal weighing for each category as compared with the base case

The results shown in Figure 7-14 illustrate that the best performance for global warming potential is only a 3% improvement over the base case, indicating that the system is largely optimised for global warming already. This is because in the base case, half of the production is from Latin America in any case and this is the preferred copper source as there is a large percentage of hydropower in Latin America with a correspondingly small greenhouse burden. Although Central Asia (Russia et al.) has a higher ore grade than Latin America (1.51% for Central Asia vs. 1.00% for Latin America), its energy source is not as clean with respect to global warming.

When optimising for the minimum acidification burden, the global warming burden increases by 85%. This can be explained as copper is preferentially sourced from Oceania where there are no reverberatory smelters (hence a low acidification burden) and then once Oceania's supply constraint is reached, from North America (which has the second lowest proportion of reverberatory smelters). However, both Oceania and North America have a greater dependency on fossil fuel based energy supplies than Latin America which results in a drastically increased global warming burden.

Seeking to minimise ecotoxicity, results in a 30% reduction of ecotoxicity potential compared with the base case, with copper being sourced from Central Asia (Russia et al.) and Africa. In this configuration, the global warming burden is slightly higher than for the base case, however, the acidification potential is almost double the base case. The reason for such a dramatic increase in the acidification potential is that Africa and Central Asia have the highest proportion of reverberatory smelters for any world region.

For the multi-criteria case where each impact is equally important, copper is sourced from Central Asia (Russia et al.) and East Asia (China et al.). Here, the global warming and acidification impacts are 10–15% larger than for the base case, while the ecotoxicity is reduced by approximately 25%. The use of multi-criteria methods has been demonstrated using equal weights. It provides a methodology by which decision makers can evaluate trade-offs, especially in cases with a large number of criteria, for which it becomes difficult to comprehend performance scores graphically. In practice, not all criteria are likely to be equally important to all stakeholders. For example, initiatives such as the Kyoto protocol can lead to a dominant focus on a single environmental concern (global warming), for which seeking an impact reduction may give benefits to one party in the form of carbon credits, whilst leading to an uncompensated increase in a different impact. Such an outcome is illustrated by the results in Figure 7-14 where a marginal improvement in global warming potential (labelled 'Best GWP') comes at the expense of an increased ecotoxicity impact. Consequently, the choice of weights for different impacts should involve consultation with stakeholders in the minerals industry as part of the decision making process, which is an important step that is often overlooked (Stewart, 2001).

7.3.7 *Discussion*

This case study successfully demonstrated the coupling of regional actors, technology specific models and inter-regional material flows, with LCA indicators to assess baseline performance and the improved environmental performance possible for bringing metal to market in Europe within existing infrastructure.

The results clearly show the trade-offs in acidification and ecotoxicity associated with seeking to minimise the global warming burden associated with the imported copper brought to market for consumption in Europe. Furthermore, a significant reduction in the global warming burden associated with imported copper to Europe cannot be made within the constraints of the existing technology infrastructure in place around the world. A small (3%) reduction is achievable by sourcing copper exclusively from Latin America, which also gives rise to an increased local ecotoxicity burden and decreased regional acidification burden for the supply of copper, however, the effects occur in the producing countries. Consequently, the ability for producing countries to manage an increased ecotoxicity potential must be better understood.

The case study provides a basis for more informed decisions to be made regarding the minimisation of impacts at different scales and in different regions which arise from the demand for copper in Europe.

7.4 CONCLUSIONS

The characterisation across scales, of principal material and energy flows within the value chain and their environmental impact, was successfully demonstrated in this chapter. The aggregated global characterisation used a snapshot model to identify dominant material flows; energy was used as a proxy measure of environmental performance. It concluded that little copper is dissipated in the processing or use phases and that processing virgin ore uses much more energy (and has a higher environmental impact) than processing secondary (scrap) resources.

To further investigate the effect of technology on the impact of primary processing, steady state technology models were developed representing the three main technology classes. The steady-state models provided an inventory of inputs and wastes which were linked with LCA impact categories to provide comparisons of technology-specific environmental performance. The technology specific comparisons concluded that:

- ageing reverberatory smelters have the highest acidification effect (an order of magnitude larger than flash smelting and SX/EW)
- flash smelters have the lowest impact across most environmental performance categories
- the increasingly popular SX/EW technology with its ability to process lower grade ores, has the highest global warming and ecotoxicity impact.

By combining the impact profiles for each technology with consideration of the distribution of technologies operating on each continent around the world, a regional impact profile was developed. This profile includes region-specific values for key variables influencing environmental performance, which were identified through a sensitivity analysis. These variables are: ore grade, recovery and energy mix. By comparing the locations of high environmental impact with the locations of high consumption, it is clear that the majority of burden for bringing copper to market occurs in the southern hemisphere, whilst the majority of use occurs in the northern hemisphere. A greater responsibility must be taken by consumers of metal, for the impacts attributable to its production.

Building on the technology models with regional sensitivities, the potential for the developed world to take responsibility for bringing copper to market with lesser environmental burden attributable to its processing, was investigated for the case of Europe. It concluded that the system is currently close to best performance from a global warming perspective, but that this leaves the regions of Latin America and Central Asia – where copper processing occurs – with a significant acidification effect. If seeking to minimise acidification, copper would be sourced from Oceania and North America, but with a resultant increase in global warming potential almost twice the status quo. If seeking best performance for ecotoxicity, acidification increases to almost twice the base case

These results highlight the need to better understand the impacts associated with hydrometallurgy and the relationship between the actor-controlled variables and the potential improvement in environmental performance. To this end, an innovative hydrometallurgical technology is studied in Chapter 8 using pilot plant data. The design of alternate futures that introduce new technology and new configurations of value chain flows is then explored in Chapter 9.

CHAPTER EIGHT

Evaluating an innovative technology

A baseline for the environmental performance of the copper value chain was explored in Chapter 7, including an example of the performance improvement possible when using existing value chain infrastructure. Future value chains will need to incorporate new technologies in their infrastructure. This chapter demonstrates a new approach for evaluating the environmental performance of a future technology in the context of improving value chain performance. In particular, it explores the performance improvement associated with changes to actor-controlled and external variables for the technology developer/operator. There are two consequences of this analysis. Firstly, potential partnerships with external actors are identified that improve the overall environmental performance of producing copper with the new technology. Secondly, a modified indicator is developed to better represent the potential toxicity of the solid waste from the process. The ecotoxicity potential associated with hydrometallurgical processing was highlighted as an area requiring further investigation in Chapter 7. The results of this case study are used to guide the creation of a 'new technology profile' which is used in Chapter 9 to test the impact of incorporating new technology into the value chain.

THIS CHAPTER CONTAINS INFORMATION THAT MAY BE PROPRIETARY AND ONLY THE ABOVE SUMMARY IS AVAILABLE PUBLICLY.
THE REMAINDER OF THIS CHAPTER (pp.227-244) HAS BEEN REMOVED.

CHAPTER NINE

Towards preferred futures

Previous case studies assessed the environmental performance of the copper value chain;

- globally and regionally for the status quo (in Chapter 7)
- for Europe considering imports from different regions to minimise impact within existing infrastructure (in Chapter 7), and
- for new infrastructure, innovative hydrometallurgical technology (in Chapter 8).

Using the approach developed in Chapter 5, this chapter explores paths toward preferred futures for the copper value chain in the USA. Copper value chains containing new and existing technology infrastructure are investigated. The influence and timing of interventions by actors (both individually and collectively) to implement preferred futures are identified and quantified with respect to environmental performance. Modelling the impact of external influences and constraints on the value chain, in addition to the impact of actor decisions, allows the consequences of implementing preferred futures to be more fully understood. This enables better-informed planning for a future that brings metal to market with less environmental burden.

9.1 INTRODUCTION

9.1.1 *Copper in the USA*

The USA is the largest consumer of copper in the world, with consumption in 1999 of 3.1 million tonnes (Edelstein, 1999; Moreno, 1999). The ore grades being mined in the USA are amongst the lowest in the world at approximately 0.45% Cu, giving rise to the highest environmental burden per tonne associated with the production of copper from primary ore, with respect to CO_2 emissions. While consumption has increased from 2 million tonnes per annum in 1960 to over 3 million tonnes per annum in 1999, the recovery of old scrap has remained approximately constant at 0.5 million tonnes per annum (Zeltner et al., 1999). This indicates a potentially missed opportunity for the increased utilisation of scrap in the value chain. However, modern infrastructure for processing secondary resources in the USA is lacking. Dedicated secondary smelters and refineries processing secondary scrap are closing from a combination of old equipment which is operating inefficiently and low copper prices making it uneconomic to recycle and upgrade recycling infrastructure. Some scrap is recycled into primary smelters. The high consumption of copper in the USA combined with highly impacting primary processing and limited use of secondary processing provides the motivation to re-evaluate the current value chain configuration and plan for a more sustainable future.

This case study has been chosen to build upon the existing work of authors including Zeltner et al. (1999) and Graedel et al. (2004) who have characterised material flows for the region. However they did not assess the environmental performance of these flows nor the potential effects resulting from future changes to flows and technology infrastructure within the value chain. The main measures of environmental performance used in this case study will be global warming and ecotoxicity impacts to represent both global and local effects. In addition to building on previous studies of the USA, this case study further develops insights derived from previous case studies in this thesis.

9.1.2 *Insights from preceding case studies*

The process of envisioning preferred futures for the value chain in the USA will begin with an analysis of the status quo (i.e. current value chain configuration) for the USA as per the methodology outlined in Chapter 4.[1] Alternate futures are then created using the approach developed in Chapter 5. Additional to this, the relevant insights from previous case studies are summarised in Table 9-1.

[1] While case studies demonstrating characterisation of current value chain configurations were undertaken in Chapter 7, they did not have a specific USA focus and an equivalent analysis is undertaken in this chapter with a USA-specific focus.

Table 9-1: Outcomes from earlier case studies used to direct the exploration of preferred futures for the value chain in USA

Outcome	Relevance
Small Cu Dissipation Globally, a small percentage of copper is ultimately dissipated in its use (Ch 7)	Focus value chain improvements on mining and refining, rather than reducing dissipative uses
High energy usage creates significant impacts Energy requirements for mining and refining technologies are a significant contributor to the overall environmental impact associated with the production of one tonne of copper (Ch 7)	Include the impacts of a technology's energy requirements in more detail (e.g. coal, gas, hydropower, nuclear) when envisioning preferred futures
Impact affected by energy mix & Cu ore grade These factors have a significant impact on the environmental burden associated with the production of one tonne of copper (Ch 7)	Confirm these effects in sensitivity analysis for USA
Impact varies with technology & recovery Technology choice for primary processing affects environmental burden, especially Cu recovery (Ch 7)	Include changes to technology mix when envisioning preferred futures
Cu recycling reduces impact Energy requirements (and environmental burden) can be significantly reduced by increasing the proportion of secondary copper used to meed demand (Ch 7 and Appendix A)	Include increased utilisation of secondary processing in preferred futures
New technologies can tolerate impurities The innovative hydrometallurgical technology assessed has the ability to process 'dirtier' feed streams. With greater impurities in the process feed, it was important to better quantify the ecotoxicity potential to include a measure of solid waste stability (Ch 8)	Declining ore grades will necessitate the greater use of hydrometallurgy which can tolerate impurities
New technology has higher impact – reduce by combining with clean energy source Innovative hydrometallurgical technology has higher global warming and ecotoxicity impacts. Global warming impact can be reduced by coupling to clean energy source (Ch 8)	Implementation of new technology will require improved impact profile achievable through coupling to clean energy

These insights offer supporting information to the discussion in Section 9.3 as to the actors and system variables that should be considered in presenting an alterative future. They are presented here to highlight the links between this case study and earlier case studies.

9.1.3 *Chapter aim and outline*

Areas for improvement identified in earlier case studies were summarised in Section 9.1.2. This case study aims to demonstrate the approach developed in Chapter 5 for considering value chain improvements that create preferred futures and the environmental performance associated with transition paths toward preferred futures.

An outline of the chapter is shown in Figure 9-1. First, section 9.2 and 9.3 consider the status quo and future value chain configurations in 50 years time for the cases when actors make improvements individually and collectively. These two options are compared in section 9.4. Then, changes in external variables and actor behaviour are considered in Sections 9.5 for paths through time to alternate future states to identify those with least impact and their ability to be implemented.

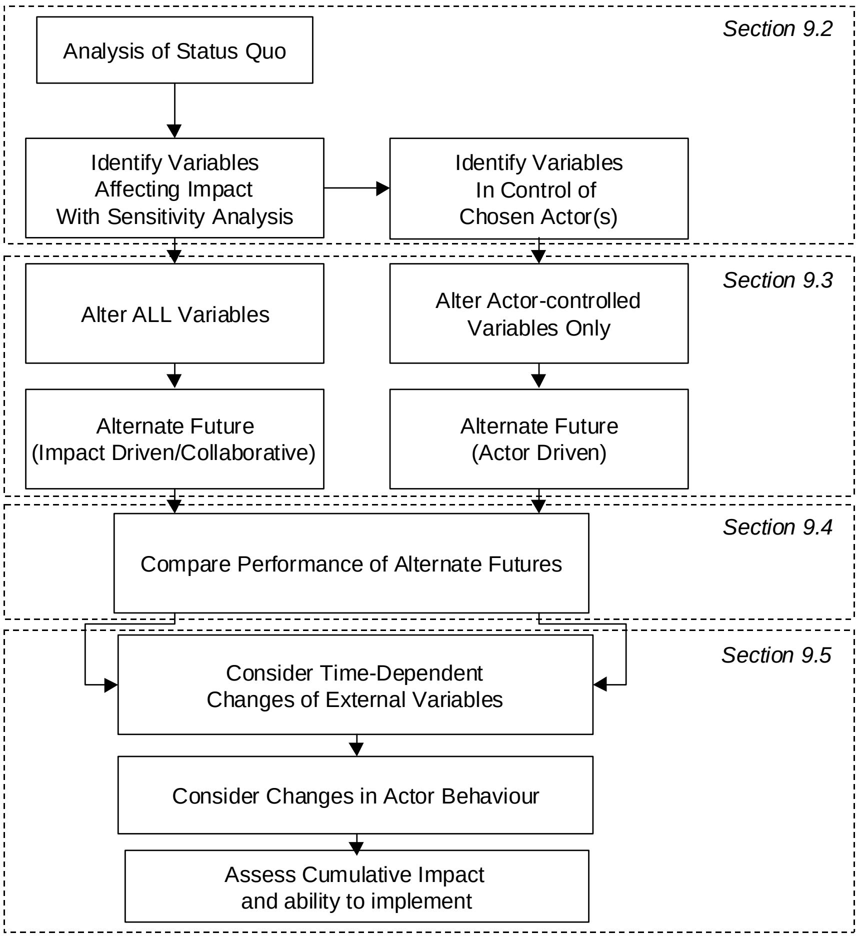


Figure 9-1: Approach to evaluating transitions to alternate value chain configurations

9.2 CURRENT MATERIAL CHAIN CONFIGURATION: USA

The first step in considering more sustainable futures for the value chain is to determine the status quo configuration, namely, the quality, quantity and splits of flows between technologies and then the associated environmental performance of this configuration. The objective of this section is to evaluate the status quo of copper flows in the USA using the technology models developed in Chapter 7 (for primary processing) and Appendix A (for secondary processing).

9.2.1 *Current distribution of flows in value chain and their impact*

The baseline performance assessment for the USA value chain is based on the following values of key variables for resource quality and the distribution of splits between flows in technologies, based on the status quo as shown in Table 9-2.[2]

Table 9-2: Assumptions for base case value chain configuration in USA

Assumptions for base case	
Ore grade	0.45%
Proportion of primary processing via Flash Smelting	65%
Proportion of primary processing via Heap Leach SX/EW	35%
Percent of total demand met via secondary scrap recycling	18%
Secondary - Very High Quality 'No1' scrap (99% copper)	25%
Secondary - High Quality 'No2' scrap (95% copper)	37.5%
Secondary - Low Quality Scrap (30% copper)	37.5%
Annual demand (t)	3 101 000
Imports / Exports	Nil

Brass is excluded from the analysis as it is usually recycled as 'new scrap' (Gaines, 1980) (meaning that scrap from the production of brass goods is recycled before reaching the marketplace). 'New scrap' from off-cuts of manufacturing is considered 'in-process copper, not a source of supply' (Biswas and Davenport, 1994). This contrasts 'old scrap' which is discarded after use by a consumer and which constitutes the secondary scrap resource considered in this case study.

The effect on environmental performance of considering imports was demonstrated in a previous case study in Section 7.3 and imports/exports are excluded in this case study.

---

[2] N.B. the technology split between primary technologies for the USA in Table 9-2 is not to be confused with that presented in Figure 7-9 which referred to North America and hence also included Canada.

By limiting the number of system variables which are re-configured in preferred futures, the new approach developed in Chapter 5 is demonstrated more clearly.

The technology models developed in Chapter 7 and Appendix A are re-calibrated with the USA's ore grade and energy mix (which is approximately half coal and the remainder a mix of natural gas, hydro and nuclear). The relative impacts associated with this system configuration are shown in Figure 9-2. This shows that the majority of impact associated with bringing metal to market in the USA is currently associated with primary processing. Total burdens for each category are shown in Table 9-3.

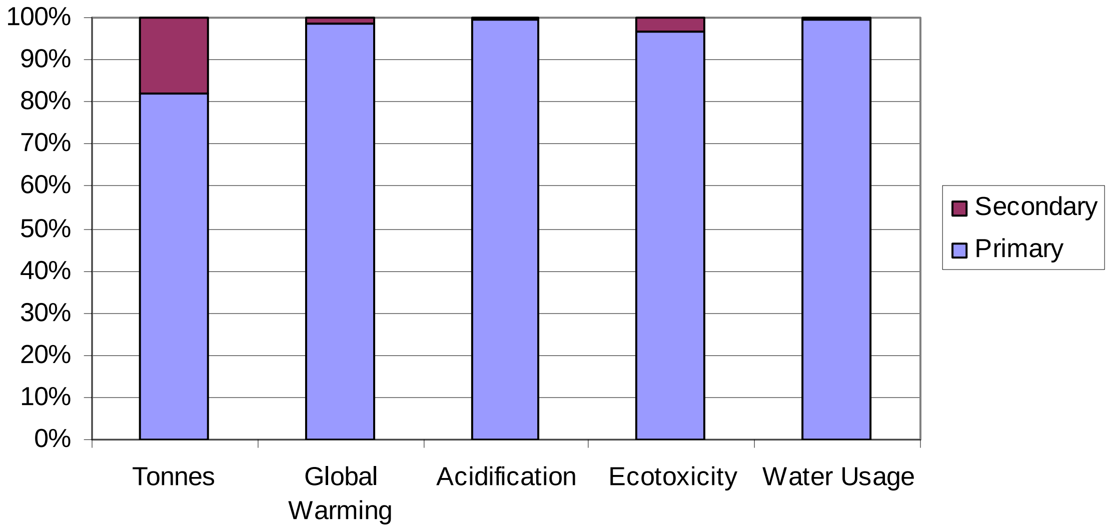


Figure 9-2: Relative contribution of primary and secondary processing to impacts

Table 9-3: Total environmental impacts for primary and secondary processing

	Greenhouse (kg. CO_2 eq.)	Acidification (kg. SO_2 eq.)	Eco-toxicity (Relative units)	Water (t)
Primary Refining	$22\,000 \times 10^6$	$40\,000 \times 10^4$	$16\,000 \times 10^{12}$	$120\,000 \times 10^4$
Secondary Refining	360×10^6	140×10^4	580×10^{12}	360×10^4

9.2.2 *Introducing a new technology*

To assess the introduction of new technology into the value chain, a 'future technology' profile for the refining of primary ore is created, informed by the case studies in Chapters 7 and 8. Due to declining ore grades, future technologies will be required to better handle impurities and be able to process lower grade ores. Consequently a 'future technology' based on hydrometallurgy is advocated. This is consistent with the current increase in the uptake of hydrometallurgical technologies reported by (Davenport, 1999). The technology case study in Chapter 8 concluded that to reduce the indirect effects of global warming and acidification, the process requires coupling to a cleaner energy source.

The 'future technology' profile in this case study is based on the existing SX/EW technology, which is proven at a large scale, coupled to hydro-electricity.[3] This will be used to demonstrate how the introduction of a new technology can be evaluated in the context of the overall value chain. Assuming pyrometallurgical processes will remain in future, an upper limit for the market penetration of new technology uptake is taken as 70% by 2050 to illustrate the savings potential under this scenario.[4] Backcasting the value for this parameter is an important overall driver of the scenario and its sensitivity is acknowledged here, but it should not be viewed as a forecast.

9.2.3 *Identifying sensitive variables*

Two sensitivity analyses are performed with the following aims:

1. to determine sensitivities within each technology, and
2. to determine sensitivities to splits between technology nodes.

Sensitive variables within each technology are identified and then classified as either actor-controlled or externally determined. All remaining variables with low sensitivities (i.e. low influence on environmental performance) are taken as constants for the remainder of the analysis. Each variable included in the technology models of the status quo is changed +/–20% and the resultant impact is noted (after Sinnott, 1989).[5]

The within technology sensitivity analysis was already undertaken in Chapter 7 and the results are shown in Appendix A & B. The sensitivity analyses within technology nodes reveal the most sensitivity to resource quality (in this case ore grade and also scrap

---

[3] The new process studied in Chapter 8 is not used as the generic future technology *per se*, as it is yet to be proven at full scale.

[4] Selecting this factor is part of backcasting the scenario and should not be viewed as a prediction, the results show what is achievable under such a scenario. Factors considered in selecting the conservative value for this parameter (i.e. less than 100%) included: slow uptake of technology in the minerals industry and infrastructure which remains in place for decades, for example, reverberatory smelting accounts for 15% of copper processing even though the last reverberatory smelter was built in 1976 (Biswas and Davenport, 1994); rate of technology diffusion (see Pizer et al., 2002 for discussion); current trends of SX/EW uptake in USA (Bartos, 2002).

[5] The aim is to determine relative sensitivity between variables, so a value of +/–10% could also be used, as long as each variables is changed by a consistent amount.

grade), energy mix, percentage recovery and final demand as the principal sensitivities. These become key variables to consider when envisioning alternate futures.

The sensitivities to flows through different technology nodes are explored here for the case of USA. Changes to the relative material flows directed through different technologies represent decision variables for actors.

The principal choices for which sensitivities must be determined are:

- splits between primary / secondary resources used to meet demand
- splits between primary technologies for total flows through primary technologies
- splits between secondary technologies for total flows through secondary technologies.

Case studies in Chapter 7 showed the sensitivity to performance per tonne of product for differences between primary refining technologies and similarly for secondary processing technologies in Appendix A. The impacts are calculated specifically for the USA in Table 9-4 showing the performance for each technology (per tonne of product).

Table 9-4: Impact per tonne of product for primary and secondary technologies

	Greenhouse (kg. CO_2 eq.)	Acidification (kg. SO_2 eq.)	Eco-toxicity (Relative units $\times 10^6$)	Water (t)
PRIMARY				
Flash Smelting	6 300	190	3 200	420
Heap Leach SX/EW	8 000	66	8 700	210
New technology (Hydrometallurgical)	2 500	34	12 000	1.1
SECONDARY				
Secondary Processing- Very high grade (No1)	400	1.3	190	1.7
Secondary Processing- High grade (No2)	600	2.4	170	100
Secondary Processing- Low grade scrap	1 200	5.2	3 900	110

In summary, the key sensitive variables are as follows:

- ore grade (and quantity)
- scrap quality (and quantity)
- energy mix
- technology recovery

- primary technology choice
- secondary technology choice
- split between primary and secondary technology used to meet demand
- demand.

Note that in considering the feasibility of alternate futures, the availability of resource stocks will also need to be considered, hence ore grade quantity and scrap quantity have been added as variables.

9.3 ENVISIONING PREFERRED FUTURES

Key system variables were identified in Section 9.2. The aim of this section is to identify the range of actors being considered in this case study and to assess which system variables each can control and which are beyond their control. Futures can then be envisioned by changing either one or all of the variables which actors under consideration can control. The influence of external variables is considered in Section 9.5.

9.3.1 *Influence of actors over sensitive variables*

Many actors are potentially involved in processing primary and secondary resources in the USA. With a specific focus on bringing metal to market the range of actors to be considered is outlined in Table 9-5.

Table 9-5: Actors involved in bringing metal to market in USA

Actors	Considered in this case study
Miners of ore	Yes
Primary refining technology operators	Yes
Importers/exporters	No
Technology designers	Yes
Energy suppliers	Coupled with new technology
Secondary resource collectors	Yes
Secondary processors	Yes
Government/industry regulators	Yes

From the list in Table 9-5, this case study takes a particular focus on the primary refining technology operators who currently process the majority of copper in the USA and give rise to significant environmental impacts. End-users such as manufacturers and consumers are considered external. While they act to set demand, they are not directly involved in bringing refined metal to market.

The energy mix effect is implicitly incorporated with the installation of the new technology coupled to a cleaner energy source with respect to global warming impact and ecotoxicity. It is consequently assumed for alternate future scenarios, that the remaining infrastructure runs on an energy mix similar to that currently in place in the USA.

Using the approach developed in this thesis (outlined in Chapter 5) for all actors being considered, each variable is classified as either:

(A) directly controllable by the actor in question;

(P) partially / potentially controllable by the actor
(for example, controlled by another actor with whom the actor in question could co-operate in future from the list of those considered);

(E) externally controlled, beyond the potential influence of the actor.

Consequently, the rating from greatest to least control is A>P>E. This is summarised in Table 9-6. Actor groups listed are treated collectively for this case study, rather than as an individual company. For example, while an individual miner will have control over the quality of output from the mine, as a collective group, the average ore quality produced at a future time will be largely a function of geology, hence external to their control when considered as a group.

Table 9-6: Influence of actors over key system variables

VARIABLE	ACTOR GROUPS						
	Miners of Ore	1° Tech Operator	Tech Designer	2° Scrap Collector	2° Tech Operator	Gov/Ind Regulator	Highest Rating
Quality of primary ore	E	E	E	E	E	E	E
Quantity of primary ore	E	E	E	E	E	E	E
Primary technology mix	P	A	P	P	P	P	A
Cu recovery of technology	A	A	A	P	A	P	A
Ratio of primary to secondary feed	P	P	P	P	P	P	P
Quality of secondary feed (and secondary technology used)	E	E	P	A	P	P	A
Quantity of secondary scrap	E	E	E	A	A	P	A
Demand for Copper	E	E	E	E	E	E	E

In Table 9-6 the 'highest rating' final column identifies variables which can be influenced from the collective group of actors which make up the other columns. This represents the full selection of actor-controlled or potentially controllable variables in the case that all actors were to collaborate. These variables will be changed in the backcasting of an alternate future in Section 9.3.2. In this analysis, the external variables (classified E) beyond actor control are the quality and quantity of primary ore (which is geological) and the final demand for copper (which is set by consumers). The only variable not directly controllable by a single actor (and consequently which would require collaboration to change) is the overall ratio of primary to secondary feed used to meet the final demand. This analysis is useful in its own right.

The aim is then to determine how much improvement can be achieved acting alone and compare this with the improvement possible through wider collaboration as a basis for determining whether new partnerships are necessary and how much benefit they may offer. The impact improvement which can be achieved by changing the variables within the control of a specific actor – for this case study the primary technology operator – will be compared with impact improvement arising from changing all variables. This is elaborated in Section 9.3.3.

9.3.2 *Impact driven future: changing all variables*

In this case study, the impact reduction is sought for the copper value chain in the USA where current levels of demand are maintained. The impact driven future changes all system variables classed as either A (actor-controlled) or P (partially/potentially) in Table 9-6, representing the combined improvement potential when all actors collaborate to effect supply side strategies for the materials value chain. The impact driven future will be used as a basis against which the actor-driven scenario will be compared, to determine the improvement which a single actor can make in comparison to collective action. Initiatives aimed at reducing impact through demand reduction (demand side management) can be linked to this approach by future studies.

The envisioning of an alternate system state in this case uses the same technology models and performance indicators as for modelling of the status quo, it is just the final configuration of flows and splits between technologies that changes for the final system state. For modelling the new technology, it is taken as the hydrometallurgical heap leach SX/EW combination linked to hydro-electricity.

For the final system state envisioned in this case, the assumptions are as detailed in Table 9-7.

Table 9-7: Assumptions for impact-driven future

Variable	Value for future state	Comment
Quality of primary ore	As for status quo	Beyond actor control; external
Quantity of primary ore	As for status quo	Beyond actor control; external
Primary technology mix	Up to 70% new technology (relative splits of remaining technologies as for status quo)	Reasonable level of uptake
Cu recovery of technologies	As for status quo	Note: this is an actor controlled variable, improved recoveries may be possible in future, as well as grade/recovery trade-offs in concentration, but not explored in this work
Ratio of primary to secondary feed	Up to 70%	Proposed that impact associated with recycling increases at very low and very high rates.[6] 70% is taken as reasonable maximum
Quality of secondary feed (and secondary technology used)	As for status quo	Note: actor controlled variable, will depend on available supply, taken as for status quo as a balance between desirable and realistic. A move toward higher grade scrap is desirable, but trend is toward more lower grade scrap
Quantity of secondary scrap	Assume available	Will be checked in time-dependent modelling in Section 9.5
Demand for Copper	As for status quo	Beyond actor control: external

The impacts associated with this system configuration are given in Figure 9-3 in Section 9.4, together with those for the actor-driven future whose assumptions are presented next in Section 9.3.3.

9.3.3 *Actor driven future: changing actor controlled variables*

The actor driven future has a focus on changing system variables within the control of refiners of primary ore, to determine whether technological advancements will still afford the provision of metal to market from primary ore a viable place within a more sustainable future.

6 See discussion by McLaren et al. (2000).

The key variable under direct control of the primary resource processing companies is the choice of technology used to prepare metal for use (and the energy mix to which the technology is coupled, which is incorporated into the new technology implementation). This is shown in Table 9-8.

Table 9-8: Assumptions for actor-driven future

Variable	Value for future state	Comment
Quality of primary ore	As for status quo	Beyond actor control
Quantity of primary ore	As for status quo	Beyond actor control
Primary technology mix	Up to 70% new technology (with relative split of remaining technologies as for status quo)	Reasonable level of uptake, given that some flash smelting & current SX/EW will remain
Cu recovery of technologies	As for status quo	Note: this is an actor controlled variable, improved recoveries may be possible in future, as well as grade/recovery trade-offs in concentration, but not explored in this work
Ratio of primary to secondary feed	Up to 70%	Beyond direct control of actor
Quality of secondary feed (and secondary technology used)	As for status quo	Beyond direct control of actor
Quantity of secondary scrap	Assume available	
Demand for Copper	As for status quo	Because external

The results for the environmental impact of both the impact driven and actor driven futures are presented in Section 9.4.

9.4 COMPARISON OF FUTURE STATES

This section compares the impact driven and actor driven futures. A summary of changes to system variables for future states is given in Table 9-9 and the results are shown in Figure 9-3 as performance increase or decrease relative to the status quo.

Table 9-9: Values of key variables for status quo and alternate futures

	Status Quo	Impact Driven Future	Actor Driven Future
Primary – Flash	65%	20%	20%
Primary - New technology	0%	70%	70%
Primary - SX/EW	35%	10%	10%
Percent demand from secondary	18%	70%	18%
Secondary - 'No 1' very high quality scrap remelting	25.0%	25.0%	25.0%
Secondary - 'No 2' high quality scrap remelting and re-refining	37.5%	37.5%	37.5%
Secondary - Low quality scrap processing in blast furnace	37.5%	37.5%	37.5%
Demand (external)	Constant	Constant	Constant
Ore grade (external)	Constant	Constant	Constant

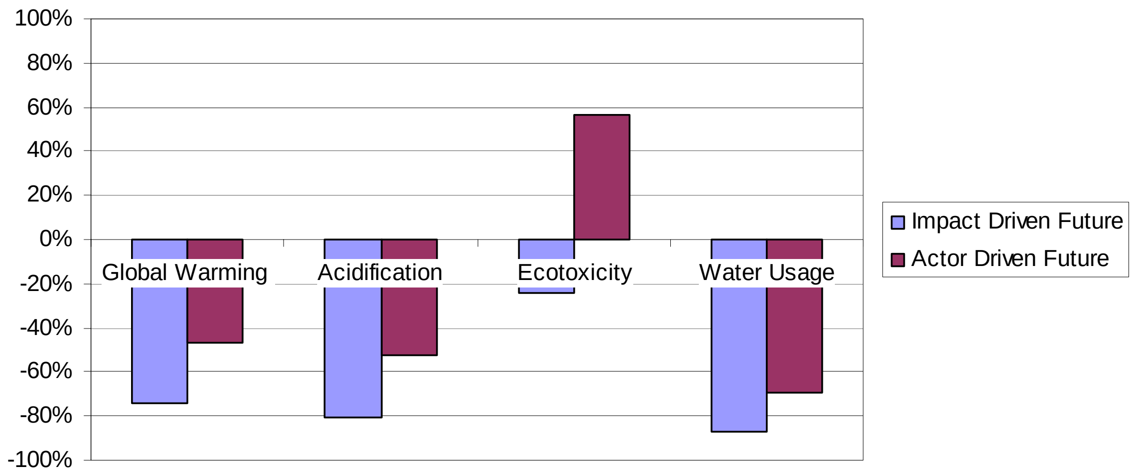


Figure 9-3: Comparison of impact-driven and actor-driven futures expressed as percentage change from base case for each impact category

The results in Figure 9-3 show that when new primary processing technology and increased recycling are introduced (impact driven future) there is a reduction in all impact categories. However, when only new primary processing technology is introduced (actor driven future) there are reductions in global warming, acidification and water usage, but a higher potential ecotoxicity impact. This is because the new primary processing technology introduced is hydrometallurgical. Hydrometallurgical technologies have a lower copper recovery than for pyrometallurgical processes, meaning more ore processing and waste streams per tonne of copper product. Hence, the greater introduction of new hydrometallurgical technology (even when coupled to clean electricity), raises the potential ecotoxicity impact.

By contrast, the increased use of secondary resources reduces the ecotoxicity potential per tonne of metal produced. The extent of secondary resource use in the impact driven future is such that the overall system impact for ecotoxicity is less than for the status quo. The saving from the increased use of secondary resources outweighs the increase from the greater use of hydrometallurgy.

The backcasting of future states has established the impact profile for two alternative futures, from both an actor-driven and impact-driven perspective. This technique successfully contrasts the potential improvement which can be achieved by changing system variables currently within the control of primary technology processors, with that which could be achieved thorough greater collaboration between actors including secondary processors to more ambitiously change the system.

Beyond the identification of value chain configurations at a future point in time, there are time-dependent considerations associated with implementing the transition from the status quo to either alternate future which must be considered. As identified in Chapter 5, it is possible that over the 50 year time horizon for which the projection is made, advancing immediately to implement a modest improvement (Alternate A), may provide greater cumulative benefit than waiting many years for a technological breakthrough (Alternate B). This concept is re-illustrated in Figure 9-4, with the cumulative improvement achieved represented by the area under the curve.

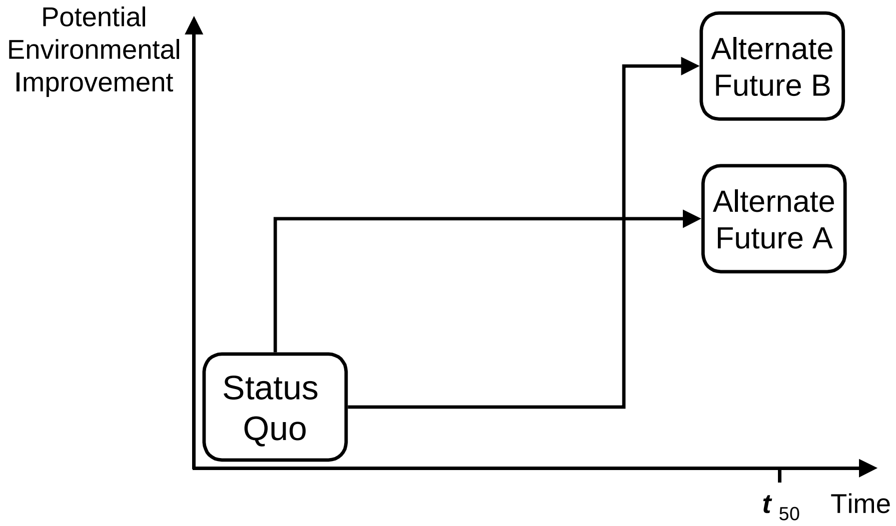


Figure 9-4: Comparison of rapid transition to an alternate state offering moderate improvement, and a slow transition to a state offering greater improvement

Consequently, the timing of actor behaviours which change system states must be explicitly included in the analysis. Furthermore, in each alternate state which has been proposed in this section, there are still external variables which are beyond the control of actors being considered in the system. We must determine whether the variation in these external variables is such that they could assist or hinder the transition from status quo to alternate state and additionally, the impact that changes in these variables have on the overall environmental performance of the system. These questions are explored in Section 9.5.

9.5 EVALUATING TRANSITIONS TO FUTURE STATES

The impacts associated with changes to system configuration at time intervals between the status quo and the alternate future are best understood by examining time-dependent transitions to alternate future states.

System impacts will vary with time, due to:

- the timing and extent of changes in actor-controlled variables, and
- changes in external variables beyond actor control.

Understanding the effects of these two factors is the aim of this section.

Changes in actor-controlled variables may be:

- slow or rapid,
- implemented by single actors or multiple actors collectively,
- part of a pre-determined strategy or responsive to system performance.

Changes in externally-controlled variables are functions of one or more of:

- time
- system configuration
- system performance.

The ability to monitor the changes in system performance through time, relies on the development of a dynamic model of material flows able to represent the system configuration at each time interval, inclusive of changes to actor-controlled and external variables. Such a model as outlined generically in Chapter 5, is developed specifically for this case study in Section 9.5.1. Both the impact-driven and actor-driven futures from section 9.4 are considered for further analysis through time.

9.5.1 *Dynamic model of material and energy flows*

By developing a dynamic model of material flows, the environmental performance of the system at time intervals, from the status quo to the alternate future, can be explored. This is achieved, by coupling a dynamic model of material flows to technology specific models which the inform environmental performance of bringing metal to market as outlined in Chapter 5.

What are the key features which must be captured in the model for the USA? This thesis considers supply-side strategies for bringing metal to market, so the way in which the quality and quantity of available resources for supply (be they primary or secondary) must be known; both change with time, but for different reasons. The declining quality of primary copper ores for the USA, can be approximately modelled through time by an exponential decay function using data from Ayres et al. (2001).[7] The quantity of available ore, depends on the existing stocks and rate of new discovery.

[7] This is particularly the case for industrialised regions such as the USA, where new high grade ore-bodies are less likely to be discovered than in less developed continents (e.g. Africa) where geopolitical factors may have limited mineral exploration or utilization to date in some cases.

Conversely, secondary resource quality depends on the product types in which copper used and their residence time in use before being discarded.

Historically, copper's dominant uses were as pure copper (pipes and wires), whereas more recently, greater usage in composite electronic equipment is occurring. Electronic equipment gives rise to a lower grade scrap than copper pipes and wires, due to the other components present in the electronics. Additionally, it has a shorter useful life before being discarded. Consequently, the stock and quality of available secondary resources depends on total copper demand, the types of products in which copper is used and their residence time in use. This changing nature of resource stocks and qualities is the first dynamic element which must be represented in the model as resource stocks act as a constraint on possible supply.

The second feature which must be represented in the model is the set of changes to system configuration brought about by changes in actor-controlled variables. These actions may depend on a pre-determined strategy by the actor, but also in response to system performance – for example, actors may be forced to upgrade to new technologies in response to the introduction of stricter environmental requirements.

9.5.2 *Model Description*

A conceptual description of the model used to describe the value chain for the USA is shown in Figure 9-5, outlining nodes and links between nodes. The environmental performance of bringing metal to market is determined by the quantity, quality and split of resource flows through primary and secondary technologies.

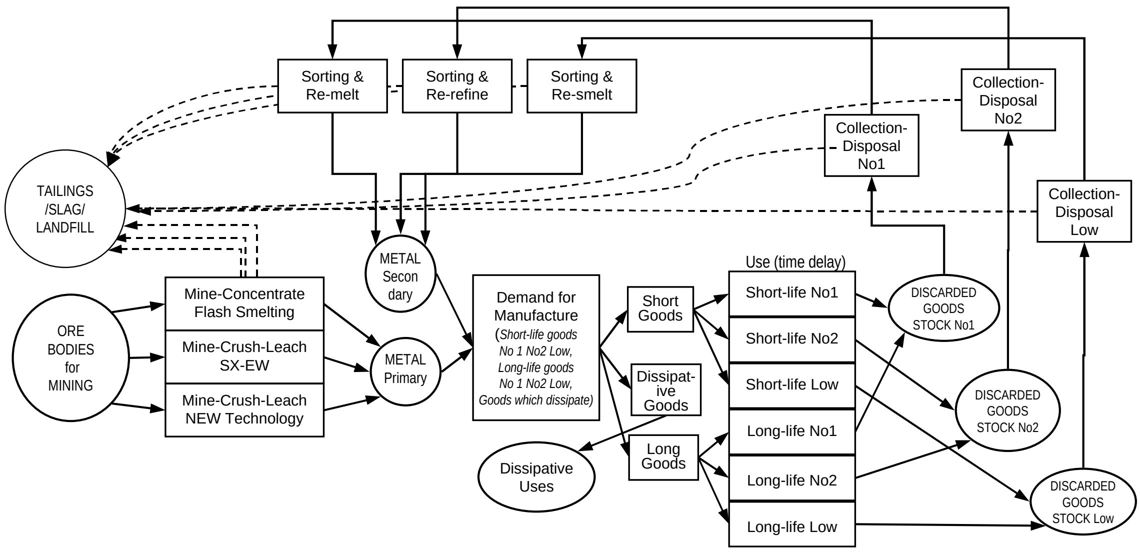


Figure 9-5: Dynamic model of material flows in the value chain (stocks represented in ovals, processed in boxes)

Figure 9-5 shows three technology options for processing primary ore bodies. There are also three technology options for processing secondary scrap, one unique technology for each type of scrap.[8] Very high grade No1 scrap (99% copper) is sorted and then remelted. High grade No2 scrap (95% copper) is sorted and must then be remelted and re-refined. Low grade scrap (30% copper) must be re-smelted in a similar process to smelting from primary ore. Demand for copper is met by primary and secondary copper. 'Short' goods have a short residence time in use of several years (such as computers, mobile telephones) while 'Long' goods have a residence time in use of decades (such as electrical wiring and piping). Some demand goes to 'dissipative uses' from which copper cannot practically be recovered. The above configuration of the model, shows waste flows 'to' landfill and the design of the model is such that cases where landfill is considered a future resource can easily be explored.

---

[8] In practice, some secondary scrap is also re-processed in primary smelters and it is assumed that the environmental performance of this practice is similar to dedicated processing through secondary technologies.

So that each node and material flow can be described more explicitly, the model representation in Figure 9-5 has been numbered as shown in Figure 9-6.

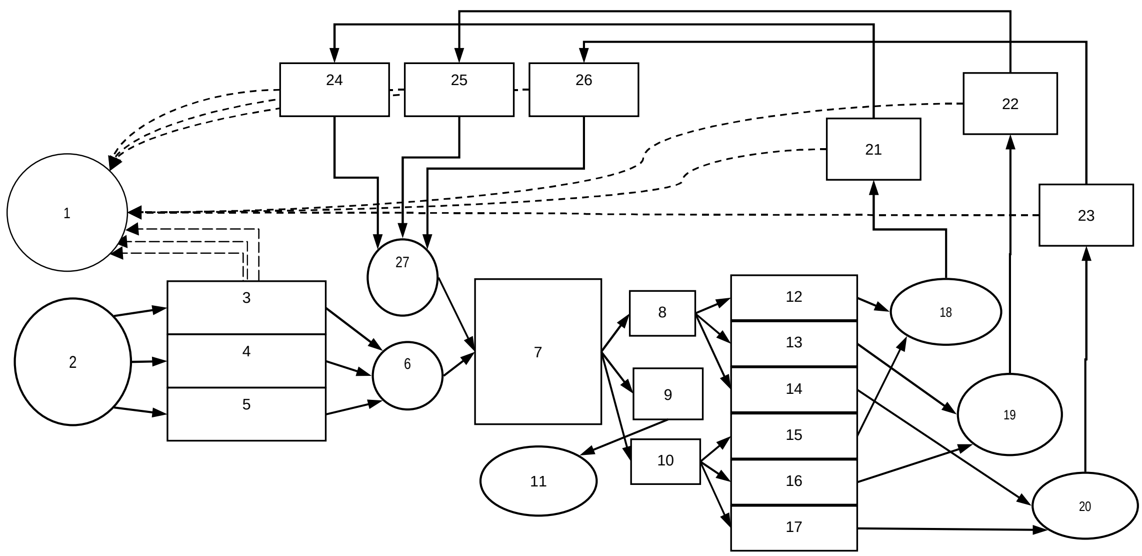


Figure 9-6: Dynamic model of the materials value chain with numbered processes

The model is described by 27 nodes and 42 flows between nodes. Using the notation $S^{(i)}(t)$ for stock in node i at time t and $m_{i,j}(t)$ for flow between node i and j at time (t) 69 equations describe mass balances for the model and 29 parameters (R_i) must be specified. Note, the change in stock with respect to time is denoted $\dot{S}^{(i)}(t)$. All model equations and initial values of stocks at t=0 are shown in Appendix B.

9.5.3 *Actor behaviour: Incremental transition to future*

When evaluating a path from the status quo toward alternate future, the timing of actor-led decisions must be projected. The transition may be an incremental progression from status quo to alternate future, or, the transition may occur in step-changes at discrete points in time corresponding with new infrastructure being built or policy decisions actioned. The incremental progression is explored for the cases of primary technology operators acting alone to introduce new technology, and then for the collaborative case of increasing recycling in addition to the introduction of new technology as described in 9.4.

9.5.3.1 *Path toward actor-driven future: new primary technology*

Table 9-10 shows the transition values as a linear implementation between the start time (t_0) and end time (t_{50})when the primary technology operators introduce new technology at a constant rate across the 50 year time period. This occurs in the absence of any change to external variables. The transition path is reconsidered in Section 9.5.4 with changes to external variables to illustrate the difference between the two cases.

Table 9-10: Values for key model parameters between status quo & actor-driven future

	Var	t_0	Path	t_{50}
Split between primary technologies				
Flash	$R_{10}(t)$	65%	$R_{10}(t) = -0.009t+0.65$	20%
SX/EW	$R_{11}(t)$	35%	$R_{12}(t) = -0.005t+0.35$	10%
New technology	$R_{12}(t)$	0%	$R_{11}(t) = 0.014t$	70%
Split between secondary technologies				
No1	$R_{13}(t)$	25.0%	constant	25.0%
No2	$R_{14}(t)$	37.5%	constant	37.5%
Low	$R_{15}(t)$	37.5%	constant	37.5%
Split between primary /secondary tech				
Demand fraction met by secondary	$R_{16}(t)$	18%	constant	18%

The values for principal material flows for the transition between current configuration and actor-driven future are shown in Figure 9-7 and graphically illustrate the transition values outlined in Table 9-10.

Figure 9-7(a) shows no change to total demand (which is an external variable held constant at this stage) and a fixed proportion of secondary processing meeting total demand, which is constant through time. Figure 9-7(b) shows the progressive implementation of the new hydrometallurgical technology and the proposed decline of the current flash smelting and solvent extraction-electrowinning infrastructure for primary processing.

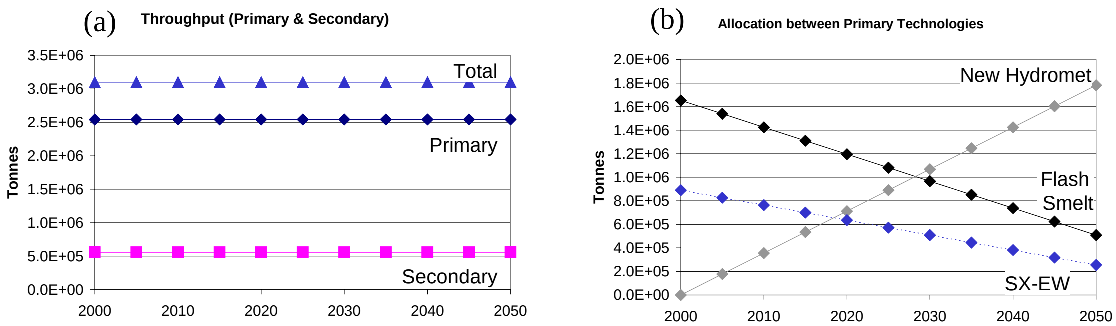


Figure 9-7: Material flow changes in transition to actor-driven future

The results for the actor-driven future are shown in Figure 9-8, expressed as a percentage of the status quo impacts. It is observed that ecotoxicity increases with time (due to the increased use of the new technology which has a higher ecotoxicity potential than the flash smelter). Conversely, global warming, acidification and water usage effects all decrease to between 30% to 60% of their original value.

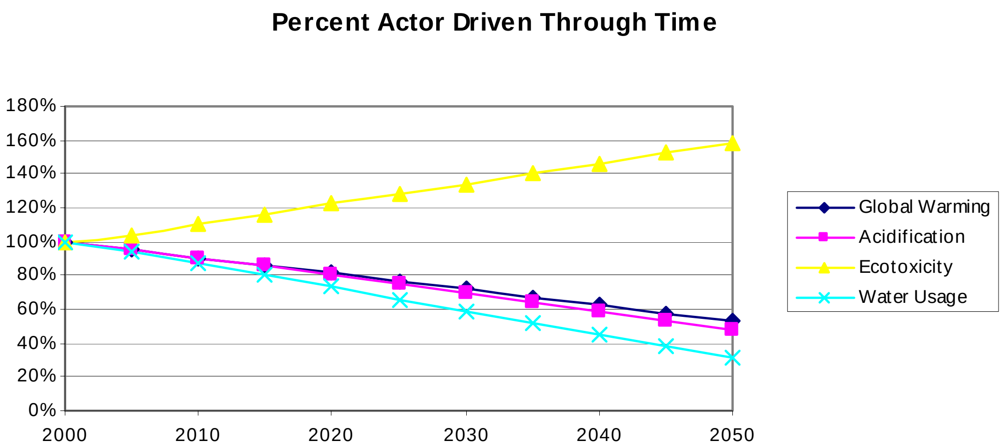


Figure 9-8: Change in impacts with time for actor-driven future

The usefulness of Figure 9-8 is twofold: first, to give an indication of the form of the transition, which is approximately linear through time, and second to demonstrate which impacts track similarly through time. The analysis of impact categories that track similarly through time can be simplified to look at just one of those categories. In this case, global warming, acidification and water usage follow similar trends. Subsequent analysis will focus on the trade-off between global warming and ecotoxicity.

The components of total burden for global warming and ecotoxicity which arise from the primary processing and secondary processing of copper respectively are shown in Figure 9-9. It is clear that the total contribution of primary processing is significantly grater than that for secondary processing. This is due to a higher per tonne impact associated with primary processing and the greater proportion of demand which is met from primary processing.

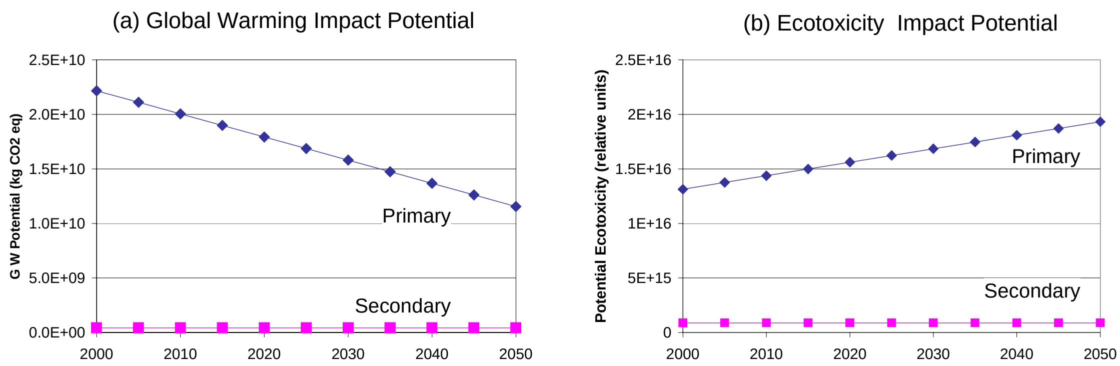


Figure 9-9: Impacts from primary and secondary production in actor-driven future

9.5.3.2 *Path toward impact-driven future: new primary technology & recycling*

Table 9-11 shows the transition values as a linear implementation between then start and end value when the primary technology operators incrementally introduce new technology and increased recycling evenly across the 50 year time period for the case of collaboration between value chain actors. The resultant material flows for the transition are shown in Figure 9-10.

Table 9-11: Values for model parameters between status quo & impact-driven future state

	Var	t_0	Path	t_{50}
Split between primary technologies				
Flash	$R_{10}(t)$	65%	$R_{10}(t) = -0.009t+0.65$	20%
SX/EW	$R_{11}(t)$	35%	$R_{12}(t) = -0.005t+0.35$	10%
New	$R_{12}(t)$	0%	$R_{11}(t) = 0.014t$	70%
Split between primary technologies				
No1	$R_{13}(t)$	25.0%	constant	25.0%
No2	$R_{14}(t)$	37.5%	constant	37.5%
Low	$R_{15}(t)$	37.5%	constant	37.5%
Split between primary /secondary tech				
Demand fraction met by secondary	$R_{16}(t)$	18%	$R_{16}(t) = -0.0104t+0.18$	70%

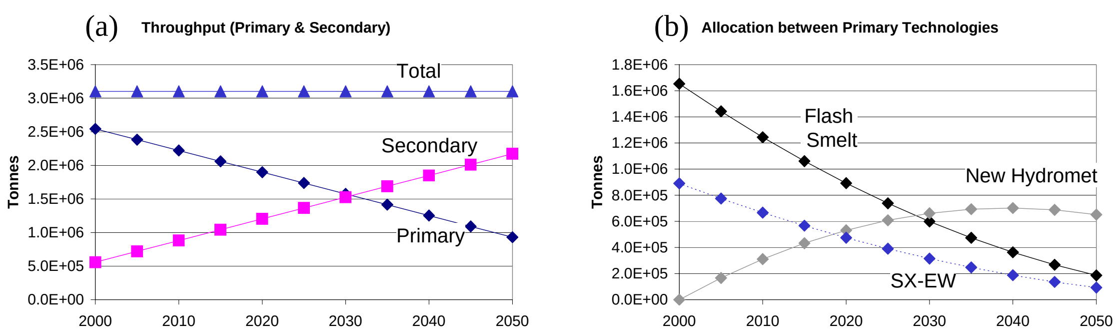


Figure 9-10: Material flows for impact-driven future

In Figure 9-10(a) it is observed that the proportion of total demand met by secondary processing increases linearly as a function of time, with a corresponding decrease in primary processing. The mass flows through primary processing technologies are illustrated in Figure 9-10(b). This shows an increase in the tonnes processed with the new hydrometallurgical technology, up to a peak in 2040, after which production declines as a result of the decline in total primary production. In practice, significant volumes of secondary scrap in future may be processed via primary technologies, in addition to dedicated secondary smelters. For modelling purposes in this case study, separate primary and secondary processing routes have been chosen to reflect the relative environmental performance of both routes.

The environmental performance for the impact-driven future where all system variables are changed to bring about improvement is shown in Figure 9-11.

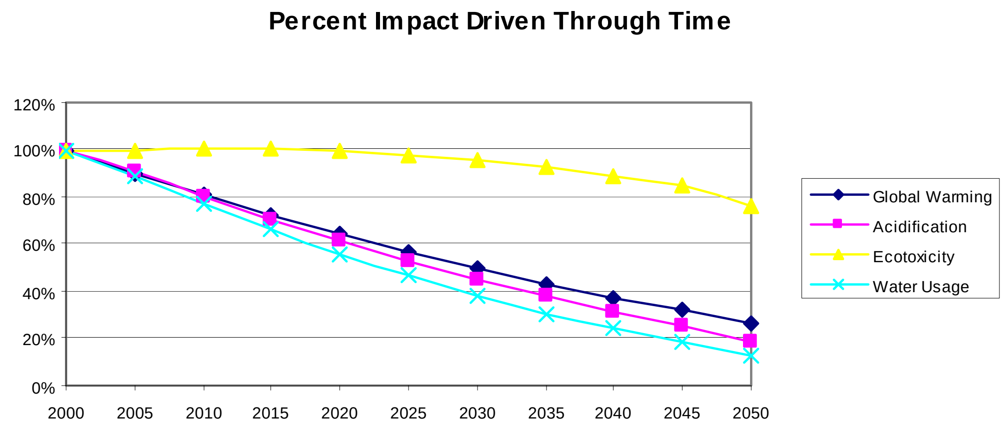


Figure 9-11: Change in impacts with time for impact-driven future

Unlike the linear transitions between status quo and alternate futures in Figure 9-8, the impact profiles through time for the impact-driven future is non-linear. For eco-toxicity, there is a slight increase for the first 15 years as new technology is introduced and after this the overall impact declines, as the level of secondary resource utilisation is such that the saving it effects is greater than the increase attributable to the introduction of new technology. This is illustrated in Figure 9-12 where the contributions to environmental burden from primary and secondary processing are noted separately. The decrease in all other effects is attributable to the introduction of new technology and the increase in secondary resource utilisation. It is observed that both effects track similarly for these impact categories.

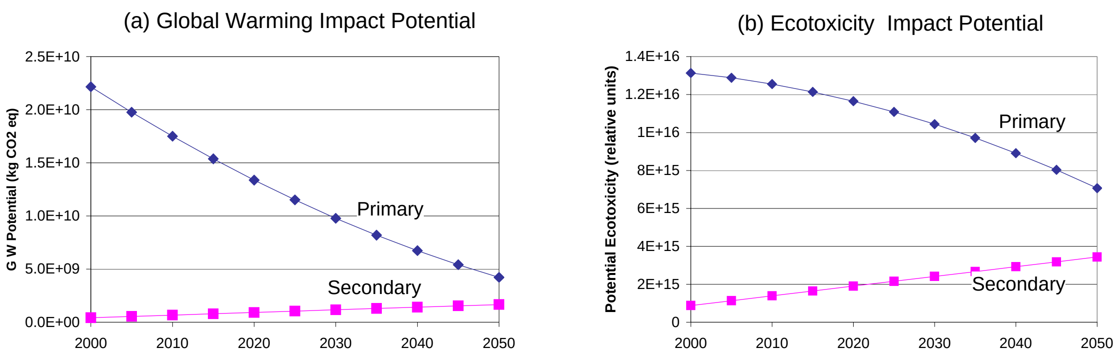


Figure 9-12: Impacts from primary and secondary production in impact-driven future

The final performance scores for the impact driven future are as low as 20% or less than the performance scores for the status quo. However, these values assume that there in no change in the external variables (such as declining ore grade and increasing demand) which would act to limit this improvement. The effect of changes in external variables beyond the control of actors is explored in Section 9.5.4 (more specifically, beyond the control of actors involved with mining and refining of primary and secondary resources listed in Table 9-5).

9.5.4 *External Behaviours*

The key external variables are modelled with the following functions as shown in Table 9-12. The modelling of external behaviours is needed to better understand the influence of changes in system variables which actors control in light of external changes beyond their control. This provides a better indication of the efficacy of their actions in the context of overall system performance. A logistic expression for demand is used in which the demand curve flattens out with time as shown in Figure 9-13. A linear demand curve which continues to increase also fits historical data and this alternative is presented in Appendix B.[9]

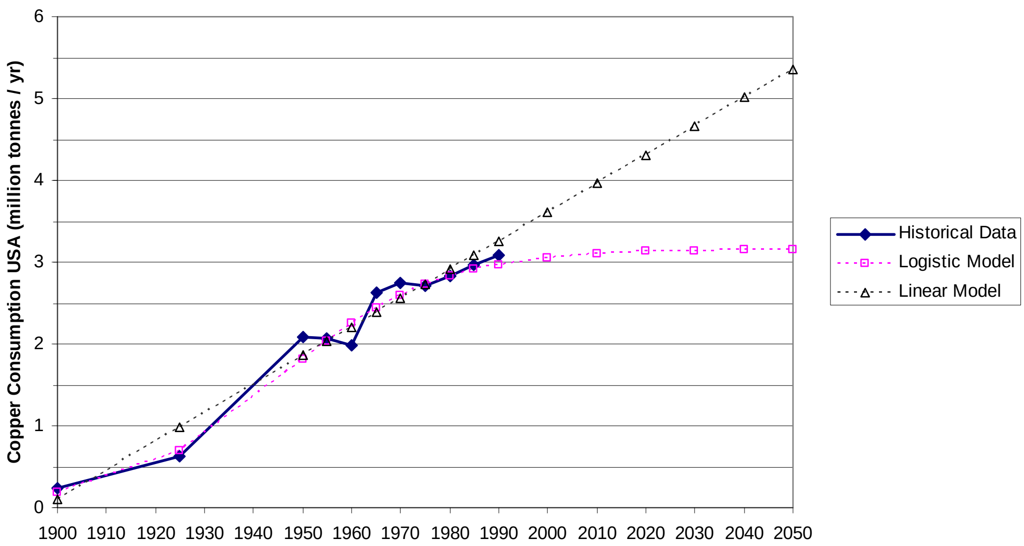


Figure 9-13: Models of demand for consumption in the USA (data from Zeltner et al., 1999)

[9] An 'intensity of use' model for demand patterns has also been proposed (see Ayres et al., 2001). With this model, the amount of copper used per person increases as a function of economic activity for a country during its industrialisation, then peaks and declines for a post-industrial developed nation.

Table 9-12: Classification of model parameters and external system variables

Variable	Value	Comment
Primary Ore grade: $q_2(t)$	$\text{Ore grade} = 4\times10^{13}\cdot e^{-0.01845(\text{year})}$ *N.B. year expressed as 2005, 2006, 2007... in this expression rather than t = 0, 1, 2....*	Derived from (Ayres et al., 2001)
Recoveries		
Flash: $R_1(t)$	88%	(Biswas and Davenport, 1994)
SX/EW: $R_2(t)$	62%	(Young, 1999)
New: $R_3(t)$	62%	(Young, 1999)
Collect No1: $R_4(t)$	70%	Estimated
Collect No2: $R_5(t)$	70%	Estimated
Collect Low: $R_6(t)$	70%	Estimated
No1: $R_7(t)$	97%	As for Low
No2: $R_8(t)$	97%	As for Low
Low: $R_9(t)$	97%	(Biswas and Davenport, 1994)
Demand (tonnes) $R_{17}(t)$	$\text{Demand} = \frac{180{,}000}{0.057+(1-0.057)e^{-0.062(t-1900)}}$ *note year expressed as 2005, 2010 etc. in this expression*	Logistic expression for demand from (Zeltner et al., 1999)
Long-Goods	65%	
No1: $R_{18}(t)$	60% of long goods: $R_{18}(t)$=0.39$R_{17}(t)$	Derived from (Edelstein, 1999)and (Biswas and Davenport, 1994)
No2: $R_{19}(t)$	20% of long goods: $R_{19}(t)$=0.13$R_{17}(t)$	
Low/Brs: $R_{20}(t)$	5% /15% of long goods: $R_{20}(t)$=0.13$R_{17}(t)$	
Short Goods	35%	
No1: $R_{21}(t)$	10% of short goods: $R_{21}(t)$=0.035$R_{17}(t)$	Derived from (Edelstein, 1999) and (Biswas and Davenport, 1994)
No2: $R_{22}(t)$	10% of short goods: $R_{22}(t)$=0.035$R_{17}(t)$	
Low/Brs: $R_{23}(t)$	60%/20% of short goods: $R_{23}(t)$=0.28$R_{17}(t)$	
Dissipated	0.5%	(Henstock, 1996)
Discard	(based on time in use: t_{short} =5, t_{long} 35)	(Göckmann, 1992)
Short No1: $R_{24}(t)$	$R_{24}(t) = R_{17}(t - t_{short})$	(McLaren et al., 2000)
Long No1: $R_{25}(t)$	$R_{25}(t) = R_{17}(t - t_{long})$	"
Short No2: $R_{26}(t)$	$R_{26}(t) = R_{17}(t - t_{short})$	"
Long No2: $R_{27}(t)$	$R_{27}(t) = R_{17}(t - t_{long})$	"
Short Low: $R_{28}(t)$	$R_{28}(t) = R_{17}(t - t_{short})$	"
Long Low: $R_{29}(t)$	$R_{29}(t) = R_{17}(t - t_{long})$	"

The results of a 'base case + external' scenario, highlighting the effect of changes to external variables on material chain flows and environmental performance (in the absence of actor controlled changes) are given in Figure 9-14.

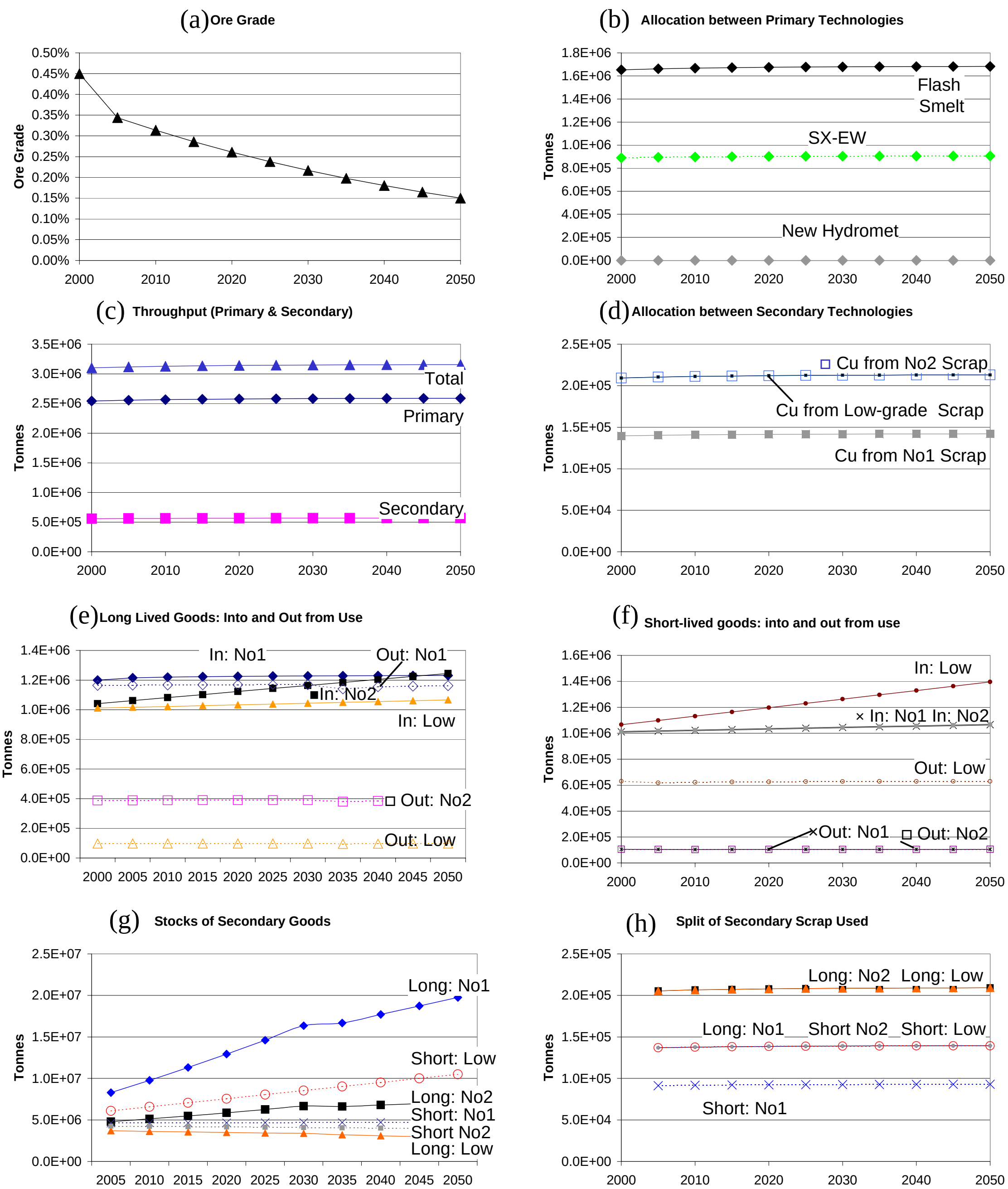


Figure 9-14: Base case with external variables

The declining ore grade with time as an input to primary processing is shown in Figure 9-14(a), approximately following an exponential decay. In Figure 9-14(b, c, d, h) there is no change in the proportions of metal coming from primary or secondary sources, nor the relative splits between primary and secondary technologies (as this is for the base case). There is a slight increase in demand, consistent with the logistic expression for demand growth. Figure 9-14(e) show the flows of copper 'in' to make long-lived goods which then go on to become scrap of either No1 (very high grade), No2 (high grade) or low grade. It also shows the copper 'out' of long-lived goods from the use phase. The model assumes that the historical stock of goods in use has the same residence time profile as the current goods in use. This means that for long-lived goods with a residence time of 35 years, these exit from use now, assuming a similar inflow from 35 years ago.[10] Similarly, Figure 9-14(f) shows the case for short-lived goods. The secondary stocks are dependent on inflows from goods exiting the use phase and outflows which are collected for reprocessing as shown in Figure 9-14(g).

This sub-section has illustrated the resultant changes to material flows from changes to external variables. Their effect on the environmental performance of transitions to actor-driven and impact-driven futures are now evaluated.

9.5.5 *Comparison of Futures including External Changes*

The principal material flows in each case are shown in Figure 9-15. As the increase in total demand with logistic growth is limited, the material flows for the actor-driven and impact-driven futures are similar to the cases considered earlier where external variables were not considered. Selected results for the case where demand increases linearly are presented in Appendix B.4.

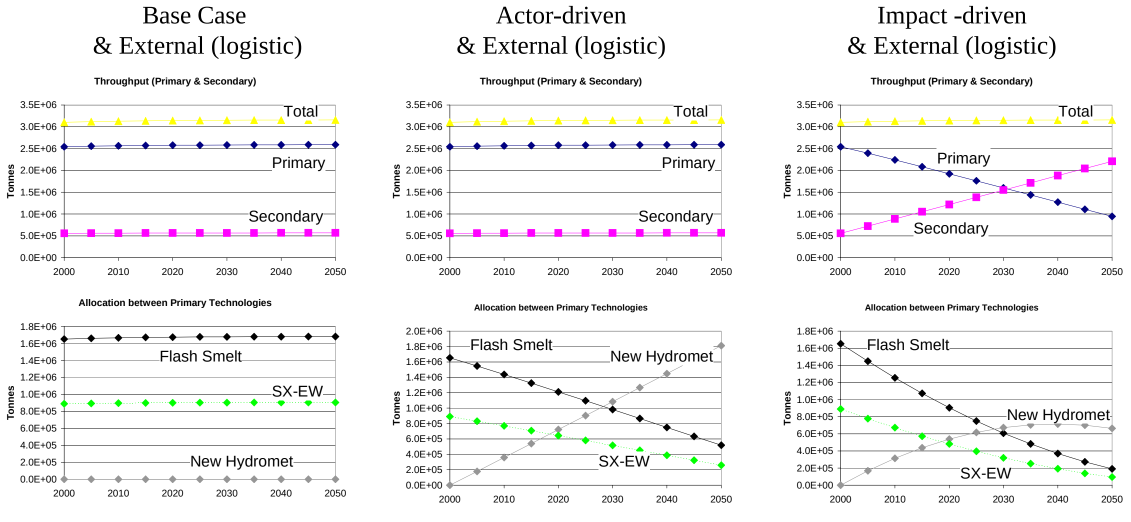


Figure 9-15: Principal material flows for actor-driven and impact-driven futures as compared to the base case and allowing for changes to external variables

[10] Changing residence times of goods in use through time can be represented in the model by calibrating background stocks against historical usage.

9.5.5.1 *Global warming impact*

Figure 9-16 compares five impact profiles with respect to global warming.

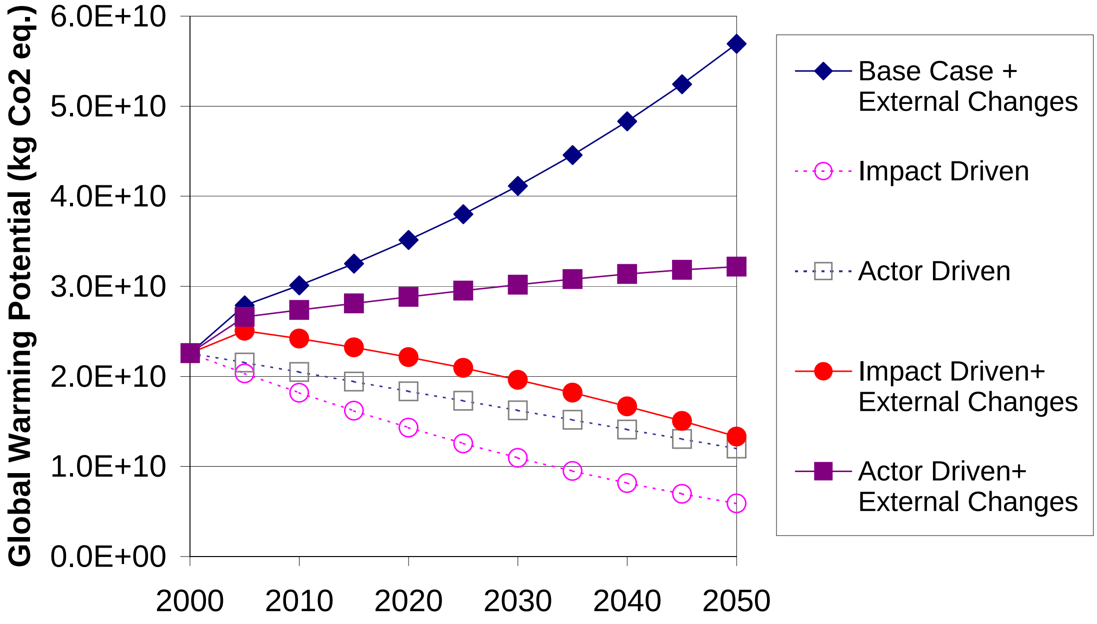


Figure 9-16: Change in global warming impact potential for actor-driven and impact-driven futures, with and without the influence of changes in external variables

The solid diamond referring to 'base case + external changes' tracks the effect of changes to external variables where all decision variables remain as for the status quo. The second series indicated by the open circle is for the impact-driven future (changing primary technology and recycling rate) whilst the open square refers to the transition toward actor-driven future (changing primary technology only), both assuming no changes in external variables. The fourth and fifth profiles detailed in the legend of Figure 9-16 show the combination of transitions toward impact driven and actor driven futures in the context of changes in external variables, indicated by solid circles and solid boxes respectively.

Comparison of the three trajectories indicated by solid symbols is most meaningful as a point of departure; they each include changes in external variables (declining ore grade and changing demand) for the base case (◆), actor driven future (■) and impact driven future (●). The absence of any intervention, predicts a base case with an impact that more that doubles over the modelling period from 2000 to 2050, principally due to the effect of a declining ore grade (which requires more energy to process and results in a higher global warming burden) and to a much lesser extent the slight increase in demand.

Strikingly for the actor driven future, the improvements achieved through the progressive introduction of a new primary processing technology do not compensate for the increased impacts from changes in external variables: the future value chain configuration in 50 years has a higher global warming impact than for the base case, in stark contrast to the performance improvements suggested in Figure 9-3 where changes to external variables were not considered (compare solid and hollow squares in Figure 9-16). Although the new primary processing technologies deliver improvements, their effect is outweighed by the greater influence of declining ore grades on overall performance. With the system configuration still heavily reliant on primary processing, the effect of the declining ore grade dominates. This indicates that the introduction of new primary processing technology alone does not constitute a strategy that will result in a reduced global warming burden in the USA.

The impact driven future (introducing new primary technology and increasing the recycling rate) is the only strategy to show an overall reduction in the global warming impact, despite increases in demand and declining ore quality. The declining ore grade increases the impact attributable to primary production, however, primary production represents a smaller fraction of the overall supply in the impact driven future, due to the increased utilisation of secondary resources. This increasing role of secondary processing in meeting demand explains the smaller change between considering external variables and not considering external variables for the impact-driven futures (● and ○) rather than for the actor driven futures (■ and □) in Figure 9-16. The trends observed for global warming are assumed representative of acidification and water usage effects based on observations in Figure 9-11.

The relative contribution to global warming impact from primary and secondary sources for the actor-driven and impact-driven transitions to preferred futures are shown in Figure 9-17. The major contribution to global warming potential in each case comes from primary processing.

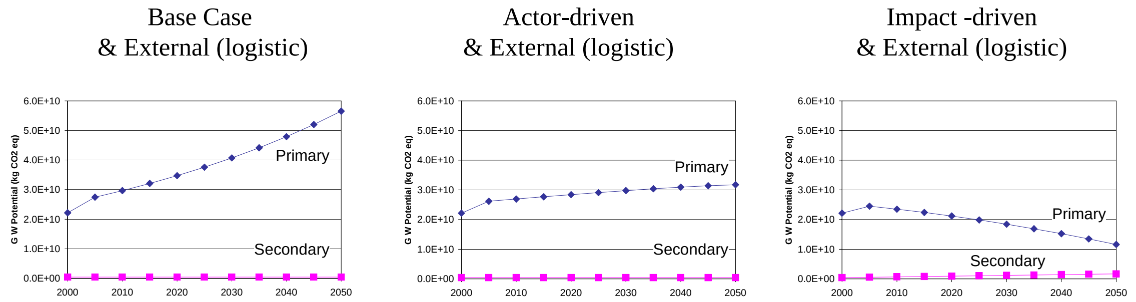


Figure 9-17: Comparison of primary and secondary contributions to global warming burdens for base case, actor-driven and impact-driven future transitions

9.5.5.2 *Ecotoxicity impact*

The same five case that were indicated for global warming impact in Figure 9-16 are plotted in Figure 9-18 for potential ecotoxicity.

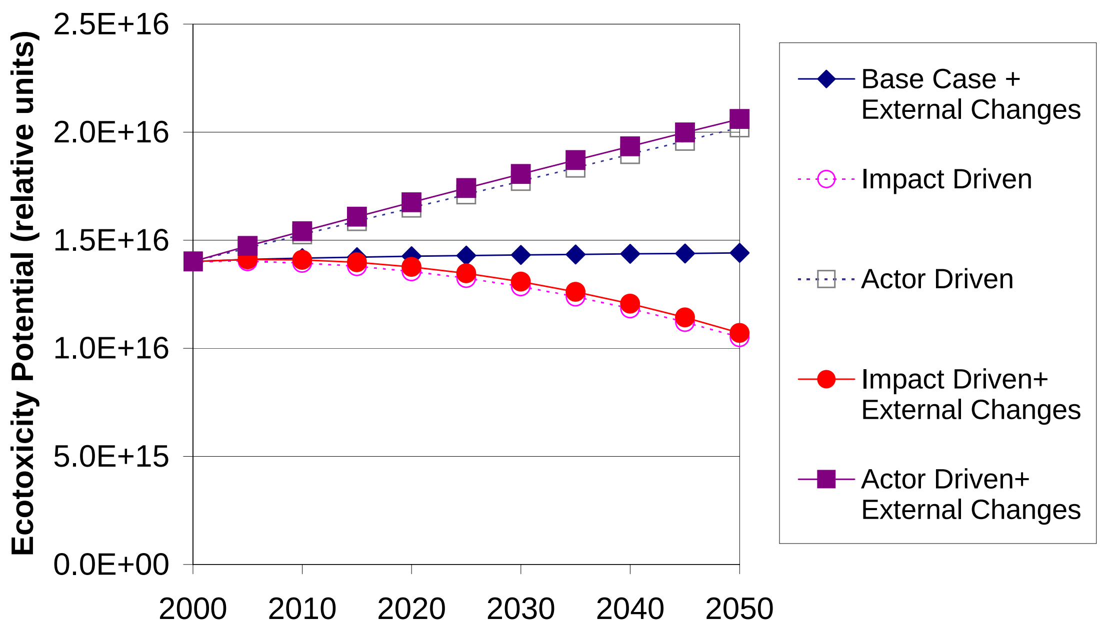


Figure 9-18: Change in potential ecotoxicity impact for actor-driven and impact-driven futures, with and without the influence of changes in external variables

Interestingly, the base case with changes to external variables shows only a minor increase to the potential ecotoxicity impact (due to increasing demand) as ecotoxicity is more a function of technology recovery (between flash and SX/EW and between primary and secondary) than a function of ore grade for any given technology. For this reason, the impact for the actor driven and impact driven futures which include the effect of external variables is similar to the respective cases without consideration of external variables (namely, little difference between ■ and □; similarly, little difference between ● and ○). Consequently, when no changes are made to the current configuration and pyrometallurgy continues to be the dominant primary production technology, ecotoxicity will not increase greatly. However, when the share of hydrometallurgy increases as a percentage of primary production (in the actor-driven future) then ecotoxicity increases significantly. Only when combined with the reduction in ecotoxicity from the increased recycling (in the collaborative, impact-driven future) does a net reduction occur over the 50 year period.

The breakdown of contributions from both primary and secondary processing is shown in Figure 9-19.

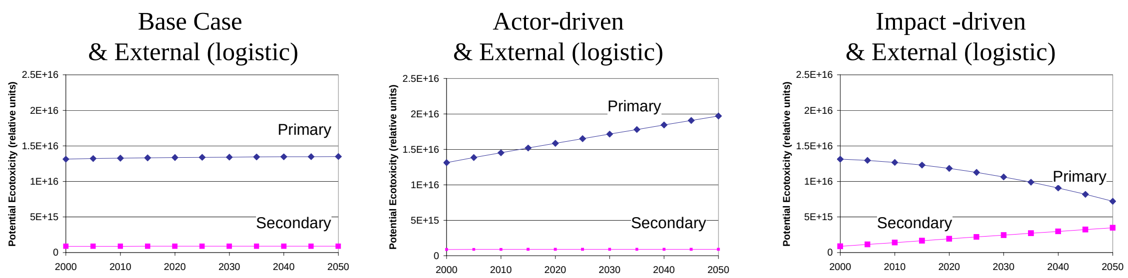


Figure 9-19: Ecotoxicity potential of base case, actor-driven & impact-driven transitions to alternate futures comparing contributions from primary & secondary processes

The transition paths to alternate futures in this section have assumed a progressive implementation at each time step from status quo to alternate future. The timing of the implementation of initiatives will affect the overall performance of the path toward the alternate future and is explored in Appendix B.

9.5.6 *Discussion of reward for effort*

Using the results from Figure 9-16 and Figure 9-18, the average increase or decrease in potential impact associated with three transition paths to three alternate futures can be considered. The strength of the case for collaboration across the material chain to deliver preferred futures, depends on the difference between the progress which can be achieved individually and collectively.

The three cases examined were as follows:

- no change by actors (changes only in external variables: declining ore grade, increasing demand)
- single actor driven future (change to new primary processing technology of hydrometallurgy coupled with clean electricity in context of externally controlled decline in ore grade and increase in demand)
- collaborative future / impact driven future (change to new primary processing technology and increased recycling in the context of externally controlled decline in ore grade and increase in demand).

The important points to note are:

- taking no action results in a vastly increased global warming burden
- the introduction of new technology on its own increases the ecotoxicity relative to the case where no action is taken (as it is based on hydrometallurgy linked to hydro-electricity) and pyrometallurgy continues to dominate the primary production mix and still does not reduce the global warming burden below current levels (although it does act to limit the increase)
- only with collaborative action between primary and secondary processors across the materials chain can a decrease to both ecotoxicity and global warming impact potentials below current levels be achieved: while more effort, a collaborative approach must be pursued together with strategies discussed in this thesis.

Furthermore, it should be noted that that collaborative action proposed, still only gives an outcome that slightly improves both ecotoxicity and global warming potential. Given that current emissions are considered unsustainable, it suggests that strategies targeting reductions in overall demand for copper within the material chain should be pursued.

9.5.7 *Actor behaviour: system responsive*

The previous scenarios have considered pre-determined actor behaviour for changing system variables, irrespective of the system state. This section demonstrates the ability of the model to include 'rules' for the behaviour of actors which are responsive to the performance of the system. Two cases are explored:

- first, the fraction of demand met by secondary processing increases when environmental performance is poor, as an actor-led response to improve overall performance

- second, the types of secondary materials sourced (either No1 very high grade, No2 high grade, or Low grade) are made dependent on the available quality and quantity of secondary scrap. This case is presented in Appendix B.

9.5.7.1 *Fraction of demand met by secondary processing*

In this scenario, we consider the introduction of an environmental emission protocol (such as Kyoto) which results in penalties for increasing emissions beyond the status quo (or earlier reference year). As environmental performance deteriorates through time (due to declining ore grades and increased demand), then the penalties that occur encourage actors in this example to adopt new infrastructure or change the configuration of flows within the value chain for less environmental burden. The actor behaviour is simplified to show how it can be incorporated in the approach.

For the decision variables shown in Table 9-13, actor behaviour changes in response to the environmental performance of the system. This means that new technologies are introduced to primary production when the environmental performance of the value chain exceeds a threshold level. Similarly, the amount of secondary resource processing increases when the environmental performance of secondary processing exceeds a threshold. The performance indicator used is global warming potential.

As shown in Table 9-13, the split between primary technologies will reach their target value at t_{50}, in the same incremental implementation as for the actor-driven and impact-driven futures. By contrast, the changes in the recycling rate is dependent only on the global warming performance and the end value is not fixed.

Table 9-13: Parameters for system responsive cases

	Var	t_0	Path	t_{50}
Split between primary technologies				
Flash	$R_{10}(t)$	65%	$R_{10}(t) = -0.009t+0.65$	20%
SX/EW	$R_{11}(t)$	35%	$R_{12}(t) = -0.005t+0.35$	10%
New	$R_{12}(t)$	0%	$R_{11}(t) = 0.014t$	70%
Split between primary technologies				
No1	$R_{13}(t)$	25.0%	Constant	25.0%
No2	$R_{14}(t)$	37.5%	Constant	37.5%
Low	$R_{15}(t)$	37.5%	Constant	37.5%
Split between primary /secondary tech	$R_{16}(t)$	18%	Increase following poor environmental performance (see below)	?
Demand (tonnes)	*D(t)*		$D(t)$= 110 000+35 000(*t-1910)* *note year expressed as 2005, 2010 etc. in this expression*	

A representative logic to demonstrate the potential for modelling actor behaviour is given below, however detailed modelling of actor behaviour is beyond the scope of this work. As an extension, the approach developed in this thesis could be coupled with more complex models for representing actor behaviours. For further details on such approaches see (Bousquet and Le Page, 2004; North et al.; Posch, 2004).

For the split between primary and secondary the actor-logic to determine when the recycling rate is increased is expressed as follows:

For $R_{16}(t) \leq 70\%$ and t =1 to 11 (where one time iteration represents 5 years)[11]

If ($GWP_{Overall}(t)<k_{1,threshold}*GWP(t-1)$), Then $R_{16}(t) = R_{16}(t-1)$

Else If ($GWP_{Overall}(t)<k_{2,threshold}*GWP(t-1)$), Then $R_{16}(t) = k_{a,infrastructure}*R_{16}(t-1)$

Else If ($GWP_{Overall}(t)<k_{3,threshold}*GWP(t-1)$), Then $R_{16}(t) = k_{b,infrastructure}*R_{16}(t-1)$

Else $R_{16}(t) = k_{c,infrastructure}*R_{16}(t-1)$ (up to maximum of 70%) Equation 9-1

The constants for this example are shown in Table 9-14.

Table 9-14:Threshold constants

Pollution Threshold Constants	Value
k_1	1.05
k_2	1.10
k_3	1.20
Infrastructure Investment Constants	
k_a	1.20
k_b	1.25
k_c	1.30

The mass flows through time in the material chain which result from the actor-responsive case are illustrated in Figure 9-20 together with the associated global warming impact potential. Figure 9-20 shows a step-wise increase in the amount of secondary resources used to meet demand after one or two time periods. The fluctuating utilisation of primary resources results from the difference in the similar rate at which the externally controlled demand increases and the rate at which actors increase secondary resource utilisation as a result of increasing global warming burden.

[11] One time step was made to equal a period of 5 years to improve computation time. The illustrative logic only increases secondary resource utilisation as a result of an increase relative to the previous time step which limits that rate of increase, but not the total emissions. It is also dependent on the time period chosen and constants *k*.

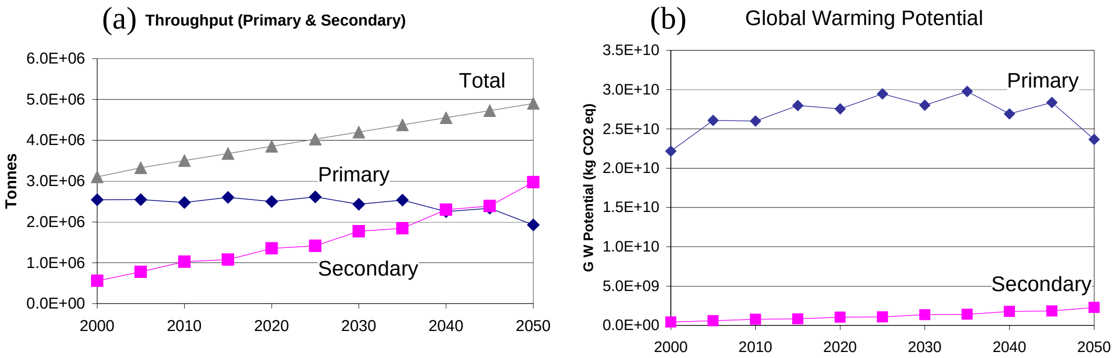


Figure 9-20: Principal material flows and global warming potential for actor-responsive case

Likewise, the fluctuating environmental performance results from performance exceeding the set threshold as a result of declining ore grade and increasing demand, actors respond by introducing system changes which reduce impact. With these changes in place, the influence of external variables acts to increase environmental burden through time, until such point that the next threshold is exceeded and additional system re-configurations are made. While this case is for illustrative purposes, it highlights the ability of the approach to allow actor responses to policy frameworks based around legislative limits to be explored.

9.5.7.2 *Type of secondary processing responsive to scrap quality and quantity*

This case is presented in Appendix B.3.

9.6 CONCLUSIONS

The aim of this analysis has been to demonstrate the potential impacts associated with interventions of actors within the minerals industry and of variables beyond their control. Understanding the link between decisions to change system variables and the resultant impacts in the value chain, provides the basis for discussing the required choices which lead to a preferred future and exploring their ability to be implemented.

This case study has served to demonstrate the way to envision and evaluate different paths toward alternate futures for the value chain in the USA. It showed that a collaborative effort between actors is required to bring about improved future environmental performance of the value chain across impact categories.

Both the introduction of new processing technology and additional secondary processing infrastructure is required. The magnitude of the difference in environmental performance profiles between the implementation of new primary technology alone, and then in conjunction with increased recycling, demonstrates that a much greater reward is possible from pursuing the collaborative option and also the benefits of recycling per se even using current technology. Furthermore, it allows each actor to clearly see the potential improvements arising from their choices, within the context of a dynamic value chain subject to external influences.

By only achieving a modest improvement even with collaborative action, makes the case to use the information from the analysis to also change behaviours currently considered beyond control. While the external factor of declining ore grades cannot be changed, the other key external factor was increasing demand. This analysis strengthens the case for pursuing research into strategies for reducing demand as a means of delivering improved environmental performance across the material chain.

CHAPTER TEN

Conclusions and Recommendations

This thesis explored the environmental implications of changes to the configurations of flows and infrastructure in metal value chains, in the context of assisting this industry sector to become more sustainable.

The specific objectives of this work were to:

(a) develop a classification tool that facilitates understanding the interaction between actors, system flows and impacts across geographic scales in the material chain;

(b) develop tools that characterise material and energy flows at different scales, where characterisation includes linking the ability of actors to change material chain configurations and their resultant impacts;

(c) develop an approach to evaluate dynamic transition paths from current to preferred future material chain configurations which can be used to guide more sustainable choices in the minerals industry.

These objectives were met by:

- ♦ developing a unified reference schema to classify and interpret scale at the local, regional and global level for varied levels of complexity of the value chain – ranging from within a process to across multiple value chains;
- ♦ developing models of material and energy flows that can be applied at different scales to characterise the environmental impacts for current value chain configurations and which can then be used to identify key variables via a sensitivity analysis and the controlling actors of these variables – thus, providing insight into the institutional arrangements which could be required to change key system variables for improved system performance;
- ♦ developing a structured approach to backcasting of preferred futures for the material

chain and the development of dynamic models to evaluate the environmental impacts of transition paths from the status quo toward preferred futures;

- demonstrating the methodology using copper-specific case studies.

10.1 GENERAL CONCLUSIONS

These conclusions are drawn from the methodological development of the thesis in Chapters 2, 3, 4 and 5.

10.1.1 *Minerals, metals, environmental performance and sustainability*

The minerals industry has committed to the goal of sustainable development and seeks to close the material loop, but lacks an approach to translate high level goals into required actions, hence the motivation for this work.

Research from this thesis concludes that:

- Sustainability in the minerals and metals industry is a multi-scale problem which must be addressed with explicit consideration of multiple spatial and time scales.
- There is currently a discord between the Domain of Interest of actors, their Domain of Influence and Domain of Impact that their actions produce which is viewed as symptomatic of an unsustainable system. As a first step to creating a more sustainable system, current material and energy flows, their impacts and the actors controlling key system variables must be better characterised using a structured approach.
- The structured approach must be applicable across scales and clearly link actions that change the configurations of material flows and technology infrastructure in the material chain, with consequential environmental impacts.
- The minerals industry makes decisions with limited focus within the materials chain, limiting its improvement options. A 'whole of material chain' approach provides the necessary basis for making decisions to improve performance that considers both supply and demand options. This thesis begins this process by exploring supply-side options for processing metal with reduced environmental burden from both primary and secondary sources.

10.1.2 *Realising futures that reduce environmental impacts*

The key conclusions from the methodological development are summarised below.

- The existing classifiers for environmental decision making of 'strategic', 'tactical' and 'operational' do not have the coherent value chain focus required for designing improved metal cycles.
- The reference schema developed to classify decision problems, based on variations in spatial scale and materials chain focus, is a practical and important basis for understanding scale issues in metal cycles and guiding the level of information detail used in analyses.
- Using the reference schema to classify decision problems – including potential system variables and actors – represents an innovative way of understanding the multi-scale dimension to sustainability problems in the minerals industry; in particular, the relationship between domain of influence, interest and impact.
- The materials value chain is modelled as a series of connected nodes (representing transformation processes or material stocks) that track material flows and the splits of flows between nodes at each stage in the material chain in a Microsoft Excel – Visual Basic environment. Splits of flows between nodes may be a function of the system/technology or be actor-controlled or external variables. Material and associated energy flows are linked to their contribution to multiple environmental impacts with trade-offs between impacts being made explicit. The holistic assessment of environmental performance includes modelling the impacts associated with transport and different energy mixes.
- Modelling the performance of current material chain configurations using steady state models allows key variables to be identified with a sensitivity analysis and the influence of actors controlling key variables to be rated. Strategies to be implemented for performance improvement within existing infrastructure can then be developed.
- Preferred futures to achieve sustainability goals are envisioned by backcasting changes to variables within the control of actors for a particular scale as identified in the reference schema.
- Company and sector-wide strategies for realising preferred futures can be developed by comparing the improvements which actors achieve individually and collectively.
- Dynamic models are used to assess the impacts through time of actor-controlled choices regarding supply-side strategies. These strategies are assessed in the context of

an operating environment where particular variables are beyond the direct control of the minerals processing actors (e.g. consumer demand, declining ore grades in mines dictated by remaining available reserves). This modelling directs the scale and timing of required interventions by actors to achieve preferred futures.

- By using the methodology, actors can see the impacts of their actions across scales, understand which collaborations are necessary to achieve preferred futures and assess the influence of external variables on the impact of their decisions. This collectively provides the basis for better informed decision making and establishes the material chain approach to assessing flows and impacts. The material chain approach is central to both assessing supply-side options (as in this work where primary and secondary resources are considered) and for a necessary future consideration of potential demand reduction initiatives and business models that utilise less metal in providing services to society.

10.2 SPECIFIC CONCLUSIONS FROM CASE STUDIES

The studies of the copper value chain spanned spatial scales and considered improvements possible within existing and future infrastructure. The insights from each case study follow.

10.2.1 *Global analysis of status quo*

The first-pass snapshot analysis of the flows of copper through the material chain shows that there is moderate global resource scarcity for copper ores. Copper will be available from currently identified primary ore-bodies for another 30–50 years if usage continues at current rates.

Little copper is directed to dissipative end-uses (1–3%, mainly in chemicals and brake-pad linings for vehicles) which allows the potential for increased recycling from the accumulating pool of copper currently in use and that which continues to be discarded but is not fully recycled. Such products may be either in relatively pure form, as alloys or as complex product mixtures, for example, electronic scrap.

There are large energy requirements to bring copper metal to market, especially for primary processing from ores. These requirements are between 4–20 times larger than the energy requirements for refining metal from secondary (recycled) sources.

10.2.2 *Technology-specific models for primary processing*

The environmental impacts of the three main classes of primary processing technologies for copper were explored. The first technology, reverberatory smelting, has the highest acidification impact per tonne of copper produced due to its lack of effective SO_2 capture and is currently being phased out around the world.

The second technology, flash smelting, has the lowest impact potential across impact categories, but has a limited ability to utilise the more prevalent lower grade ores, due to their greater impurities.

Thirdly, heap leach solvent extraction / electrowinning (SX/EW) is increasingly being utilised as a technology for primary copper refining. It successfully processes lower grade ores, with a comparable global warming impact potential to flash smelting, but with the highest ecotoxicity impact per tonne of all technologies. This is due to the lower copper recovery with hydrometallurgy, meaning a greater quantity of ore must be processed to deliver an equivalent amount of copper product. Greater understanding of the potential ecotoxicity impact is required to inform management practices of the final solid waste burden.

10.2.3 *Regional analysis of status quo*

The calculation of baseline impact profile for regions across the globe illustrated the distribution of impacts associated with copper mining and refining worldwide. Total impact differs by a factor of 2–10 between world regions.

Variables most affecting environmental performance are associated with changes to ore grade, recovery (from both primary and secondary resources) and electricity mix (being for example coal, oil, gas, hydropower, nuclear).

Countries in the southern hemisphere have larger impacts associated with processing copper than countries in the northern hemisphere, due to the higher volume of primary production for copper occurring in the southern hemisphere. The highest consumption occurs in the northern hemisphere and represents a future resource base to be drawn from recycled goods.

10.2.4 *Improvements possible through changing imports into Europe*

The difference in impact associated with copper from specific world regions, operating different technologies with varied ore grades and electricity mixes, offers the potential to alter the impact profile associated with importing refined copper into Europe.

Understanding trade-offs with favouring options that have a lower global warming burdens could be of interest for participants in the Kyoto protocol.

Current imports to Europe from Central Asia and Latin America offer close to best performance with respect to global warming. Seeking the absolute minimum global warming impact raises the local ecotoxicity impact for regions outside Europe. Seeking to minimise acidification results in an 80% increase to the global warming potential relative to the base case, while seeking to minimise ecotoxicity results in a 90% increase to the acidification impact potential, giving rise to a trade-off. Acidification is of less concern over the long term as the reverberatory smelters responsible for this effect are being phased out, however, there is a pressing need to better understand the increased ecotoxicity impact as the use of hydrometallurgy is growing. Multi-criteria analysis is used to demonstrate how weightings can be given to impact categories to facilitate selection of a preferred alternative – a process requiring input from stakeholders to determine appropriate weightings.

10.2.5 *Detailed evaluation of innovative copper refining technology*

Extending the generic material chain and technology modelling approach to the site-specific level to include actual plant data from the operation of a proprietary demonstration plant in Australia has enabled the impact of changes to process design parameters to be assessed. This allows the technology's role in improving material chain performance to be evaluated and to identify actions both within and beyond the plant boundary that will improve performance.

Global warming and acidification impacts associated with the innovative hydrometallurgical technology are primarily attributable to energy provision. This is an indirect impact (occurring off-site), however the value chain approach coupled with Life Cycle Assessment extends the Domain of Interest and prompts responsibility for the Domain of Impact outside the plant boundary. Recognising that addressing this issue lies beyond the direct Domain of Influence of the technology operator, collaborative action with 'cleaner' energy providers is recommended for future full-scale technology installations.

Ecotoxicity is primarily attributable to the process solid waste and is highly dependent on the composition of the feed to the process. Studying the chemical stability of the solid waste provides valuable information in the selection of waste management practices and could be used to direct process operation to deliver a more inert waste or additional processing to recover mobile metals.

A modified three-step sequential leach protocol is developed to measure waste stability as the existing TCLP measure of waste stability is poorly suited to quantifying the mobility of minerals wastes. Metal mobilised at each stage of the sequential leach protocol is linked with potential waste management strategies.

This thesis develops an 'informed mobility indicator' based on the metals leached at the second sequential leach stage. A better quantification of the ecotoxicity impact potential is developed, advancing the usefulness of Life Cycle Assessment in the minerals context, by now taking account of the stability of the waste when assessing impact potential.

Iron and sulfur together account for more than 50% of the mass of the solid waste residues for the proprietary technology investigated. Results of the modified sequential leach protocol show that only 10% of iron and 10% of sulfur are mobilised under conditions similar to an uncapped waste deposit. This result is a stark contrast to the potential ecotoxicity impact of iron and sulfur, which accounts for 90% of total ecotoxicity when the stability of the iron and sulfur compounds and their potential mobility is not taken into account.

10.2.6 *Paths toward alternate futures in USA*

The future configuration of the copper value chain in the USA is backcast to consider the introduction of a new hydrometallurgical primary process coupled to 'clean' energy generation with a low global warming potential. Additionally, the ratio of metal supplied to market from secondary resources is increased. Together these variables represented the most influential actor-controlled changes to enhance system performance through supply-side strategies.

Considering only the configuration of preferred future states (in the year 2050), the sole introduction of new technology for primary refining (to a level which represents 70% of all primary refining), produces a substantial reduction in global warming burden, but at the expense of an increased ecotoxicity potential. Increasing the processing of scrap to meet 70% of demand (in addition to introducing new primary refining technology), further decreases the global warming potential and results in an overall decrease in the ecotoxicity potential compared with the status quo.

When considering an incremental transition from the status quo to alternate future in the context of changes to external variables beyond the control of actors in the minerals industry (namely overall demand, average ore grade and residence time in use of copper goods) the introduction of new primary refining technology alone, does not produce a net improvement in the global warming potential compared with the status quo. Instead, it is the increased processing of recycled scrap that has a much larger impact on reducing burden. Although demand does not increase significantly in the scenario, ore grades decline, which increases the relative and absolute impacts associated with primary processing (compared to secondary processing). When the increased processing of scrap is combined with the incremental introduction of new primary refining technology over 50 years, it results in a decreased global warming burden relative to the status quo.

An illustrative case study models the behaviour of actors as responsive to the environmental performance of the system, rather than following a pre-determined implementation strategy over the modelling period. This shows how the developed approach can be extended to include models of actor-behaviour whose decisions are based on system performance at each time step.

A collaborative effort between primary processing and recycling actors is required to improve the future performance of the materials chain beyond current performance. This necessitates a major focus on increasing recycling rates. Increased recycling plays a greater role in improving environmental performance in the material chain than the introduction of new primary processing technologies.

10.3 RECOMMENDATIONS FOR FUTURE WORK

Additional insights will be gained by extending the development and application of the methodology in the following areas:

- Promote the uptake of the methodology by industry for its future planning, especially the need to include consideration of the material chain across scales as the starting point for considering changes to flows and technology infrastructure.
- Apply the methodology to establish an industry benchmark for current performance and for more sustainable future configurations, against which industry performance is tracked. This could be extended to have companies report the environmental burden of each tonne of metal produced. Furthermore, explore instruments that promote the production of metal with the lowest environmental burden (e.g. from recycled sources) and the development of products that facilitate recycling.
- Apply the methodology to further case studies to explore preferred futures for nations, regions and companies.
- Explore strategies for delivering the services provided by metals whilst reducing the absolute demand for metal in the economy – this could include consideration of

product compositions and lifetimes together with instruments (regulatory, voluntary, market-based) that promote the sale of a 'service' rather than a good.

- Extend the scope of analysis to include multiple value chains and additional performance criteria (for example, economic and social criteria).
- Extend the quantification of feedback mechanisms across scales and model the self-organising nature of system actors and their behaviour in a competitive environment, for example, using agent-based models.
- Include more detailed residence-time distributions for the quantity of goods in use and the operational duration of technology infrastructure.
- Incorporate measures of system flexibility, robustness and resilience to further assess sustainability of value chain configurations comparing constant external environments and changing external environments in which greater flexibility would be more important (through the maintenance of technological diversity in the system configuration).
- Further develop a measure to assess the alignment between domain of interest, impact and influence as a measure of sustainable system operation.

10.4 CLOSING DISCUSSION

This work contributes to advancing the sustainability of the minerals industry by developing an approach that links changes by actors to material chain configurations with resultant impacts across scales and uses this information to design and evaluate paths toward preferred futures.

A more sustainable metals cycle will only be achieved with a greater understanding of the scale at which impacts occur and at which improvements should be made.

Scale must be understood in multiple areas, particularly the scale at which:

- connections between nodes in value chain occur (system configuration)
- actors can effect change (domain of influence)
- actors focus attention (domain of interest)
- impacts are manifested (domain of impact).

Actors must become more aware of the impacts they are generating which are currently externalised. This provides greater insight into the current problem and how it can be addressed. Developing the reference schema allows industry and government actors to grasp the concept of scale in a common language and appreciate the system variables over which each party has influence. An important aspect of developing more sustainable systems is to better understand the current role of individual parties, future roles in a more sustainable system, what collaboration is required to deliver change and what tensions are likely between parties in making this transition. With a clear mechanism for characterising responsibility for impacts arising from material chain activities, parties are better placed to reach a consensus on how responsibility for future burdens and benefits will be divided.

The next task is to ensure that improved understanding of links between actions and impacts leads to improved decision making for sustainability. The developed methodology highlights the effects of changing actor-controlled and external variables on resultant impacts. A sustainable system will be both responsive and proactive to the knowledge that chosen actions have adverse impacts and use this information to influence individual and collective action. This requires industry and government to direct legislation and economic incentives toward promoting sustainable choices. It also requires further consideration of the scale at which such directives are effective. It is suggested that if actors generate impact within their domain of interest, they are more likely to respond to reduce that impact. A balance must be struck between encouraging broader domains of interest that targets improved performance for the global value chain as a whole, but which may be an unrealistic focus for individual actors, and on the other hand, having a narrow focus for which many impacts are manifested externally to the domain of interest which makes an effective feedback signal to reduce impact problematic to implement.

The focus of this work has been on environmental performance. To deliver a sustainable outcome, decision makers will need to take this environmental information and couple it with economic and social outcomes (which could be based on a similar methodological approach) in their decision making. By developing an approach that delivers a comprehensive assessment of the scale and timing of required interventions to reduce the impact of metal cycles, industry is much better placed to make tangible progress towards improved outcomes for society in the longer term.

APPENDIX A

Additional information for Chapter 7

Appendix A supplements the case studies in Chapter 7. It provides detailed assumptions and results related to the technology models of primary processing presented in Chapter 7 and additional technology models for secondary processing which were used to quantify the status quo for Europe and are again used in the case study in Chapter 9.

A.1 ASSUMPTIONS FOR PRIMARY TECHNOLOGY MODELS

A.1.1 *Flash Smelting*

Underground		Reference
MineUG_Elec_Rate_kWh_per_t ore	95	(MIM, 1999)
MineUG_Water_Rate_t_per_t ore	1.16	(MIM, 1999)
MineUG_Diesel_Rate_t_per_t ore	0	not known
Open Cut		
MineOpen_Elec_Rate_kWh_per_t ore	20	(MIM, 1999)
MineOpen_Water_Rate_t_per_t ore	0.58	(MIM, 1999)
MineOpen_Diesel_Rate_t_per_t ore	0.002	(Norgate and Rankin, 2000)
Mine_CO2_Rate_t_per_t_Diesel	3.64	(PRè, 2000)
Opencut_Rate_percent	95%	(Biswas and Davenport, 1994)
Concentrate-Ore Properties		
Ore_Cu_Rate_percent	0.5%	(Ayres et al., 2001)
Ore_Fe_Rate_percent	calculated	
Ore_S_Rate_percent	calculated	
Ore_SiO2_Rate_percent	calculated	
Ore_Contaminants_Rate_percent	calculated	
Ore_Balance(Gangue)_Rate_percent	calculated	
Conc_Cu_Recovery_percent	90%	(Biswas and Davenport, 1994)

Tail_Fe_Cu_Ratio	0.88	Assumes all Cu not recovered which ends up in tailings is associated with CuFeS2. So M(Cu)/M(Fe)=1.14, hence ratio Fe:Cu = 1/1.14 = 0.88
Tail_S_Cu_Ratio	1.00	m(S)/m(Cu) = 2*M(S)/M(Cu) = 2*32/64=1
Tail_SiO2_Cu_Ratio	2.00	Estimate
Tail_Contaminants_Cu_Ratio	0.10	Estimate
Conc_Cu_Rate_percent	30%	(Biswas and Davenport, 1994)
Conc_Fe_Rate_percent	27%	(Biswas and Davenport, 1994)
Conc_S_Rate_percent	30%	(Biswas and Davenport, 1994)
Conc_SiO2_Rate_percent	7%	(Biswas and Davenport, 1994)
Conc_Contaminants_Rate_percent	1%	(Biswas and Davenport, 1994)
Conc_Balance(Gangue)_Rate_percent	5%	(Biswas and Davenport, 1994)
Smelting		
Smelt_Oil_Rate_t_per_t_conc	0.044	(Riekkola-Vanhanen, 1999)
Smelt_Elec_Rate_kWh_per_t conc	120	(Riekkola-Vanhanen, 1999)
Smelt_SiO2_Rate_t_per_t_conc	0.1	(Biswas and Davenport, 1994)
Smelt_O2_Rate_t_per_t_conc	0.2	(Biswas and Davenport, 1994)
Smelt_Slag_Recycle_t_per_t_conc	0.05	(Biswas and Davenport, 1994)
Smelt_Slag_Cu_Rate_percent	1.5%	(Biswas and Davenport, 1994)
Smelt_Matte_Cu_Rate_percent	62%	(Biswas and Davenport, 1994)
Smelt_CO2_Rate_t_per_t_oil	3.82	(PRè, 2000)
Smelt_SO2_Rate_t_per_t Cu_in_conc	2	from conc. composition
Converting		
Convert_O2_Rate_t_per_t conc	0.127	(Biswas and Davenport, 1994)
Convert_SO2_Rate_t	0	assume all in smelter
Convert_Slag_Cu_Rate_percent	2.50%	(Biswas and Davenport, 1994)
Blister_Cu_Rate_percent	0.997	(Biswas and Davenport, 1994)
Electro-refining		
ERefine_Elec_Rate_kWh_t Cu	400	(MIM, 1999)
ERefine_Water_Rate_t_t Cu	1	(MIM, 1999)
ERefine_Effluent_Rate_t_t Cu	0.128	(MIM, 1999)
ERefine_Metals_Rate_t_t Cu	0.00000565	(MIM, 1999)
Electric Slag Cleaning Furnace		
SlagClean_Elec_Rate_kWh_t_Cu	40	(Biswas and Davenport, 1994)
SlagClean_Slag_Cu_Rate_percent	0.50%	(MIM, 1999)
SlagClean_Slag_Fe_Rate_percent	36.7%	(MIM, 1999)
SlagClean_Slag_S_Rate_percent	0.5%	(MIM, 1999)
SlagClean_Slag_SiO2_Rate_percent	36%	(MIM, 1999)
SlagClean_Slag_Contaminants_Rate_percent	2%	Estimate
SlagClean_Slag_Balance_Rate_percent	24%	By difference
Gas Treatment		
GasTreat_O2_Rate_t_t SO2	*0.2325*	*By stoichiometry 2SO2+O2-->2SO3 [0.5*32/64*percent to acid]*
GasTreat_Water_Rate_t_t SO2	*0.2615625*	*By stoichiometry SO3+H2O-->H2SO4 (18/64*percent to acid)*
GasTreat_SO2_to_acid_Rate_percent	93%	(Riekkola-Vanhanen, 1999)
GasTreat_Elec_Rate_kWh_t_conc	120	(Riekkola-Vanhanen, 1999)

A.1.2 *Reverberatory Smelting*

Underground		Reference
MineUG_Elec_Rate_kWh_per_t ore	95	(MIM, 1999)
MineUG_Water_Rate_t_per_t ore	1.16	(MIM, 1999)
MineUG_Diesel_Rate_t_per_t ore	0	not known
Open Cut		
MineOpen_Elec_Rate_kWh_per_t ore	20	(MIM, 1999)
MineOpen_Water_Rate_t_per_t ore	0.58	(MIM, 1999)
MineOpen_Diesel_Rate_t_per_t ore	0.002	(Norgate and Rankin, 2000)
Mine_CO2_Rate_t_per_t_Diesel	3.64	(PRè, 2000)
Opencut_Rate_percent	95%	(Biswas and Davenport, 1994)
Concentrate-Ore Properties		
Ore_Cu_Rate_percent	0.5%	(Ayres et al., 2001)
Ore_Fe_Rate_percent	calculated	
Ore_S_Rate_percent	calculated	
Ore_SiO2_Rate_percent	calculated	
Ore_Contaminants_Rate_percent	calculated	
Ore_Balance(Gangue)_Rate_percent	calculated	
Conc_Cu_Recovery_percent	90%	(Biswas and Davenport, 1994)
Tail_Fe_Cu_Ratio	0.88	Assumes all Cu not recovered which ends up in tailings is associated with CuFeS2. So M(Cu)/M(Fe)=1.14, hence ratio Fe:Cu = 1/1.14 = 0.88
Tail_S_Cu_Ratio	1.00	m(S)/m(Cu) = 2*M(S)/M(Cu) = 2*32/64=1
Tail_SiO2_Cu_Ratio	2.00	Estimate
Tail_Contaminants_Cu_Ratio	0.10	Estimate
Conc_Cu_Rate_percent	30%	(Biswas and Davenport, 1994)
Conc_Fe_Rate_percent	27%	(Biswas and Davenport, 1994)
Conc_S_Rate_percent	30%	(Biswas and Davenport, 1994)
Conc_SiO2_Rate_percent	7%	(Biswas and Davenport, 1994)
Conc_Contaminants_Rate_percent	1%	(Biswas and Davenport, 1994)
Conc_Balance(Gangue)_Rate_percent	5%	(Biswas and Davenport, 1994)
Smelting		
Smelt_Oil_Rate_t_per_t_conc	0.141	(Biswas and Davenport, 1994)
Smelt_Elec_Rate_kWh_per_t conc	120	(Riekkola-Vanhanen, 1999)
Smelt_SiO2_Rate_t_per_t_conc	0.1	(Biswas and Davenport, 1994)
Smelt_O2_Rate_t_per_t_conc	0.1	(Biswas and Davenport, 1994)
Smelt_Slag_Recycle_t_per_t_conc	0.05	(Biswas and Davenport, 1994)
Smelt_Slag_Cu_Rate_percent	0.9%	(Biswas and Davenport, 1994)
Smelt_Matte_Cu_Rate_percent	45%	(Biswas and Davenport, 1994)
Smelt_CO2_Rate_t_per_t_oil	3.82	(PRè, 2000)
Smelt_SO2_Rate_t_per_t Cu_in_conc	2	from conc. composition
Converting		
Convert_O2_Rate_t_per_t conc	0.224	(Biswas and Davenport, 1994)
Convert_SO2_Rate_t	0	assume all in smelter
Convert_Slag_Cu_Rate_percent	2.50%	(Biswas and Davenport, 1994)
Blister_Cu_Rate_percent	0.997	(Biswas and Davenport, 1994)

Electro-refining		
ERefine_Elec_Rate_kWh_t Cu	400	(MIM, 1999)
ERefine_Water_Rate_t_t Cu	1	(MIM, 1999)
ERefine_Effluent_Rate_t_t Cu	0.128	(MIM, 1999)
ERefine_Metals_Rate_t_t Cu	0.00000565	(MIM, 1999)
Gas Treatment		
GasTreat_O2_Rate_t_t SO2	*0.2325*	*By stoichiometry 2SO2+O2-->2SO3 [0.5*32/64*percent to acid]*
GasTreat_Water_Rate_t_t SO2	*0.2615625*	*By stoichiometry SO3+H2O-->H2SO4 [18/64*percent to acid]*
GasTreat_SO2_to_acid_Rate_percent	5%	(Biswas and Davenport, 1994; Riekkola-Vanhanen, 1999)
GasTreat_Elec_Rate_kWh_t_conc	95	(Riekkola-Vanhanen, 1999)

A.1.3 *Heap Leach Solvent Extraction Electrowinning*

Mining		Reference
Mining_Elec_Rate_kWh_per_t_ore	13	(Norgate and Rankin, 2000)
Mining_Diesel_Rate_t_t_ore	0.002	(Norgate and Rankin, 2000)
Crushing		
Crushing_Elec_Rate_kWh_per_t_ore	2	(Norgate and Rankin, 2000)
Ore		As for flash/reverb
Ore_Cu_Rate_percent	0.5%	As for flash/reverb
EW_RefinedCu_Cu_Rate_percent	100%	Product Quality
Liq_Cu_Recovery_per_t_ore	65%	(Biswas and Davenport, 1994; Jenkins et al., 1999; Norgate and Rankin, 2000)
Liq_Fe_Recovery_per_t_ore	80%	
Liq_S_Recovery_per_t_ore	65%	
Liq_SiO2_Recovery_per_t_ore	0%	
Liq_Contaminants_Recovery_per_t_ore	10%	
Liq_Balance(Gangue)_Recovery_per_t_ore	0%	
Solvent Extraction		
SX_Elec_Rate_kWh_per_t Cu	2500	(Norgate and Rankin, 2000)
SX_Steam_Rate_t_per_t Cu	0.23	(Norgate and Rankin, 2000)
SX_H2SO4_Rate_t_per_t_Cu	1.7	(Biswas and Davenport, 1994)
Electrowinning		
EW_Elec_Rate_Kwh_per_t Cu	2000	(Biswas and Davenport, 1994)

A.2 SENSITIVITIES FOR PRIMARY TECHNOLOGY MODELS

A.2.1 *Flash Smelting*

	Base Value	Greenhouse	Acidification	Eco-toxicity	Water
Open Cut Mining					
MineOpen_Elec_Rate_kWh_per_t ore	20				
Plus 20%		5%	1%	0%	3%
MineOpen_Water_Rate_t_per_t ore	0.58				
Plus 20%		0%	0%	0%	8%
MineOpen_Diesel_Rate_t_per_t ore	0.002				
Plus 20%		3%	2%	0%	0%
Mine_CO2_Rate_t_per_t_Diesel	3.64				
Plus 20%		3%	0%	0%	0%
Concentrate-Ore Properties					
Ore_Cu_Rate_percent	0.5%				
Plus 20%		-13%	-4%	0%	-15%
Minus 20%		19%	6%	0%	23%
Ore_Cu_Rate_percent	2.0%				
Plus 20%		-7%	-1%	0%	-12%
Minus 20%		11%	2%	0%	19%
Conc_Cu_Recovery_percent	90%				
Minus 20%		19%	6%	69%	23%
Tail_Fe_Cu_Ratio	0.875				
Plus 20%		0%	0%	1%	0%
Tail_S_Cu_Ratio	1				
Plus 20%		0%	0%	1%	0%
Tail_SiO2_Cu_Ratio	2				
Minus 20%		0%	0%	0%	0%
Tail_Contaminants_Cu_Ratio	0.1				
Plus 20%		0%	0%	1%	0%
Conc_Cu_Rate_percent	30%				
Plus 20%		-3%	-6%	1%	-1%
Minus 20%		5%	10%	-1%	2%
Conc_Fe_Rate_percent	27%				
Plus 20%		0%	0%	0%	0%
Conc_S_Rate_percent	30%				
Plus 20%		0%	0%	0%	0%
Conc_SiO2_Rate_percent	7%				
Plus 20%		0%	0%	0%	0%
Conc_Contaminants_Rate_percent	1%				
Plus 20%		0%	0%	0%	0%
Conc_Balance(Gangue)_Rate_percent	5%				
Plus 20%		0%	0%	0%	0%
Smelting					
Smelt_Oil_Rate_t_per_t_conc	0.044				
Plus 20%		1%	1%	0%	0%
Smelt_Elec_Rate_kWh_per_t conc	120				
Plus 20%		1%	0%	0%	0%
Smelt_SiO2_Rate_t_per_t_conc	0.1				
Plus 20%		0%	0%	0%	0%
Smelt_O2_Rate_t_per_t_conc	0.2				
Plus 20%		1%	0%	0%	0%
Smelt_Slag_Recycle_t_per_t_conc	0.05				
Plus 20%		0%	0%	-1%	0%
Smelt_Slag_Cu_Rate_percent	2%				
Plus 20%		0%	0%	0%	0%
Smelt_Matte_Cu_Rate_percent	62%				
Plus 20%		0%	0%	-1%	0%
Smelt_CO2_Rate_t_per_t_oil	3.82				
Plus 20%		1%	0%	0%	0%
Smelt_SO2_Rate_t_per_t Cu_in_conc	1				
Plus 20%		0%	7%	0%	0%
Converting					
Convert_O2_Rate_t_per_t conc	0.127				
Plus 20%		0%	6%	0%	0%
Convert_SO2_Rate_t_per_t O2	2				
Plus 20%		0%	6%	0%	0%
Convert_Slag_Cu_Rate_percent	0.025				
Plus 20%		0%	0%	0%	0%
Blister_Cu_Rate_percent	0.99999435				
Minus 20%		0%	0%	154%	0%
Electro-refining					
ERefine_Elec_Rate_kWh_t Cu	400				
Plus 20%		1%	0%	0%	0%
ERefine_Water_Rate_t_t Cu	1				
Plus 20%		0%	0%	0%	0%
ERefine_Effluent_Rate_t_t Cu	0.128				
Plus 20%		0%	0%	0%	0%

A.2.2 *Reverberatory Smelting*

PRE-PROCESSING	Base Value	Greenhouse	Acidification	Eco-toxicity	Water
Open Cut					
MineOpen_Elec_Rate_kWh_per_t ore	20				
Plus 20%		7%	0%	0%	5%
Minus 20%		-7%	0%	0%	-5%
MineOpen_Water_Rate_t_per_t ore	0.58				
Plus 20%		0%	0%	0%	13%
Minus 20%		0%	0%	0%	13%
MineOpen_Diesel_Rate_t_per_t ore	0.002				
Plus 20%		5%	0%	0%	0%
Minus 20%		-5%	0%	0%	0%
Mine_CO2_Rate_t_per_t_Diesel	3.64				
Plus 20%		5%	0%	0%	0%
Minus 20%		-5%	0%	0%	0%
Concentrate-Ore Properties					
Ore_Cu_Rate_percent	0.5%				
Plus 20%		-10%	0%	0%	-15%
Minus 20%		15%	0%	0%	23%
Conc_Cu_Recovery_percent	90%				
Plus 20%					
Minus 20%		15%	0%	0%	23%
Tail_Fe_Cu_Ratio	0.88				
Plus 20%		0%	0%	2%	0%
Minus 20%		0%	0%	-2%	0%
Tail_S_Cu_Ratio	1.00				
Plus 20%		0%	0%	3%	0%
Minus 20%		0%	0%	-2%	0%
Tail_SiO2_Cu_Ratio	2.00				
Plus 20%		0%	0%	-2%	0%
Minus 20%		0%	0%	0%	0%
Tail_Contaminants_Cu_Ratio	0.10				
Plus 20%		0%	0%	3%	0%
Minus 20%		0%	0%	-2%	0%
Conc_Cu_Rate_percent	30%				
Plus 20%		-6%	-10%	0%	-1%
Minus 20%		9%	15%	0%	2%
Smelting					
Smelt_Oil_Rate_t_per_t_conc	0.044				
Plus 20%		5%	0%	0%	0%
Minus 20%		-5%	0%	0%	0%
Smelt_Elec_Rate_kWh_per_t conc	120				
Plus 20%		1%	0%	0%	0%
Minus 20%		-1%	0%	0%	0%
Smelt_SiO2_Rate_t_per_t_conc	0.1				
Plus 20%		0%	0%	0%	0%
Minus 20%		0%	0%	0%	0%
Smelt_O2_Rate_t_per_t_conc	0.2				
Plus 20%		0%	0%	0%	0%
Minus 20%		0%	0%	0%	0%
Smelt_Slag_Recycle_t_per_t_conc	0.05				
Plus 20%		0%	0%	0%	0%
Minus 20%		0%	0%	0%	0%
Smelt_Slag_Cu_Rate_percent	1.5%				
Plus 20%		0%	0%	0%	0%
Minus 20%		0%	0%	0%	0%
Smelt_Matte_Cu_Rate_percent	62%				
Plus 20%		0%	0%	5%	0%
Minus 20%		0%	0%	-7%	0%
Smelt_CO2_Rate_t_per_t_oil	3.82				
Plus 20%		5%	0%	0%	0%
Minus 20%		-5%	0%	0%	0%
Smelt_SO2_Rate_t_per_t Cu_in_conc	1				
Plus 20%		0%	8%	0%	0%
Minus 20%		0%	8%	0%	0%
Converting					
Convert_O2_Rate_t_per_t conc	0.127				
Plus 20%		1%	12%	0%	0%

A.2.3 *Heap Leach Solvent Extraction Electrowinning*

Assumptions		Greenhouse	Acidification	Eco-toxicity H	Water
Mining_Elec_Rate_kWh_per_t_ore	13				
Plus 20%		6%	4%	0%	9%
Minus 20%		-6%	-4%	0%	-9%
Mining_Diesel_Rate_t_t_ore	0.002				
Plus 20%		6%	10%	0%	0%
Minus 20%		-6%	-10%	0%	0%
Crushing_Elec_Rate_kWh_per_t_ore	2				
Plus 20%		1%	1%	0%	1%
Minus 20%		-1%	-1%	0%	-1%
Ore_Cu_Rate_percent					
Plus 20%		-11%	-13%	2%	-9%
Minus 20%		17%	19%	2%	13%
Liq_Cu_Recovery_per_t_ore	0.65				
Plus 20%		-11%	-13%	-19%	-9%
Minus 20%		17%	19%	33%	13%
Liq_Fe_Recovery_per_t_ore	0.8				
Plus 20%		0%	0%	2%	0%
Minus 20%		0%	0%	2%	0%
Liq_S_Recovery_per_t_ore	0.65				
Plus 20%		0%	0%	2%	0%
Minus 20%		0%	0%	2%	0%
Liq_SiO2_Recovery_per_t_ore	0				
Plus 20%					
Minus 20%					
Liq_Contaminants_Recovery_per_t_ore	0.1				
Plus 20%		0%	0%	2%	0%
Minus 20%		0%	0%	2%	0%
Liq_Balance(Gangue)_Recovery_per_t_or	0				
Plus 20%					
Minus 20%					
SX_Elec_Rate_kWh_per_t Cu	2500				
Plus 20%		4%	3%	2%	5%
Minus 20%		-4%	-3%	2%	-5%
SX_Steam_Rate_t_per_t Cu	0.23				
Plus 20%		0%	0%	2%	0%
Minus 20%		0%	0%	2%	0%
SX_H2SO4_Rate_t_per_t_Cu	1.7				
Plus 20%		0%	0%	2%	0%
Minus 20%		0%	0%	2%	0%
EW_Elec_Rate_Kwh_per_t Cu	2000				
Plus 20%		3%	2%	2%	4%
Minus 20%		-3%	-2%	2%	-4%

A.3 SECONDARY TECHNOLOGY MODELS

A.3.1 *Description of secondary production*

Copper production from secondary sources can either be through dedicated secondary processes or by feeding copper scrap into primary production facilities, both are used. The link between technology used is dependent on the quality of the scrap.

A.3.2 *Feed types*

Copper scrap is commonly divided into four classes based on copper content, as per Table A-1.

Table A-1: Copper classifications (Biswas and Davenport, 1994)

Category	Range of Copper Content	Representative Content Used	Examples
No 1 Scrap	> 99%	99%	copper wire, heavy scrap
No 2 Scrap	88% - 99%	95%	auto radiators, wires & cables
Low Grade Scrap	10% - 88%	20%	printed circuit boards, electronics
Brasses	65% - 85%	82%	yellow and red brass

The breakdown of representative scrap compositions used for modelling are shown in Table A-2

Table A-2: Representative scrap composition (Biswas and Davenport, 1994; Göckmann, 1992)

Type	No1 Scrap	No2 Scrap	Low Grade	Brass
Cu_Rate_percent	0.99	0.95	0.20	0.82
Fe_Rate_percent			0.08	
S_Rate_percent				
SiO2_Rate_percent			0.15	
Zn_Rate_percent			0.01	0.1
Organic_Rate_percent			0.25	
OtherMetal_Rate_percent	0.01	0.05	0.08	0.03
OtherNonMetal_Rate_percent			0.18	
Contaminants/Precious Metal_Rate_percent			0.05	0.05
Total	1.00	1.00	1.00	1.00

A.3.3 *Feed streams, technologies and flowsheets*

For modelling purposes, it is assumed that all secondary scrap is processed in dedicated technologies. Approximately 55% of old scrap is recycled in dedicated facilities, with the remainder being added to the feed stream of primary production (Gaines, 1980). In practice this will be region specific, for which there is little data, however, this approach simplifies the allocation of environmental burden associated with the processing of secondary scrap. Technologies for each scrap type and their associated flowsheet are described below.

A.3.3.1 *Gas induction: No 1 scrap*

The processing of two feed stream types is represented in Figure A-1: uncut wire and heavy scrap (e.g. copper pipes). After chopping and sorting, plus an mechanical/air separation for wire to remove its coating[1], the scrap feed proceeds to a natural gas-fired furnace which is often similar in design to a conventional reverberatory furnace. The furnace melts the feed into a copper product.

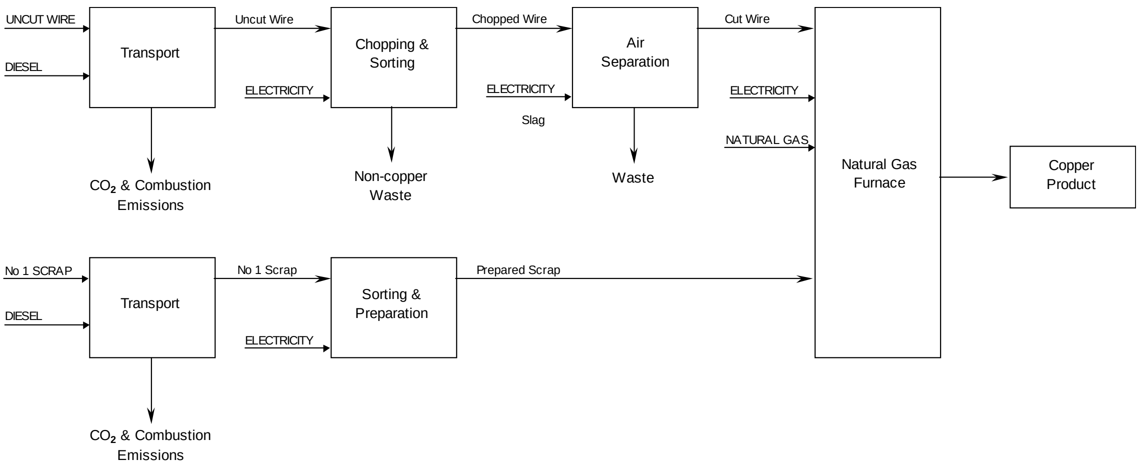


Figure A-1: Technology flowsheet for processing No1 scrap

[1] (Gaines, 1980) notes that a cryogenic separation technique may also be used to remover the coating from wires

Assumptions used to model the processing of No 1 scrap are given in Table A-3.

Table A-3: Assumptions for No 1 scrap model

COLLECTION & TRANSPORT OF SCRAP		REFERENCE
Transport_AVG_In_km	500	After (Norgate and Rankin, 2000)
FLOWRATE		
RecycleFeed_In_t	1.04	(back-calculated from % metal recovered to product to give 1 t of product)
FEED ASSUMPTIONS		
RecycleFeed_Cu_Rate_percent	99%	(Biswas and Davenport, 1994)
RecycleFeed_Fe_Rate_percent	0%	
RecycleFeed_S_Rate_percent	0%	
RecycleFeed_SiO2_Rate_percent	0%	
RecycleFeed_Zn_Rate_percent	0%	
RecycleFeed_Organic_Rate_percent	0%	
RecycleFeed_OtherMetal_Rate_percent	0%	
RecycleFeed_OtherNonMetal_Rate_percent	0%	
RecycleFeed_ContamPrecious_Rate_percent	1%	By difference from 100%
Total	100%	
ENERGY CONSUMPTION		
GasInductn_NatGas_Rate_t_per_t_R/Feed	0.09315	(Energetics, 1999)
Electricity source	Coal	(as per 1° technologies in Ch 7)
% METAL RECOVERIES TO PRODUCT		
Recovery_Cu_Rate_percent	97%	(Energetics, 1999)
Recovery_Fe_Rate_percent	0%	
Recovery_S_Rate_percent	0%	
Recovery_Zn_Rate_percent	0%	
Recovery_Organic_Rate_percent	0%	
Recovery_OtherMetal_Rate_percent	0%	
Recovery_OtherNonMetal_Rate_percent	50%	Estimated
Recovery_ContamPrecious_Rate_percent	40%	Estimated
PERCENT OF WIRE TO No1 SCRAP		
RecycleFeed_Wire_percent	40%	Estimated
RecycleFeed_Scrap_percent	60%	(Heavy scrap)
SORTING ASSUMPTIONS		
SortingWire_Elec_kWh_per_t_R/Feed	120	converted from BTU equivalent (Gaines, 1980)
SortingScrap_Elec_kWh_per_t_R/Feed	40	(Gaines, 1980)

A.3.3.2 *Gas induction and electrorefining: No2 scrap*

Processing of No2 scrap is similar to that for No1 scrap as shown in Figure A-2, however to increase purity, a final electro-refining step is added. Note that wire can go to both No1 and No2 scrap, depending on contamination.

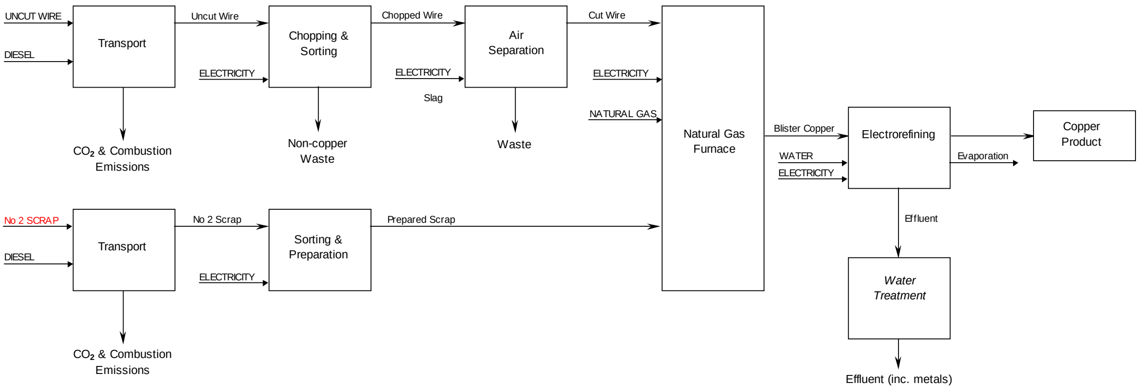


Figure A-2: Technology flowsheet for processing No2 scrap

The assumptions used in the models of No2 scrap processing are given in Table A-4.

Table A-4: Assumptions used in modelling the recycling of No 2 Scrap

COLLECTION & TRANSPORT OF SCRAP		REFERENCE
Transport_AVG_In_km	500	After (Norgate and Rankin, 2000)
FLOWRATE		
RecycleFeed_In_t	1.09	(back-calculated from % metal recovered to product to give 1 t of product)
FEED ASSUMPTIONS		
RecycleFeed_Cu_Rate_percent	95%	(Biswas and Davenport, 1994)
RecycleFeed_Fe_Rate_percent	0%	
RecycleFeed_S_Rate_percent	0%	
RecycleFeed_SiO2_Rate_percent	0%	
RecycleFeed_Zn_Rate_percent	0%	
RecycleFeed_Organic_Rate_percent	0%	
RecycleFeed_OtherMetal_Rate_percent	5%	By difference from 100%
RecycleFeed_OtherNonMetal_Rate_percent	0%	
RecycleFeed_ContamPrecious_Rate_percent	0%	
Total	100%	
ENERGY CONSUMPTION		
GasInductn_NatGas_Rate_t_per_t_R/Feed	0.09315	(Energetics, 1999)
Electricity source	Coal	(as per 1° technologies in Ch 7)
% METAL RECOVERIES TO PRODUCT		
Recovery_Cu_Rate_percent	97%	(Energetics, 1999)
Recovery_Fe_Rate_percent	0%	
Recovery_S_Rate_percent	0%	
Recovery_SiO2_Rate_percent	0%	

Recovery_Zn_Rate_percent	0%	
Recovery_Organic_Rate_percent	0%	
Recovery_OtherMetal_Rate_percent	0%	
Recovery_OtherNonMetal_Rate_percent	50%	Estimated
Recovery_ContamPrecious_Rate_percent	40%	Estimated
PERCENT OF WIRE TO No1 SCRAP		
RecycleFeed_Scrap_percent	100%	Estimated
SORTING ASSUMPTIONS		
SortingScrap_Elec_kWh_per_t_R/Feed	4	converted from BTU equivalent (Gaines, 1980)
ELECTROREFINING		
ERefine_Elec_Rate_kWh_t Cu	400	(MIM, 1999; Biswas and Davenport 1994)
ERefine_Water_Rate_t_t Cu	1	(MIM, 1999)
ERefine_Effluent_Rate_t_t Cu	0.128	(MIM, 1999)
ERefine_Metals_Rate_t_t Cu	5.6 E-6	(MIM, 1999)

A.3.3.3 *Blast furnace: Low grade scrap*

The re-processing of low grade scrap is modelled as going through a blast furnace as shown in Figure A-3.

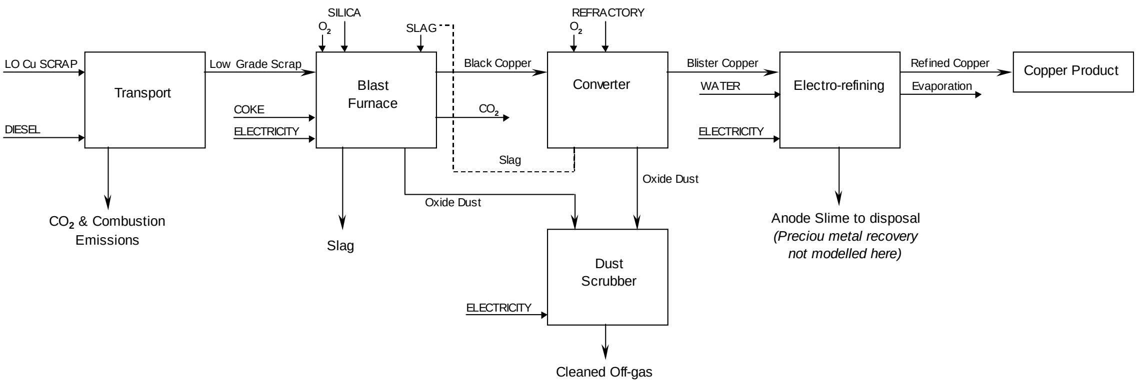


Figure A-3: Technology flowsheet for processing low grade scrap

Assumptions for modelling low grade scrap recycle through a blast furnace are in Table A-5.[2]

Table A-5: Assumptions for recycling of low grade scrap in dedicated blast furnace

COLLECTION & TRANSPORT OF SCRAP		REFERENCE
Transport_AVG_In_km	500	After (Norgate and Rankin, 2000)
FLOWRATE		
RecycleFeed_In_t	5.15	(back-calculated from % metal recovered to product to give 1 t of product)
FEED ASSUMPTIONS		
RecycleFeed_Cu_Rate_percent	20%	(Göckmann, 1992; Ayres et al. 2001)
RecycleFeed_Fe_Rate_percent	8%	"
RecycleFeed_S_Rate_percent	0%	"
RecycleFeed_SiO2_Rate_percent	15%	"
RecycleFeed_Zn_Rate_percent	1%	"
RecycleFeed_Organic_Rate_percent	25%	"
RecycleFeed_OtherMetal_Rate_percent	8%	"
RecycleFeed_OtherNonMetal_Rate_percent	18%	"
RecycleFeed_ContamPrecious_Rate_percent	5%	"
Total	100%	
ENERGY CONSUMPTION		
SmeltConvert_Coke_Rate_t_per_t_R_Feed	0.09	(Energetics, 1999)
SmeltConvert_NGas_Rate_t_per_t_prod	0.02	(Energetics, 1999)
Electricity source	Coal	(as per 1° technologies in Ch 7)
% METAL RECOVERIES TO PRODUCT		
Recovery_Cu_Rate_percent	97%	(Energetics, 1999)
Recovery_Fe_Rate_percent	0%	
Recovery_S_Rate_percent	0%	
Recovery_SiO2_Rate_percent	0%	
Recovery_Zn_Rate_percent	0%	
Recovery_Organic_Rate_percent	0%	
Recovery_OtherMetal_Rate_percent	0%	
Recovery_OtherNonMetal_Rate_percent	50%	Estimated
Recovery_ContamPrecious_Rate_percent	40%	Estimated
PERCENT OF WIRE TO No1 SCRAP		
RecycleFeed_Scrap_percent	100%	Estimated
SORTING ASSUMPTIONS		
SortingScrap_Elec_kWh_per_t_R/Feed	4	converted from BTU equivalent (Gaines, 1980)
ELECTROREFINING		
ERefine_Elec_Rate_kWh_t Cu	400	(MIM, 1999; Biswas and Davenport 1994)
ERefine_Water_Rate_t_t Cu	1	(MIM, 1999)
ERefine_Effluent_Rate_t_t Cu	0.128	(MIM, 1999)
ERefine_Metals_Rate_t_t Cu	5.6 E-6	(MIM, 1999)

[2] Some low grade scrap is recycled through primary smelters and for the purposes of this investigation, the environmental impact associated to this activity is assumed to be equivalent to recycling through a dedicated secondary blast smelter. This is justified on the basis that the concentration of copper in the feed material is a significant contributor to overall environmental performance and which is equivalent in both cases.

A.3.4 *Environmental performance*

The environmental impacts associated with the production of 1 tonne of metal recovered from No1, No2, and Low grade scrap is presented in Figure A-4. Production of 1 tonne of brass has been included for comparison although models for brass are not used further in this thesis.

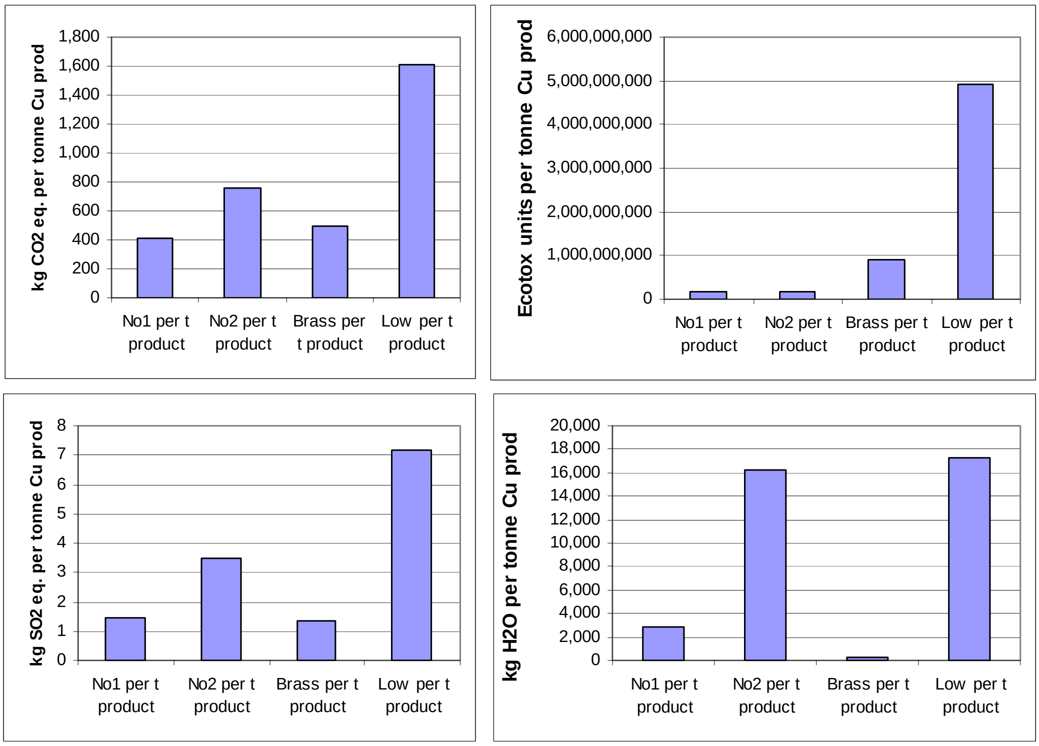


Figure A-4: Secondary process comparison per tonne product (using coal-based power)

APPENDIX B

Additional information for Chapter 9

Appendix B supplements the case studies in Chapter 9. It provides detailed assumptions and descriptions of models used in the case study.

B.1 MASS BALANCE EQUATIONS FOR DYNAMIC MODEL

MASS BALANCE EQUATIONS

The first set of equations labelled f_1 to f_{27} regard mass balance around each node:

$$f_1 = \dot{S}^{(1)}(t) - m_{3,1}(t) - m_{4,1}(t) - m_{5,1}(t) - m_{22,1}(t) - m_{21,1}(t) - m_{23,1}(t) - m_{26,1}(t) - m_{25,1}(t) - m_{24,1}(t) = 0$$

$$f_2 = \dot{S}^{(2)}(t) + m_{2,3}(t) + m_{2,4}(t) + m_{2,5}(t) = 0$$

$$f_3 = \dot{S}^{(3)}(t) - m_{2,3}(t) + m_{3,1}(t) + m_{3,6}(t) = 0$$

$$f_4 = \dot{S}^{(4)}(t) - m_{2,4}(t) + m_{4,1}(t) + m_{4,6}(t) = 0$$

$$f_5 = \dot{S}^{(5)}(t) - m_{2,5}(t) + m_{5,1}(t) + m_{5,6}(t) = 0$$

$$f_6 = \dot{S}^{(6)}(t) - m_{3,6}(t) - m_{4,6}(t) - m_{5,6}(t) + m_{6,7}(t) = 0$$

$$f_7 = \dot{S}^{(7)}(t) - m_{27,7}(t) - m_{6,7}(t) - m_{7,8}(t) + m_{7,9}(t) + m_{7,10}(t) = 0$$

$$f_8 = \dot{S}^{(8)}(t) - m_{7,8}(t) + m_{8,12}(t) + m_{8,13}(t) + m_{8,14}(t) = 0$$

$$f_9 = \dot{S}^{(9)}(t) - m_{7,9}(t) + m_{9,11}(t) = 0$$

$$f_{10} = \dot{S}^{(10)}(t) - m_{7,10}(t) + m_{10,15}(t) + m_{10,16}(t) + m_{10,17}(t) = 0$$

$$f_{11} = \dot{S}^{(11)}(t) - m_{9,11}(t) = 0$$

$$f_{12} = \dot{S}^{(12)}(t) - m_{8,12}(t) + m_{12,18}(t) = 0$$

$$f_{13} = \dot{S}^{(13)}(t) - m_{8,13}(t) + m_{13,19}(t) = 0$$

$$f_{14} = \dot{S}^{(14)}(t) - m_{8,14}(t) + m_{14,20}(t) = 0$$

$$f_{15} = \dot{S}^{(15)}(t) - m_{10,15}(t) + m_{15,18}(t) = 0$$

$$f_{16} = \dot{S}^{(16)}(t) - m_{10,16}(t) + m_{16,19}(t) = 0$$

$$f_{17} = \dot{S}^{(17)}(t) - m_{10,17}(t) + m_{17,20}(t) = 0$$

$$f_{18} = \dot{S}^{(18)}(t) - m_{12,18}(t) - m_{15,18}(t) + m_{18,21}(t) = 0$$

$$f_{19} = \dot{S}^{(19)}(t) - m_{13,19}(t) - m_{16,19}(t) + m_{18,22}(t) = 0$$

$$f_{20} = \dot{S}^{(20)}(t) - m_{14,20}(t) - m_{17,20}(t) + m_{20,23}(t) = 0$$
$$f_{21} = \dot{S}^{(21)}(t) - m_{18,20}(t) - m_{21,1}(t) + m_{21,24}(t) = 0$$
$$f_{22} = \dot{S}^{(22)}(t) - m_{19,22}(t) - m_{22,1}(t) + m_{22,25}(t) = 0$$
$$f_{23} = \dot{S}^{(23)}(t) - m_{20,23}(t) - m_{23,1}(t) + m_{23,26}(t) = 0$$
$$f_{24} = \dot{S}^{(24)}(t) - m_{21,24}(t) - m_{24,1}(t) + m_{24,27}(t) = 0$$
$$f_{25} = \dot{S}^{(25)}(t) - m_{22,25}(t) - m_{25,1}(t) + m_{25,27}(t) = 0$$
$$f_{26} = \dot{S}^{(26)}(t) - m_{23,26}(t) - m_{26,1}(t) + m_{26,27}(t) = 0$$
$$f_{27} = \dot{S}^{(27)}(t) - m_{24,27}(t) - m_{25,27}(t) - m_{26,27}(t) + m_{27,7}(t) = 0$$

NON-ACCUMULATING NODES

For technology process nodes, the assumption is made that there is no accumulation as described in equations labelled f_{28} to f_{40}. These are depicted as squares in Figure 9-6, while stocks which may accumulate are drawn as ovals. The only exceptions are nodes 12 to 17 representing the use phase, which are drawn as rectangles, but accumulation may occur, as there is a time delay between material entering and leaving which represents its useful lifetime, before being discarded.

$$f_{28} = \dot{S}^{(3)}(t) = 0$$
$$f_{29} = \dot{S}^{(4)}(t) = 0$$
$$f_{30} = \dot{S}^{(5)}(t) = 0$$
$$f_{31} = \dot{S}^{(7)}(t) = 0$$
$$f_{32} = \dot{S}^{(8)}(t) = 0$$
$$f_{33} = \dot{S}^{(9)}(t) = 0$$
$$f_{34} = \dot{S}^{(10)}(t) = 0$$
$$f_{35} = \dot{S}^{(21)}(t) = 0$$
$$f_{36} = \dot{S}^{(22)}(t) = 0$$
$$f_{37} = \dot{S}^{(23)}(t) = 0$$
$$f_{38} = \dot{S}^{(24)}(t) = 0$$
$$f_{39} = \dot{S}^{(25)}(t) = 0$$
$$f_{40} = \dot{S}^{(26)}(t) = 0$$

RECOVERIES

The recovery efficiencies for technologies are represented in the functions $R_1(t)$ to $R_9(t)$. For the primary and secondary technologies, this information is contained in the detailed technology models, with which the dynamic mass balance model links to determine environmental performance. For the collection efficiency, it is specified in the model as either a constant or a function of time. Recoveries for all other nodes in the network are taken as 100%.

Primary Technologies

$$f_{41} = \frac{m_{3,6}(t)}{m_{2,3}(t)} - R_1(t) = 0$$

$$f_{42} = \frac{m_{4,6}(t)}{m_{2,4}(t)} - R_2(t) = 0$$

$$f_{43} = \frac{m_{5,6}(t)}{m_{2,4}(t)} - R_3(t) = 0$$

Collection Efficiency

$$f_{44} = \frac{m_{21,24}(t)}{m_{18,21}(t)} - R_4(t) = 0$$

$$f_{45} = \frac{m_{22,25}(t)}{m_{19,22}(t)} - R_5(t) = 0$$

$$f_{46} = \frac{m_{23,26}(t)}{m_{20,23}(t)} - R_6(t) = 0$$

Secondary Technologies

$$f_{47} = \frac{m_{24,27}(t)}{m_{24,1}(t)} - R_7(t) = 0$$

$$f_{48} = \frac{m_{25,27}(t)}{m_{25,1}(t)} - R_8(t) = 0$$

$$f_{49} = \frac{m_{26,27}(t)}{m_{26,1}(t)} - R_9(t) = 0$$

SPLITS BETWEEN NODES

The choices of processing technologies, secondary technologies and the relative split between each, are decision variables controllable by different actors and are the key changes to the model which are explored in detail. The functions $R_{10}(t)$ to $R_{15}(t)$ represent a percentage split and can reflect a pre-determined path of action by an actor over the time horizon of study, or may be a function of environmental performance of the system and available resource stocks. This is discussed further in Section .

Between Primary Technologies

$$f_{50} = \frac{m_{3,6}(t)}{m_{3,6}(t) + m_{4,6}(t) + m_{5,6}(t)} - R_{10}(t) = 0$$

$$f_{51} = \frac{m_{4,6}(t)}{m_{3,6}(t) + m_{4,6}(t) + m_{5,6}(t)} - R_{11}(t) = 0$$

$$f_{52} = \frac{m_{5,6}(t)}{m_{3,6}(t) + m_{4,6}(t) + m_{5,6}(t)} - R_{12}(t) = 0$$

Between Secondary Technologies

$$f_{53} = \frac{m_{24,27}(t)}{m_{24,27}(t) + m_{25,27}(t) + m_{26,27}(t)} - R_{13}(t) = 0$$

$$f_{54} = \frac{m_{25,27}(t)}{m_{24,27}(t) + m_{25,27}(t) + m_{26,27}(t)} - R_{14}(t) = 0$$

$$f_{55} = \frac{m_{25,27}(t)}{m_{24,27}(t) + m_{25,27}(t) + m_{26,27}(t)} - R_{15}(t) = 0$$

Between Primary and Secondary Processing

$$f_{56} = \frac{m_{27,7}(t)}{m_{27,7}(t) + m_{6,7}(t)} - R_{16}(t) = 0$$

DEMAND

The total demand is represented by $R_{17}(t)$, demands for No1, No2, Low grade long-lived goods and No1, No2 and Low grade short-lived goods ($R_{18}(t)$, $R_{19}(t)$, $R_{20}(t)$, $R_{21}(t)$, $R_{22}(t)$, $R_{23}(t)$) are percentages of total demand, with the unspecified remainder being the demand for goods with a dissipative use.

Total Demand

$$f_{57} = m_{27,7}(t) - m_{6,7}(t) - R_{17}(t) = 0$$

Demand for long goods

$$f_{58} = m_{8,12}(t) - R_{18}(t) = 0$$
$$f_{59} = m_{8,13}(t) - R_{19}(t) = 0$$
$$f_{60} = m_{8,14}(t) - R_{20}(t) = 0$$

Demand for short goods

$$f_{61} = m_{8,15}(t) - R_{21}(t) = 0$$
$$f_{61} = m_{8,16}(t) - R_{22}(t) = 0$$
$$f_{62} = m_{8,17}(t) - R_{23}(t) = 0$$

RESIDENCE TIME IN USE

The outflow from the use phase is equal to the inflow, multiplied by a delay function, equivalent to the average time in use of the goods in the inflow stream.

Discard of No 1 goods after use

$$f_{64} = m_{12,18}(t) - R_{24}(t) \cdot m_{8,12}(t) = 0$$
$$f_{65} = m_{15,18}(t) - R_{25}(t) \cdot m_{10,15}(t) = 0$$

Discard of No2 goods after use

$$f_{66} = m_{13,19}(t) - R_{26}(t) \cdot m_{8,13}(t) = 0$$
$$f_{67} = m_{16,19}(t) - R_{27}(t) \cdot m_{10,16}(t) = 0$$

Discard of Low grade goods after use

$$f_{68} = m_{14,20}(t) - R_{28}(t) \cdot m_{8,14}(t) = 0$$
$$f_{69} = m_{17,20}(t) - R_{29}(t) \cdot m_{10,17}(t) = 0$$

Collectively, these equations define the mass flows of copper in the system. Consistent with the modelling approach outlined in Chapter 4, additional information is required regarding the quality of copper is required. This information is only required for resources entering primary and secondary technologies, as it will affect the energy requirements for processing and consequently the environmental performance of these processes. Primary resource quality ($q_2(t)$) is modelled as a function of time. Secondary resource quality is divided into three classes: No1 (q_{18}) for copper of 99% purity, No2 (q_{19}) for copper of 95% purity and Low grade (q_{20}) for copper of 30% purity.[1]

The starting stocks for each type of secondary scrap are approximated as 5,000,000 tonnes and primary stocks as 100,000,000 tonnes. The primary aim of the model is not to predict capacity constraints, but to show how differences in environmental performance between configurations of flows and infrastructure in the value chain can be assessed. To consider capacity constraints associated with future technology configurations, further consideration of imports and exports should be included.

B.2 IMPACT OF TIMING OF DECISIONS BY ACTORS

7.1.2 *Timing of changes by actors*

This sub-section contrasts two paths of action to demonstrate that actions determining when the alternate future is achieved is equally as important as the configuration of the final state. Two new scenarios compared are:

1. Doubling the recycling rate from 18% of demand to 36% of demand in five years and continuing recycling at this rate until 2050.

2. Deciding in 2005 to develop a new technology for primary processing, spend 10 years developing and testing the technology, then by 2020 introduce the new technology to account for 20% of primary production and then each subsequent 5 years, the new technology accounts for another 5% of primary production up to a total of 50% in 2050.

[1] The purity of low grade copper could also be modelled as a function of time, however data is unavailable to infer how the quality of low grade copper will change with time.

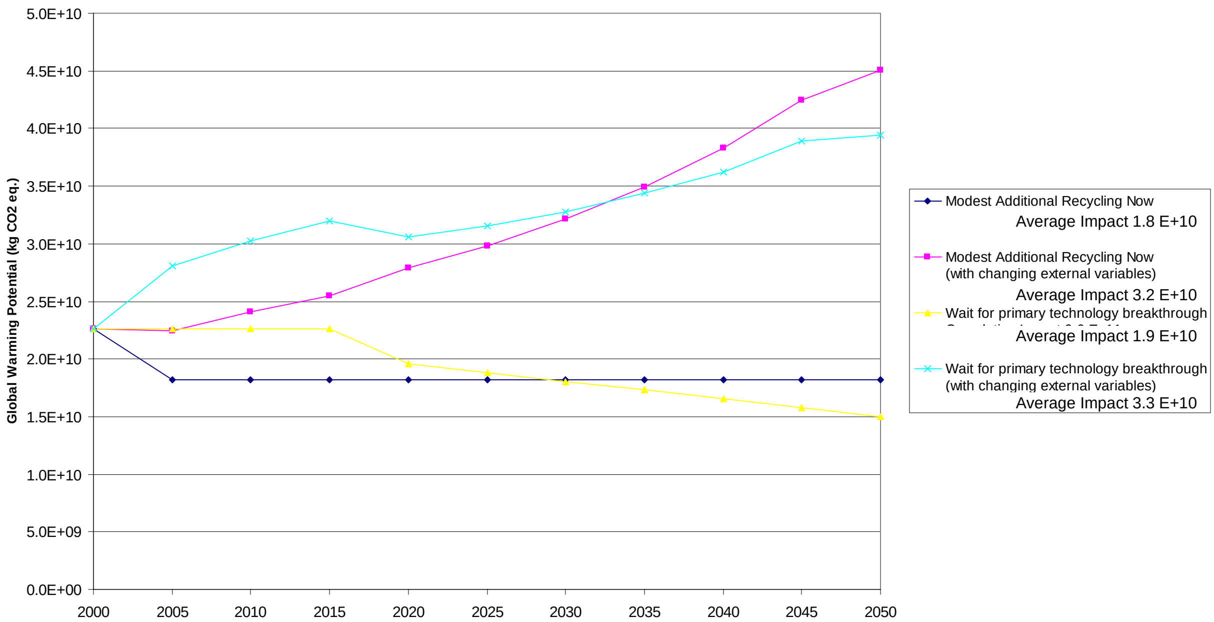


Figure B-1: Comparison of immediate and delayed system changes for global warming impact potential

Each scenario represents a plausible path of action for the industry. The aim is not to predict which scenario is most likely, but to provide actors with the ability to see the impact of their action or inaction over the fifty year planning horizon. By linking actor influence to impact over the time horizon, actors are able to measure the potential reward for their effort in the context of the entire value chain's operation. Such information is crucial to informed planning by the minerals industry and the approach developed in this work makes such information accessible.

From Figure B-1 it is observed that waiting for the development of a technology breakthrough for primary production and a significant uptake of this technology, leads to a final alternate state will less environmental burden than for the case where the recycling rate is immediately doubled. However, when examining the path through time accounting for changes in external variables, the delay in the implementation of the new technology (which is characteristic of lead times for technology development in the industry) results in an equivalent average impact over the 50 year time horizon. From the perspective of potential global warming impact, these results show that the increased utilisation of secondary resources immediately may be just as important as improved technology breakthroughs. In practice, dedicated processing facilities for secondary copper in the USA have mostly closed due to the "poor economic environment for processing scrap and the easy availability of low-priced primary refined copper"(Jolly, 2002). This means that there are limited options for domestic reprocessing; some copper can be recycled in primary refining infrastructure, some scrap can be exported (for example to China). From an environmental perspective, transporting low grade scrap long distances adds a significant impact to the environmental burden. Additional infrastructure for domestic recycling must form part of a transition to a more sustainable value chain, especially in highly industrialised regions where the high quantity of copper in use makes it a future source of secondary supply.

B.3 RESPONSIVE SECONDARY MATERIAL SELECTION

The split between secondary technologies is modelled as dependent on the stock of each secondary resource (No1, No2 and Low) and its copper content representing a measure of its value (99%, 95%, 30% respectively).

From Figure B-2 it is observed that with a higher priority given to the quality of the scrap, the greatest quantity of scrap reprocessed is first No1 (very high quality) then No2 (high quality) and then Low grade scrap. However, when the volume of available scrap becomes the main consideration in the mix which is sourced, then Low grade scrap is sourced to a greater degree than No2 after 50 years, No1 is still most used due to its high quality and high volume of available stocks (as the model assumes that the largest fraction of goods made from copper go into long lived products which later go on to become No1 scrap.

Quality of Secondary Scrap 80% Important
Volume of Secondary Scrap 20% Important

Quality of Secondary Scrap 20% Important
Volume of Secondary Scrap 80% Important

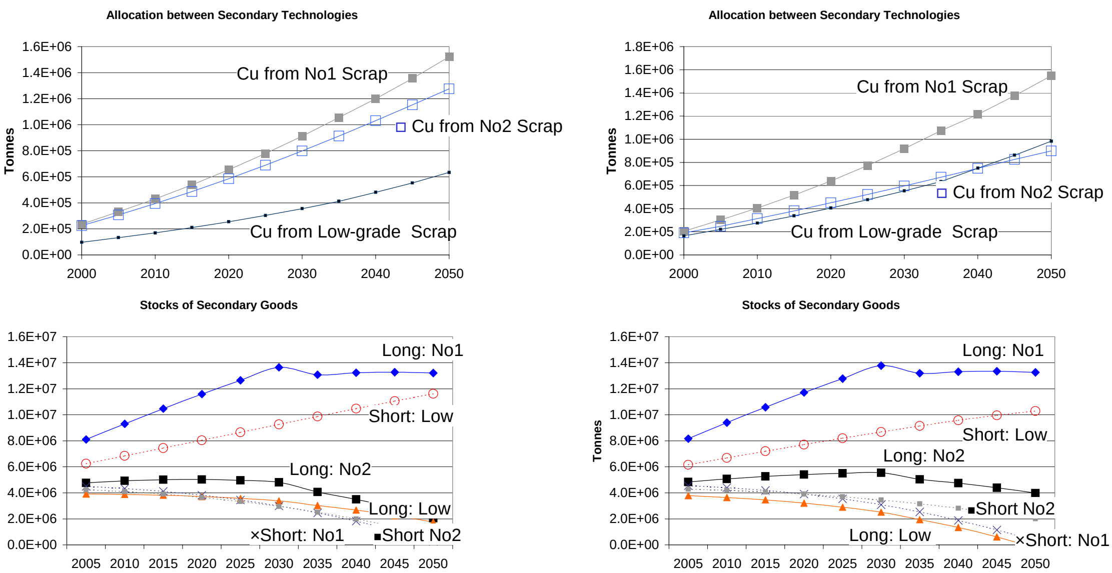


Figure B-2: Secondary mass flows and stocks for case responsive to secondary material quality and quantity

The global warming impact potential associated with the above material flows is approximately 10% higher for the case where volume is more important than quality, as a result of the greater degree of low grade scrap which is processed which is more energy intensive. The global warming impact potentials are shown for each case in Figure B-3.

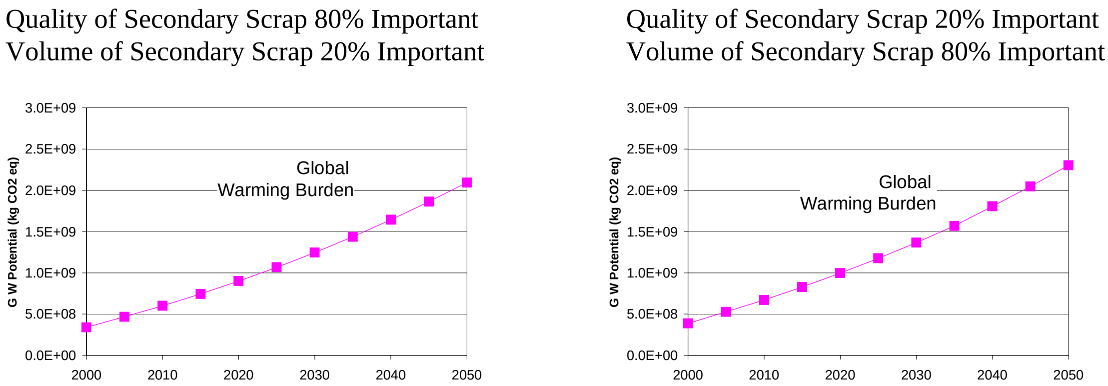


Figure B-3: Global warming potential when composition of secondary scrap changes

B.4 BASE CASE PLUS LINEAR INCREASE IN DEMAND

Figure B-4 shows the average global warming potential under case for the linear demand as 20% higher (at 5 $\times 10^{10}$ kg CO_2 eq.) than for the logistic case (at 4 $\times 10^{10}$ kg CO_2 eq.) and a potential impact in 2050 that is 50% higher, highlighting the need to reduce consumption to improve value chain performance as well as increasing recycling.

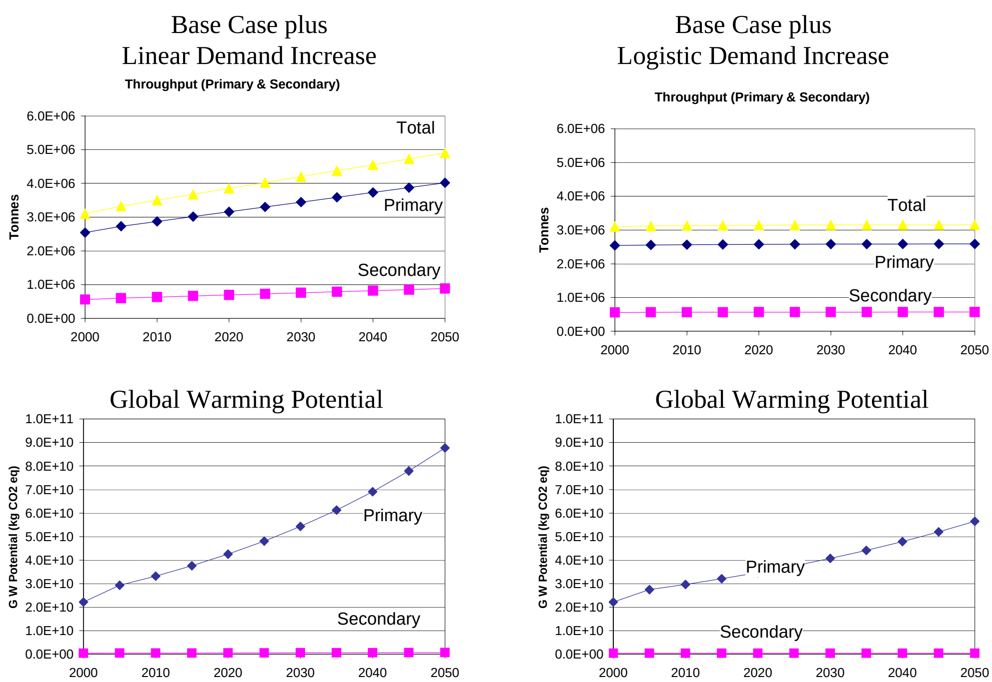


Figure B-4: Comparison of base case for linear and logistic demand

REFERENCES

ADL, 2002. The business case for corporate citizenship. Arthur D. Little (ADL). Cited in 'Quantifying the business case for sustainability' presentation by Bob Willard.

Allen, D., Consoli, F., Davis, G., Fava, J. and Warren, J., 1997. Public policy applications of Life-Cycle Assessment. Society for Environmental Toxicology and Chemistry (SETAC), Penascola.

Allenby, B., 1992. Design for environment: implementing industrial ecology. PhD Thesis, Rutgers Univ.

Althaus, H.-J. and Classen, M., 2005. Life Cycle Inventories of Metals and Methodological Aspects of Inventorying Material Resources in ecoinvent. International Journal of Life Cycle Assessment, 10(1): 43–49.

Alvardo, S., Maldonado, P., Barrios, A. and Jaques, I., 2002. Long term energy-related environmental issues of copper production. Energy policy, 27(2): 183-196.

Anderson, K., 2001. Reconciling the electricity industry with sustainable development: backcasting – a strategic alternative. Futures, 33(7): 607-623.

Annema, J. and Ros, J., 1994. Management of the zinc chain. Resources, conservation and recycling, 12: 209-219.

Anthony, R., 1965. Planning and control systems: a framework for analysis. Harvard University: Boston.

ANZECC, 2000. Core environmental indicators for reporting on the state of the environment. Australian and New Zealand Environment Conservation Council: Canberra.

Auty, R. and Warhurst, A., 1993. Sustainable development in minerals exporting economies. Resources Policy, 19(1):14-29.

Ayres, R., 1997. The life-cycle of chlorine. Part I. Journal of Industrial Ecology, 1(1): 81-94.

Ayres, R., Ayres, L. and Råde, I., 2001. The life cycle of copper, its co-products and by-products, Mining Minerals Sustainable Development Project.

Ayres, R., van den Bergh, J. and Gowdy, J., 1999. Viewpoint: Weak versus strong sustainability. www.tinbergen.nl/discussionpapers/98103.pdf

Azapagic, A., 1996. Environmental systems analysis: the application of linear programming to life cycle assessment. PhD Thesis, University of Surrey, UK.

Azapagic, A., Clift, R. and S. Perdan (Editors), 2004. Sustainable development in practice: case studies for engineers and scientists. John Wiley and Sons, Chichester.

Baccini, P. and Bader, H.-P., 1996. Regionaler Stoffhaushalt. Spektrum Akademischer Verlag, Heidelberg.

Bakan, J., 2004. The corporation: the pathological pursuit of profit and power. Constable, London.

Bakshi, B., 2002. A thermodynamic framework for ecologically conscious process systems engineering. Computers & Chemical Engineering, 26(2): 269-282.

Bana e Costa, C. (Editor), 1990. Readings in multiple criteria decision aid. Springer-Verlag, Berlin.

Bartos, P., 2002. SX-EW copper and the technology cycle. Resources policy, 28(3-4): 85-94.

Basson, L., 2004. Context, compensation and uncertainty in environmental decision making. PhD Thesis, University of Sydney.

Batterham, R.J., 2003. The mine of the future: will it be visible? In: L. Lorenzen and D. Bradshaw (Editors), XXII International Mineral Processing Congress, Cape Town, pp. 42-49.

Bauer, C., Kuckshinrichs, W., Rombach, G., Sliwka, P. and Zapp, P., (no date) A resource-orientated analysis of the material flow of aluminium: a systems analysis approach. http://sfb525.rwth-aachen.de

Bell, L., 1996. Rehabilitation of disturbed land. In: D. Mulligan (Editor), Environmental Management in the Australian Minerals and Energy Industries – Principles and Practices, UNSW Press, Sydney, pp.227-261.

Belton, V. and Stewart, T., 2002. Multiple criteria decision analysis: an integrated approach. Dordrecht, Kluwer Academic.

Berkhout, F., Hertin, J. and Jordan, A., 2002. Socio-economic futures in climate change impact assessment: using scenarios as 'learning machines'. Global Environmental Change, 12(2): 83-95.

Berkhout, F. and Howes, R., 1997. The adoption of life-cycle approaches by industry: patterns and impacts. Resources, Conservation and Recycling, 20(2): 71-94.

Bertram, M., Graedel, T., Rechberger, H. and Spatari, S., 2002. The contemporary European copper cycle: waste management subsystem. Ecological Economics, 42(1-2): 43-57.

BHP Billiton, 2005. Carbon disclosure project Questionnaire 2005. http://www.cdproject.net/responses_cdp3.asp

Binder, C., Bader, H.-P., Scheidegger, R. and Baccini, P., 2001. Dynamic models for managing durables using a stratified approach: the case of Tunja, Colombia. Ecological Economics, 38(2): 191-207.

Binswanger, M., 2001. Technological progress and sustainable development: what about the rebound effect? Ecological Economics, 36(1): 119-132.

Biswas, A. and Davenport, W., 1976. Extractive metallurgy of copper. Pergamon Press, Oxford (1st Edition).

Biswas, A. and Davenport, W., 1994. Extractive metallurgy of copper. Elsevier, Oxford.

Bossel, H., 1999. Indicators for sustainable development: theory, method, applications, International Institute for Sustainable Development (IISD), Winnipeg.

Bousquet, F. and Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. Ecological Modelling, 176(3-4): 313-332.

Bretz, R., 1998. SETAC LCA Workgroup: Data availability and data quality. Global LCA Village, pp 1-3.

Bridge, G., 2004. Contested terrain: mining and the environment. Annual Review of Environment and Resources, 29:205-259.

Brook Hunt, 2002. Mining and metal industry consultants. http://www.brookhunt.com/

Cano-Ruiz, J. and McRae, G., 1998. Environmentally conscious chemical process design. Annual Review of Energy and the Environment, 23: 499-536.

CDP, 2005. Carbon disclosure project. http://www.cdproject.net/about.asp

Chapman, P. and Roberts, F., 1983. Metal resources and energy. Butterworths, London.

Chapman, P., 1974. Energy costs: a review of methods. Energy policy, 2: 91-103.

Christen, K., 2002. EU on track to ratify Kyoto protocol. Environmental Science & Technology, 36(9): 184A.

Clift, R. and Longley, A., 1995. Clean technology and the environment. In: R. Kirkwood and A. Longley (Editors), Introduction to clean technology. Blackie, Glasgow.

Clift, R. and Wright, L., 2000. Relationships between environmental impacts and added value along the supply chain. Technological Forecasting and Social Change, 65(3): 281-295.

Coates, V., Farooque, M., Klavans, R., Lapid, K., Linstone, H., Pistorius, C. and Porter, A., 2001. On the future of technological forecasting. Technological Forecasting and Social Change, 67(1): 1-17.

Conti, S. and Dematteis, G., 1995. Enterprises, systems and network dynamics: the challenge of complexity. In: S. Conti, E. Malecki and P. Oinas (Editors), The industrial enterprise and its environment: spatial perspectives. Avebury, Aldershot, pp. 217-241.

Conti, S., Malecki, E. and Oinas, P. (Editors), 1995. The industrial enterprise and its environment: spatial perspectives. Avebury, Aldershot.

Corbiere-Nicollier, T. et al., 2001. Life cycle assessment of biofibres replacing glass fibres as reinforcement in plastics. Resources, Conservation and Recycling, 33(4): 267-287.

Costanza, R. and Patten, B., 1995. Defining and predicting sustainability. Ecological Economics, 15(3): 193-196.

Costanza, R., Low, B., Ostrom, E. and Wilson, A. (Editors), 2001. Institutions, ecosystems and sustainability. Ecological Economics Series. Lewis Publishers, Boca Raton.

Costanza, R., Low, B., Ostrom, E. and Wilson, J., 2001. Ecosystems and human systems: a framework for exploring the linkages. In: R. Costanza, B. Low, E. Ostrom and J. Wilson (Editors), Institutions, ecosystems and sustainability. Lewis, Boca Raton.

Cote, R.P. and Cohen-Rosenthal, E., 1998. Designing eco-industrial parks: a synthesis of some experiences. Journal of Cleaner Production, 6(3-4): 181-188.

Cowell, S., Wehrmeyer, W., Argust, P. and Robertson, J., 1999. Sustainability and the primary extraction industries: theories and practice. Resources policy, 25(4): 277-286.

Cragg, W., Pearson, D. and Cooney, J., 1995. Ethics, surface mining and the environment. Resources Policy, 21(4): 229-235.

Croom, S., Romano, P. and Giannakis, M., 2000. Supply chain management: an analytical framework for critical literature review. European Journal of Purchasing & Supply, 6(1): 67-83.

Dalmijn, W., Reuter, M., de Jong, T. and Boin, U., 2003. The optimization of the resource cycle impact of the combination of technology, legislation and economy. In: L. Lorenzen and D. Bradshaw (Editors), XXII International Mineral Processing Congress, Cape Town, pp. 81-106.

Daly, H. and Cobb, J., 1989. For the common good. Beacon Press: Boston.

Daniels, P. and Moore, S., 2002. Approaches for quantifying the metabolism of physical economies. Part I: Methodological Overview. Journal of Industrial Ecology, 5(4): 69-93.

Davenport, W., 1999. Copper extraction from the 60's into the 21st century. In: G. Eltringham, N. Piret and M. Sahoo (Editors), Copper 99-Cobre 99. The Minerals, Metals & Materials Society, Phoenix, pp. 55-79.

Davenport, W., King, M., Schlesinger, M. and Biswas, A., 2002. Extractive metallurgy of copper. Elsevier: Oxford.

Dreborg, K., 1996. Essence of backcasting. Futures, 28(9): 813-828.

Dudka, S. and Adriano, D., 1997. Environmental impacts of metal ore mining and processing. Journal of Environmental Quality, 26: 590-602.

Dunphy, D., Ben, S. and Griffiths, A., 2003. Organizational Change for Corporate Sustainability. Routledge, London.

Dwyer, R., 1996. Strategic planning the concept.

Dziegielewski, B., Opitz, E., Kiefer, J. and Baumann, D., 1993. Evaluating Urban Water Conservation Programs: a procedures manual, American Water Works Association.

Edelstein, D., 1999. Minerals Yearbook: Copper, United States Geological Survey, Washington, D.C.

Edelstein, D., 2001. Copper, U.S. Geological Survey.

Ehrenfeld, J., 2003. Putting a spotlight on metaphors and analogies in industrial ecology. Journal of Industrial Ecology, 7(1): 1-4.

Ehrenfeld, J., 1994. Industrial Ecology: A Strategic Framework for Product Policy and Other Sustainable Practices. Paper presented at Green Goods: The Second International Conference and Workshop on Product Oriented Policy, Stockholm.

Elkington, J., 1998. Cannibals with forks. New Society Publishers, Gabriola Island, B.C.

Energetics, 1999. Energy and environmental profile of the U.S. metalcasting industry, US Department of Energy, Office of Industrial Technologies.

Farrell, T. and Kratzing, D., 1996. Environmental Effects. In: D. Mulligan (Editor), Environmental Management in the Australian Minerals and Energy Industries – Principles and Practices, UNSW Press, Sydney, pp.14-45.

Fels, M. and Keating, K., 1993. Measurement of energy savings from demand-side management programs in US electric utilities. Annual Review of Energy and the Environment, 18: 57-88.

Finnveden, G. et al., 2003. Strategic environmental assessment methodologies - applications within the energy sector. Environmental impact assessment review, 23(1): 91-123.

Finnveden, G., 2000. On the limitations of Life Cycle Assessment and environmental systems analysis tools in general. International Journal of Life Cycle Assessment, 5(4): 229-238.

Five Winds International, 2001. Eco-efficiency and materials. International Council on Metals and the Environment, Ottawa.

Fleischmann, M., Krikke, H., Dekker, R. and Flapper, S., 2000. A characterisation of logistics networks for product recovery. Omega, 28(6): 653-666.

Frosch, R. et al., 1997. The industrial ecology of metals: a reconnaissance. Philosophical Transactions: Mathematical, Physical and Engineering Sciences. Royal Society of London, 355(1728): 1335-1347.

Frost, F. and Mensik, S., 1991. Balancing minerals development and environmental protection. Long Range Planning, 24(4): 58-73.

Gaines, L., 1980. Energy and material flows in the copper industry. W-31-109-Eng-38, Argonne National Laboratory, U.S. Department of Energy, Illinios.

George, D.B., 1998. Copper. In: J.I. Kroschwitz (Editor), Kirk-Othmer Encyclopedia of Chemical Technology. Wiley, New York, pp. 318-428.

Gibbs, D. and Healey, M., 1997. Industrial geography and the environment. Applied Geography, 17(3): 193-201.

Gibson, C.C., Ostrom, E. and Ahn, T.K., 2000. The concept of scale and the human dimensions of global change: a survey. Ecological Economics, 32(2): 217-239.

Giurco, D., Stewart, M. and Petrie, J., 2001. Decision making to support sustainability in the copper industry: technology selection, 6th World Congress of Chemical Engineering, Melbourne.

Göckmann, K., 1992. Recycling of copper. CIM Bulletin, 85(958): 150-156.

Goedkoop, M., Heijungs, R., Struis, J., Huppes, G. and van der Meent, D., 2002. Combined midpoint / endpoint impact assessment, Fifth international conference on ecobalance - practical tools and thoughtful principles for sustainability. The Society of Non-Traditional Technology, Tsukuba, Japan.

Gordon, R., Graedel, T., Bertram, M., Fuse, K., Lifset, R., Rechberger, H. and Spatari, S., 2003. The characterization of technological zinc cycles. Resources, Conservation and Recycling, 39(2): 107-135.

Gößling, S., 2001. Entropy production as a measure for resource use. PhD Thesis, Universität Hamburg.

Gowdy, J.M. and McDaniel C., 1999. The Physical Destruction of Nauru: An Example of Weak Sustainability. Land Economics, 75(2): 333-338.

Graedel, T. and Allenby, B., 1995. Industrial Ecology. Prentice Hall, Englewood Cliffs, New Jersey.

Graedel, T. and Klee, R., 2002. Getting serious about sustainability. Environmental Science & Technology, 36(4): 523-529.

Graedel, T., Bertram, M., Kapur, A., Reck, B. and Spatari, S., 2004. Multilevel cycle of anthropogenic copper. Environmental Science & Technology, 38(4): 1242-1252.

Graedel, T., 1998. Streamlined Life-Cycle Assessment. Prentice Hall, Englewood Cliffs.

Graedel, T., 2000. The evolution of industrial ecology. Environmental Science & Technology, 34(1): 28A-31A.

Graedel, T., 2002. The contemporary European copper cycle. Ecological Economics, 42(1-2): 5-7.

Griffith, S., 1971. The art of war, authored by Sun Tzu and translated [from the Chinese] by Griffith. Oxford University Press, London.

Guinée, J. et al., 1999. Evaluation of risks of metal flows and accumulation in economy and environment. Ecological Economics, 30(1): 47-65.

Guinee, J.B., Udo de Haes, H.A. and Huppes, G., 1993. Quantitative life cycle assessment of products : 1:Goal definition and inventory. Journal of Cleaner Production, 1(1): 3-13.

Haberl, H., 2001. The energetic metabolism of societies. Part I: Accounting concepts. Journal of Industrial Ecology, 5(1): 11-33.

Halin, C., Amal, R., Beydoun, D., Scott, J. and Low, G., 2003. Evaluating the applicability of a modified toxicity characteristic leaching procedure (TCLP) for the classification of cementitious wastes. Journal of Hazardous Materials, 103(1-2): 125-140.

Hamby, D., 1994. A review of techniques for parameter sensitivity analysis of environmental models. Environmental Monitoring and Assessment, 32: 135-154.

Hamilton, C., 1995. The mystic economist. Willow Park Press, Fyshwick, ACT.

Hamilton, C., 2003. Growth Fetish. Allen & Unwin, Sydney.

Hanniala, P., Helle, L. and Kojo, I., 1999. Competitiveness of the Outokumpu flash smelting technology now and in the third millennium. In: D. Gerrge, W. Chen, P. Mackey and A. Weddick (Editors), Copper 99-Cobre 99. The Minerals, Metals & Materials Society, Phoenix, pp. 55-79.

Hansen, Y., 2004. Environmental impact assessment of solid waste management in the primary industries – a new approach. PhD Thesis, University of Sydney.

Hardy, C. and Graedel, T., 2002. Industrial ecosystems as food webs. Journal of Industrial Ecology, 6(1): 29-37.

Harland, C., 1996. Supply chain management: relationships, chains and networks. British Journal of Management, 7(Special issue): S63-S80.

Helmer, O., 1983. Looking forward - a guide to futures research. Sage, Beverly Hills.

Henstock, M., 1996. The recycling of Non-ferrous metals. The International Council of Metals and the Environment, Ottawa.

Hepburn, C., 2002. Are the woods safe? New theories of environmental collapse and 'optimal scale' employing hyperbolic discounting and endogenous growth models. MPhil Thesis, University of Oxford.

Higgins, J., 1980. Strategic and operational planning systems: principles and practice. Prentice-Hall International, London.

Higuerasa, P., Oyarzunb, R., Oyarzúnc, J., Maturanad, H., Lilloe, J. and Morataf, D., 2004. Environmental assessment of copper–gold–mercury mining in the Andacollo and Punitaqui districts, northern Chile. Applied Geochemistry, 19:1855-1864.

Hilson, G., 2000a. Barriers to implementing cleaner technologies and cleaner production practices in the mining industry: a case of the Americas. Minerals Engineering, 13(7): 699-717.

Hilson, G., 2000b. Pollution prevention and cleaner production in the mining industry: and analysis of current issues. Journal of Cleaner Production, 8(2): 119-126.

Hilson, G., 2003. Defining 'cleaner production' and 'pollution prevention' in the mining context. Minerals Engineering, 16(4): 305-321.

Hoffmann, V., Hungerbühler, K. and McRae, G., 2001. Multiobjective screening and evaluation of chemical process technologies. Industrial & Engineering Chemistry Research, 40(21): 4513-4524.

Holmberg, J. and Robèrt, K-H., 2000. Backcasting from non-overlapping sustainability principles – a framework for strategic planning. International Journal of Sustainable Development and World Ecology 7:291-308.

Hooke, M., 2004. Trade reform threats to market access. Minerals Council of Australia, Annual Seminar 2 June 2004.

Humphreys, D., 2001. Sustainable development: can the mining industry afford it? Resources policy, 27(1): 1-7.

ICSG, 1999. Coper world production figures. http://mmsd1.mms.nrcan.gc.ca/icsg/markets/Summary.PDF

IISI, 2002. World steel in figures. http://www.worldsteel.org/wsif.php

Intec, 2003. What is the current status of the Intec process. http://www.intec.com.au/html/faq/default.shtm

Jackson, T., 1996. Material Concerns: pollution, profit and quality of life. Routledge, London.

Jaffe, A., Newell, R. and Stavins, R., 2005. A tale of two market failures: technology and environmental policy. Ecological Economics, 54(2): 164-174.

Janssen, R., 1994. Multiobjective decision support for environmental management. Kluwer Academic, Dordrecht.

Jensen, A. et al., 1997. Life Cycle Assessment (LCA): a guide to approaches, experiences and information sources. Environmental issues series, 6. European Environment Agency, Copenhagen.

Jenkins, J., Davenport, W., Kennedy, B. and Robinson, T., 1999. Electrolytic copper - leach, solvent extraction and electrowinning world operating data. In: G. Eltringham, N. Piret and M. Sahoo (Editors), Copper 99-Cobre 99. The Minerals, Metals & Materials Society, Phoenix, pp. 493-566.

João, E., 2002. How scale affects environmental impact assessment. Environmental impact assessment review, 22(4): 287-306.

Jolly, J., 1993. Materials flow of zinc in the United States 1850-1990. Resources, conservation and recycling, 9: 1-30.

Kandelaars, P., 1999. Economic models of material-product chains for environmental policy analysis. Kluwer Academic, Dordrecht.

Kaufman, R., 1992. Strategic planning plus: an organisational guide. SAGE Publications, Newbury Park, California.

Keeney, R., 1982. Decision analysis: an overview. Operations Research, 30(5): 803-838.

Kesler, S., 1994. Mineral resources, economics and the environment. Macmillan, New York.

Königer, P. and Janowitz, K., 1995. Drowning in information but thirsty for knowledge. International Journal of Information Management, 15(1): 5-16.

Konijn, P., de Boer, S. and van Dalen, J., 1997. Input-output analysis of material flows with application to iron, steel and zinc. Structural Change and Economic Dynamics, 8(1): 129-153.

Kuckshinrichs, W. and Schwarz, H.-G., 2000. Model-based analysis of energy use and GHG emissions of global aluminium industry, 3rd Biennial conference of the European Society for Ecological Economics, Vienna.

Kuckshinrichs, W., Schwarz, H., Zapp, P. and Hake, J., 2000. Elements of a resource-oriented analysis of the material flow of aluminium: a systems analysis approach. In: R. Singhal and A. Mehrotra (Editors), Environmental issues and management of waste in energy and mineral production. A.A. Balkema, Rotterdam, pp. 697-709.

Lambert, D., Cooper, M. and Pagh, J., 1998. Supply chain management: implementation issues and research opportunities. International Journal of Logistics Management, 9(2): 1-19.

Larson, E.D., Zongxin, W., DeLaquil, P., Wenying, C. and Pengfei, G., 2003. Future implications of China's energy-technology choices. Energy Policy, 31(12): 1189-1204.

Lee, C.-H., 1998. Formulation of resource depletion index. Resources, Conservation and Recycling, 24(3-4): 285-298.

Legarth, J., 1996. Sustainable metal resource management- the need for industrial development: efficiency improvement demands on metal resource management to enable a (sustainable) supply until 2050. Journal of Cleaner Production, 4(2): 97-104.

Lenzen, M., 2003. Environmentally important paths, linkages and key sectors in the Australian economy. Structural Change and Economic Dynamics, 14(1): 1-34.

Lowson, 1999. Modified sequential leach protocol. Australian Nuclear Science and Technology Organisation (ANSTO). Unpublished.

Lumley, S., 1997. The environment and the ethics of discounting: An empirical analysis. Ecological Economics, 20(1): 71-82.

Lunt, D., Zhuang, Y. and La Brooy, S., 2002. Life cycle assessment of process options for copper production, Green Processing Conference. The Australasian Institute of Mining and Metallurgy, Cairns, Australia, pp. 185-193.

Mackley, M., 2004. John Bridgwater retires with symposium. The chemical engineer, November 2004(761): 62.

Matthews, E. et al., 2000. The weight of nations: material outflows from industrial economies, World Resources Institute, Washington, D.C.

McAllister, M., Scoble, M. and Veiga, M., 1999. Sustainability and the Canadian mining industry at home and abroad. CIM Bulletin, 92(1033): 85-92.

McLaren, J., Parkinson, S. and Jackson, T., 2000. Modelling material cascades - frameworks for the environmental assessment of recycling systems. Resources, conservation and recycling, 31(1): 83-104.

McQuade, C. and Riley, S., 1996. Chapter 8: Water Management. In: D. Mulligan (Editor) Environmental Management in the Australian Minerals and Energy Industries, UNSW Press, Sydney.

McNevin, D., 2000. Reflections on sustainability. Green Group Seminar, Department of Chemical Engineering, University of Sydney.

Metal bulletin, 2002. The market leading source for news, prices, analysis on the world's metal markets. http://www.metalbulletin.com/

Miettinen, P. and Hämäläinen, P., 1997. How to benefit from decision analysis in environmental life cycle assessment (LCA). European Journal of Operational Research, 102(2): 279-294.

MIM, 1999. Environment Report.

Min, H. and Zhou, G., 2002. Supply chain modeling: past, present and future. Computers & Industrial Engineering, 43(1-2): 231-249.

Mingers, J. and Brocklesby, J., 1997. Multimethodology: towards a framework for mixing methodologies. Omega, 25(5): 489-509.

Mingers, J. and Rosenhead, J., 2004. Problem structuring methods in action. European Journal of Operational Research, 152(3): 530-554.

MMSD, 2002. Breaking New Ground: Mining Minerals and Sustainable Development Final Report.

Moreno, A. (Editor), 1999. World copper databook. Metal Bulletin Books, Surrey, UK.

Mulder, H. and Biesiot, W., 1998. Transition to a sustainable society- a backcasting approach to modelling energy and ecology. Advances in Ecological Economics. Edward Elgar, Cheltenham, UK.

Noranda, 2003. Copper end uses (via 'Our Businesses', Copper South America'). www.noranda.com

Norgate, T. and Rankin, W., 2000. Life cycle assessment of copper and nickel production, MINPREX 2000, Melbourne, Australia, pp. 133-138.

Norgate, T. and Rankin, W., 2002. An environmental assessment of lead and zinc production processes, Green Processing Conference. The Australasian Institute of Mining and Metallurgy, Cairns, Australia, pp. 177-184.

Norris, G., 2001. The requirement for congruence in normalization. International Journal of Life Cycle Assessment, 6(2): 85-88.

North, M., Macal, C. and Campbell, P., Oh behave! Agent-based behavioural representations in problem solving environments. Future Generation Computer Systems, In Press, Corrected Proof.

Nriagu JO. 1990. Global metal pollution. Environment 32(7):7–11, 28–33

NSW Environment Protection Agency, 2000. Profits from cleaner production: a self-help tool for small to medium-sized businesses, Sydney.

O'Connor, M., 2000. The integrity of the terroir: An appraisal of the state of France's Critical Natural Capital. C3ED: Guyancourt Cedex, France.

Odum, H. and Odum, E., 2000. Modeling for all scales: an introduction to system simulation. Academic Press, San Diego.

OECD, 2001. Sustainable development: critical issues. Organisation for Economic Co-operation and Development, Paris.

Olsen, S.I. et al., 2001. Life cycle impact assessment and risk assessment of chemicals -- a methodological comparison. Environmental Impact Assessment Review, 21(4): 385-404.

Olson, M. and Bailey, M., 1981. Positive time preference. Journal of Political Economy, 89(1): 1-25.

O'Rourke, D., Connelly, L. and Koshland, C., 1996. Industrial ecology: a critical review. International Journal of Environment and Pollution, 6(2-3): 89-112.

Pearce, D., Groom, B., Hepburn, C. and Koundouri, P., 2003. Valuing the future: recent advances in social discounting. World Economics, 4(2): 121-141.

Peterson, D., LaTourrette, T. and Bartis, J., 2001. New forces at work in mining: industry views of critical technologies, RAND.

Peterson, J., 1998. Assessment and modelling of chromium release in minerals processing waste deposits. PhD Thesis, University of Cape Town.

Petrie, J. and Raimondo, J., 1997. Attempts to close material cycles in industrialised countries: threat challenge or opportunity for minerals exporting countries? In: H. Hoberg and H. von Blottnitz (Editors), Proceedings of the XX International Mineral Processing Congress, Aachen, Germany.

Petrie, J., 2005. New models of sustainability for the resources sector – a focus on minerals and metals. Paper to be presented at 7th World Congress of Chemical Engineering: 10-14 July, Glasgow, Scotland

Pizer, W., Harrington, W., Kopp, R., Morgenstern, R. and Shih, J.-S., 2002. Technology adoption and aggregate energy efficiency. Discussion Paper 02–52. Resources for the Future, Washington, D.C.

Pohekar, S. and Ramachadnran, M., 2004. Application of multi-criteria decision making to sustainable energy planning - a review. Renewable & Sustainable energy reviews, 8: 365-381.

Porter, A. et al., 2004. Technology futures analysis: Toward integration of the field and new methods. Technological Forecasting and Social Change, 71(3): 287-303.

Posch, A., 2004. Industrial recycling networks: results of rational decision making or 'organised anarchies'? Progress in Industrial Ecology, 1(1/2/3): 112-129.

Prain, R., 1975. Copper: the anatomy of an industry. Mining Journal Books Limited, London.

PRè, 2000. Simapro LCA Software. www.pre.nl.

Rechberger, H. and Graedel, T., 2002. The contemporary European copper cycle: statistical entropy analysis. Ecological Economics, 42(1-2): 59-72.

Rees, J., 1990. Natural Resources- allocation, economics and policy. Routledge, London.

Rennings, K. and Wiggering, H., 1997. Steps toward indicators of sustainable development: Linking economic and ecological concepts. Ecological Economics, 20(1): 25-36.

Reskin, E., White, A., Kauffman Johnson, J. and Votta, T., 2000. Servicizing the Chemical Supply Chain. Journal of Industrial Ecology. 3(2-3): 19-31.

Resource Assessment Commission, 1992. Multi-criteria analysis as a resource assessment tool: Research Paper No. 6. Australian Government Publishing Service, Canberra.

Reuter, M., 1998. The simulation of industrial ecosytems. Minerals Engineering, 11(10): 891-918.

Reuter, M., Sudhölter, S., Krüger, J. and Koller, S., 1995. Synthesis of processes for the production of environmentally clean zinc. Minerals Engineering, 8(1-2): 201-219.

Riekkola-Vanhanen, M., 1999. Finnish expert report on best available techniques in copper production and by-production of precious metals, Finnish Environment Institute, Helsinki.

Rio Tinto, 2005. Carbon disclosure project Questionnaire 2005. http://www.cdproject.net/responses_cdp3.asp

Ritchie, I., 1998. The Changing Face of Extractive Metallurgy, Technology - Australia's Future: New Technology for Traditional Industries. Australian Academy of Technological Sciences and Engineering.

Robèrt, K.-H., 2000. Tools and concepts for sustainable development, how do they relate to a general framework for sustainable development, and to each other? Journal of Cleaner Production, 8(3): 243-254.

Robinson, J., 1988. Unlearning and backcasting: rethinking some of the questions we ask about the future. Technological Forecasting and Social Change, 33: 325-388.

Robinson, J., 2003. Future subjunctive: backcasting as social learning. Futures, 35(8): 839-856.

Romano, P., 2003. Co-ordination and integration mechanisms to manage logistics processes across supply networks. Journal of Purchasing & Supply Management, 9(3): 119-134.

Rosenblum, J., 2000. A deeper look at system condition four. The Natural Step Newsletter, 11(1).

Rosenhead, J., 1996. What's the problem? An introduction to problem structuring methods. Interfaces, 26(6): 117-131.

Rudberg, M. and Olhager, J., 2003. Manufacturing networks and supply chains: an operations strategy perspective. Omega, 31(1): 29-39.

Sagar, A. and Frosch, R., 1997. A perspective on industrial ecology and its application to a metals-industry ecosystem. Journal of Cleaner Production, 5(1-2): 39-45.

Sánchez, L., 1998. Industry response to the challenge of sustainability: the case of the Canadian nonferrous mining sector. Environmental Management, 22(4): 521-531.

Schmidt-Bleek, F., 1993. The fossil makers. Factor 10 Institute, Birkhäuser.

Schmidt-Bleek, F., 2001. MIPS and ecological rucksacks in designing the future, Second international symposium on environmentally conscious design and inverse manufacturing: EcoDesign 2001. IEEE, Tokyo, pp. 1-8.

Schuyler, J., 1996. Decision analysis in projects. Upper Darby, Pennsylvania, Project Management Institute.

Schwartz, P. and Webber, S., 1999. The draft GBN global scenarios and the forces driving them. In: G. Eltringham, N. Piret and M. Sahoo (Editors), Copper 99-Cobre 99. The minerals, metals & materials society, Phoenix, Arizona, pp. 21-38.

Seager, T. and Theis, T., 2002. A uniform definition and quantitative basis for industrial ecology. Journal of Cleaner Production, 10(3): 225-235.

Seppälä, J., Basson, L. and Norris, G., 2002. Decision analysis frameworks for Life-Cycle Impact Assessment. Journal of Industrial Ecology, 5(4): 45-68.

SETAC, 1992. Guidelines for conduct of LCA peer review draft paper, Society for Environmental Toxicology and Chemistry, Penascola.

Seuring, S., 2004. Industrial ecology, life cycles, supply chains: differences and interrelations. Business Strategy and the Environment, 13(5): 306-319.

Simon H., 1960. The New Science of Management Decision. New Jersey: Prentice Hall.

Sinnott, R., 1989. An introduction to chemical engineering design. Chemical Engineering, Vol. 6. Pergamon Press, Oxford.

Sippel, B. and Roos, S., 2001. Recycling. www.noranda.com

Spatari, S., Bertram, M., Fuse, K., Graedel, T. and Rechberger, H., 2002. The contemporary European copper cycle: 1 year stocks and flows. Ecological Economics, 42(1-2): 27-42.

Spatari S., Bertram, M., Fuse, K., Graedel, T. and Shelov, E., 2003. The contemporary European zinc cycle: 1 year stocks and flows. Resources, Conservation and Recycling 39(2): 137-160.

Spiegelman, J., 2003. Beyond the food web: connections to a deeper industrial ecology. Journal of Industrial Ecology, 7(1): 17-23.

Stacey, R., 1990. Dynamic Strategic Management for the 1990s. Kogan Page, London.

Stewart, M. and Petrie, J., 1996. Life cycle assessment for process design- the case of minerals processing. In: M. Sanchez, F. Vergara and S. Castro (Editors), Clean technology for the mining industry, Concepcion.

Stewart, M. and Petrie, J., 1999. Planning for waste management and disposal in minerals processing using life cycle assessment. Minerals & Energy: Raw Materials Report, 14(3): 14-36.

Stewart, M. 1999. Environmental life cycle assessment for design related decision making in minerals processing.. PhD thesis, University of Cape Town.

Stewart, M. and Weidema, B., 2004. A consistent framework for assessing the impacts from resource use: a focus on resource functionality. International Journal of Life Cycle Assessment, Online First.

Stewart, M., 2001. Report on the MMSD Life Cycle Assessment Workshop: the application of Life Cycle Assessment to mining, minerals and metals, New York.

Sutherland, J., 1992. A technical perspective on strategic projection. Technological Forecasting and Social Change, 42(2): 165-191.

Tessier, A., Campbell, P. and Bisson, M., 1979. Selective extraction procedure for the speciation of particular trace metals. Analytical Chemistry, 51(7): 884-851.

The Warren Centre, 2004. Building Construction Technology Roadmap, Copper Development Centre, Sydney. Available at http://www.copper.com.au/technology_roadmap/.

Thoresen, J., 1999. Environmental performance evaluation – a tool for industrial improvement. Journal of Cleaner Production, 7(5): 365-370.

Tilton, J., 1996. Exhaustible resources and sustainable development. Resources policy, 22(1-2): 91-97.

Treadgold, T., 1999. Resources: the nickel dream loses its shine, Business Review Weekly (BRW), Australia.

Treitz, M., 2002. Towards a strategic advantage in sustainable development: Modelling and multi-objective optimisation of supply chain networks. Diplomarbeit Thesis, Universität Karlsruhe.

Turner, R., Tonn, B. and English, M., 1997. Environmental decision making: a framework and institutional and information needs. NCEDR Publication No. 97-17, National Centre for Environmental Decision-making Research, Knoxville, Tennessee.

Turner, R.K, 1992. Speculations on weak and strong sustainability. CSERGE working paper GEC 92-26.

U.S. Department of Energy, 1999. International Energy Annual 1999, World Electricity Installed Capacity by Type, January 1, 1999. http://www.eia.doe.gov/emeu/iea/elec.html

U.S. Joint Chiefs of Staff, 2001. Joint publication 3-0, Doctrine for joint operations.

Udo de Haes, H., Huppes, G. and De Snoo, G., 1998. Analytical tools for chain management. In: P. Vellinga, F. Berkhout and J. Gupta (Editors), Managing a Material World. Kluwer Academic, Dortrecht, pp. 55-84.

UN, 2002. Report of the world summit on sustainable development, United Nations, New York.

UNEP, 1999. Towards the global use of life cycle assessment. United Nations Environment Programme, Nairobi.

Upham, P., 2000. An assessment of The Natural Step theory of sustainability. Journal of Cleaner Production, 8(6): 445-454.

USGS, 2002. Mineral Commodity Summary. http://minerals.usgs.gov/minerals/pubs/mcs/

van Beers, D., Bertram, M., Fuse, K., Spatari, S. and Graedel, T. 2003. The contemporary African copper cycle: One year stocks and flows. Journal of the South African Institute of Mining and Metallurgy 103(3): 147-162.

van Berkel, R., 2000. Sustainable development and cleaner production in minerals and energy production, Sixth international symposium on environmental issues and waste management in energy and mineral production, Calgary, Canada.

van der Voet, E., 1996. Substances from cradle to grave: development of a methodology for the analysis of substance flows through the economy and the environment of a region—with case studies on cadmium and nitrogen compounds. PhD. Thesis, Leiden University.

van Deventer, J.S.J. and Lukey, G., 2003. Sustainability in the minerals industry: threat or opportunity? In: L. Lorenzen and D. Bradshaw (Editors), XXII International Mineral Processing Congress, Cape Town, pp. 23-41.

van Vuuren, D., Strengers, B. and De Vries, H., 1999. Long-tern perspectives on world metal use – a system-dynamics model. Resources Policy, 25(4): 239-255.

Vatn, A., Bromley, D.W., 1994. Choices without prices without apologies. Journal of Environmental Economics and Management 26(2): 129–148.

Verhoef, E., Dijkema, G. and Reuter, M., 2004. Process knowledge, system dynamics and metal ecology. Journal of Industrial Ecology, 8(1-2): 23-43.

Vexler, D., Bertram, M., Kapur, A., Spatari, S. and Graedel, T., 2004. The contemporary Latin American and Caribbean copper cycle: 1 year stocks and flows. Resources, Conservation and Recycling, 41(1): 23-46.

Villas Bôas, R. and Barreto, M., 1996. Clean technologies for the minerals industries: the need of P^2 solutions. In: M. Sanchez, F. Vergara and S. Castro (Editors), Clean technology for the mining industry, Concepcion.

Viljoen, J. and Dann, S., 2000. Strategic Management: planning and implementing successful corporate strategies. Longman / Pearson Education Australia, Frenchs Forest.

von Winterfeldt, D., 1980. Structuring decision problems for decision analysis. Acta Psychologica (1-3): 71-93.

Warhurst, A., 1994. Environmental best-practice in metals production. In: R. Hester and R. Harrison (Editors), Mining and its environmental impact. Issues in environmental science and technology. Royal Society of Chemistry, Cambridge.

Warhurst, A. and Mitchell, P., 2000. Corporate social responsibility and the case of Summitville mine. Resources Policy, 26(2): 91-102.

Wedepohl, K., 1995. The composition of the continental crust. Geochimica et Cosmochimica Acta, 59(7): 1217-1232.

Westerberg, A., 2004. A retrospective on design and process synthesis. Computers & Chemical Engineering, 28(4): 447-458.

Willard, B., 2005. The next sustainability wave. New Society Publishers.

Williams, E., 2003. Forecasting material and economic flows in the global production chain for silicon. Technological Forecasting and Social Change, 70(4): 341-357.

Wrisberg, N., Udo de Haes, H., Triebswetter, U., Eder, P. and Clift, R. (Editors), 2002. Analytical tools for environmental design and management in a systems perspective. Eco-efficiency in industry and science, 10. Kluwer Academic, Dordrecht, Netherlands.

Yang, Z., 2003. Dual-rate discounting in dynamic economic-environmental modeling. Economic Modelling, 20(5): 941-957.

Yoshiki-Gravelsins, K., Toguri, J. and Choo, T., 1993. Metal production, energy, and the environment: Part I. Journal of Metals, May: 15-20.

Young, S., 1999. A look at leach SX-EW with 2020 vision. In: S. Young, D. Dreisinger, R. Hackl and D. Dixon (Editors), Copper 99-Cobre 99. The minerals, metals & materials society, Phoenix, Arizona, pp. 611-619.

Zeltner, C., Bader, H.-P., Scheidegger, R. and Baccini, P., 1999. Sustainable metal management exemplified by copper in the USA. Regional Environmental Change, 1(1): 31-46.

CURRICULUM VITAE & PUBLICATIONS

Name: Damien Paul Giurco
Born: 5 November 1974, Geelong, Australia

2005– Senior Research Consultant, Institute for Sustainable Futures, University of Technology Sydney

1999–2005 Doctor of Philosophy, Department of Chemical Engineering, University of Sydney

1999 Safety Audit Engineer at Kemcor Petrochemical Company (now Qenos), Melbourne

1993–1998 Bachelor of Science, University of Melbourne

Bachelor of Engineering (Chemical), University of Melbourne
Thesis: '*Direct contact heat exchange in ice thermal energy storage*'
undertaken on exchange at Chiang Mai University, Thailand

The following papers were written and presented at conferences by Damien Giurco using work contained in this thesis:

Giurco, D., Stewart, M., Suljada, T. and Petrie, J., 2001. *Copper recycling alternatives: an environmental analysis*, 5th Annual Environmental Engineering Research Event, 20–23 October, Noosa.

Giurco, D., Stewart, M. and Petrie, J., 2001. *Decision making to support sustainability in the copper industry: technology selection*, 6th World Congress of Chemical Engineering, 23–27 September, Melbourne.

Giurco, D., Stewart, M. and Petrie, J., 2000. *The role of LCA in performance assessment in minerals processing- a copper case study*. In: R. Singhal and A. Mehrotra (Editors), Environmental issues & management of waste in energy and mineral production – Proceedings of SWEMP 2000. A.A. Balkema, Rotterdam, pp. 267–273.

The following papers and conference presentations were authored and made by colleagues which included the work of Damien Giurco contained in this thesis:

Stewart, M,. Giurco, D. and Petrie, J. 2003. *A sustainability analysis of the metals' value chain: a focus on copper,* XXII International Mineral Processing Congress, 28 September – 3 October, Cape Town.

Petrie, J., Stewart, M., Basson, L. and Giurco, D. 2002. *Decision making for sustainability: a support framework for mining and minerals processing,* Green Processing Conference, 29–31 May, Cairns.

Giurco, D., Stewart, M. and Petrie, J. 2002. *Recycling within the Global Copper Industry*, SETAC / ISIE Conference, 2–4 December, Barcelona.

Stewart, M., Giurco, D. and Petrie, J., 2001. *Decision making for sustainability: the case of minerals development in Australia*, 6th World Congress of Chemical Engineering, 23–27 September, Melbourne.

Stewart, M., Giurco, D. and Petrie, J., 2000. *Recycling and resource constraints for minerals and metals – technical and environmental considerations*, AIChE 2000 Annual Meeting, 12–17 November, Los Angeles.