Available online at www.sciencedirect.com
ScienceDirect
Minerals Engineering 20 (2007) 842–853
MINERALS ENGINEERING
This article is also available online at:
www.elsevier.com/locate/mineng

Strategies for reducing the carbon footprint of copper: New technologies, more recycling or demand management?

D. Giurco [a,*], J.G. Petrie [b,c]

[a] Institute for Sustainable Futures, University of Technology Sydney, P.O. Box 123, Broadway, NSW 2007, Australia
[b] School of Chemical and Biomolecular Engineering, University of Sydney, Australia
[c] Department of Chemical Engineering, University of Cape Town, South Africa

Received 2 January 2007; accepted 5 April 2007

Abstract

Existing approaches to reducing environmental impacts along the metal production and consumption chain are focused largely at the plant scale for primary production, rather than considering the whole metal cycle. As such, many opportunities for systemic improvements are overlooked. This paper develops an approach to designing preferred futures for entire metal cycles that deliver reduced carbon footprints. Dynamic material flow models in Visual Basic® are used to provide life-cycle-impact-assessment indicators, which help identify key intervention points along the metal cycle. This analysis also identifies which actors or agents along the value chain are responsible for, or can influence, behaviour which affects environmental performance. With this information, it is possible to evaluate different scenarios for transition paths to achieve reduced impact. These scenarios consider combinations of new technology, increased metal recycling and demand management strategies. A case study for the copper cycle in the USA shows that to meet a CO_2 reduction target of 60% by 2050, innovative technologies for primary processing of mined ore will play a limited role, due to their increasing impacts in the future associated with mining ever lower ore grades. To compensate for this whilst meeting demand projections, recycling of old scrap would be required to increase from 18% to 80%, requiring extensive collaboration between primary and secondary producers. An alternate scenario which focuses on demand reduction for copper by 1% per year, meets the CO_2 target whilst only requiring an increase in the recycling rate from 18% to 36%. Together, these suggest that there is merit in examining the 'metal-in-use' stage of the metal value chain more closely in order to achieve targeted reductions in CO_2. The approach also highlights the inherent trade-offs between different aspects of environmental performance which are required when pursuing CO_2 reduction targets.

Keywords: Environmental; Modelling; Mining; Mineral processing; Recycling

1. Introduction

Metals are essential to our everyday lives – in machinery to harvest and transport our food; in pumps and pipes that supply our water; and in electrical wires that power lighting and communications infrastructure. However, the scale of metal usage world-wide increased dramatically throughout the 20th century; for example, the cumulative total of all copper in use in the USA in the year 1900 was approximately 2700 tonnes, whereas, by the year 2000, the *annual* production in the USA was a similar figure (Ayres et al., 2001). Metal demand is still largely satisfied through primary processing of ores rather than from recycled scrap, and, together with rising production, declining available ore grades necessitate increased energy usage for processing (Ayres et al., 2001; van Deventer and Lukey, 2003). A metal cycle as defined in this paper is analogous to what is sometimes referred to as a material chain, material-product chain, metal production and consumption chain, or value chain (i.e. ore extraction, primary processing, product manufacture and use and disposal). When considering the entire metal cycle, the

* Corresponding author. Tel.: +61 2 9514 4978; fax: +61 2 9514 4941.
E-mail address: Damien.Giurco@uts.edu.au (D. Giurco).

0892-6875/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.mineng.2007.04.014

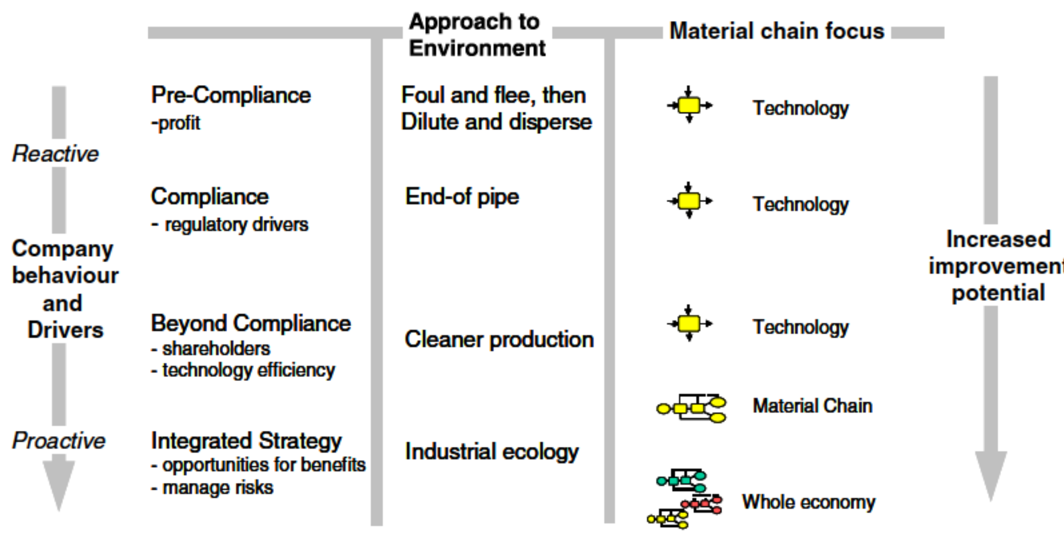

Fig. 1. Company behaviours, drivers and material chain focus (after Giurco, 2005; Willard, 2005).

scale of environmental impacts spans both global (climate change impacts) and regional/local (water use and toxic releases). Despite the introduction of new processing technologies, 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). Consequently, the mining, refining and recycling industries are under increasing pressure to improve their environmental performance (Bridge, 2004). These environmental drivers, together with financial and societal drivers pursued through regulatory and peer pressure, are part of an increasing need for companies to embrace corporate social responsibility with greater transparency (Warhurst and Mitchell, 2000). The historical transition of approaches to addressing environmental impacts is shown in Fig. 1. It shows that as we move beyond a cleaner production toward an industrial ecology approach, which seeks to close material loops, a material chain focus is necessary. This paper studies the links along the material chain between actors, current and future technological infrastructure and its associated environmental impacts, demonstrated for the case of a single metal, copper. Whilst not the focus of this paper, copper is linked to cycles of other metals through its co-depositing in ores (e.g. iron, nickel, zinc and lead) and products (such as zinc in brass). Work on the interconnectedness of material chains when considering the technical recycling of end-of-life consumer products has been undertaken by van Schaik et al. (2004a,b). The composition of metals in end-of-life consumer products is very different to that in ores for which the majority of metal recovery and refining processes are configured, which poses technical challenges for recycling. The interconnectedness of metal cycles also highlights that, for example, an extended ban on lead would affect the lead, zinc, copper, tin, silver and bismuth cycles amongst others (Verhoef et al., 2004).

Notwithstanding the complexity of connected metal cycles, the value chain perspective provides a helpful starting point from which to consider the sustainability of metal cycles at large, with explicit consideration of conflicting objectives, values and perspectives (Petrie, 2007). The key driver of material flows within the value chain is taken to be the society's need for metal; to provide useful services via metal-containing products, rather than a need for metal *per se*. This suggests that 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 it might be reduced? What is the nature of the rebound effect regarding technological progress in the minerals industry?[1] The switch from selling products to services has been occurring in several sectors (e.g. Interface Carpets Inc., Xerox® photocopiers and 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 et al. (2001)?

Several drivers are encouraging companies to move 'beyond compliance' toward an 'integrated sustainability strategy'. Investment in companies across all sectors is increasingly subject to an assessment of their 'carbon risk',

[1] 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).

evidenced by the increasing participation of institutional investors in the 'Carbon Disclosure Project' seeking to ask over 2100 companies about their own activities and their carbon risk (increased from 35 institutional investors in 2002, to 255 in 2005 controlling $31 trillion of assets, CDP, 2006). For minerals and metals specifically, the mining, minerals and sustainable development project (MMSD, 2002) placed the topic of sustainability on the agenda in 2002. However, since then change has been incremental with improvements in some areas such as sustainability reporting, whilst still lacking with respect to an integrated material chain approach to future planning. More importantly, there has been little advancement in the explicit consideration of reporting indicators in decision making for sustainability within the industry sector (Petrie et al., 2006). As an example, the current strategic document for the copper industry is the Copper Technology Roadmap (AMIRA, 2004), which focuses predominantly on improved technologies as the key to improved industry performance with limited consideration of the complementary role that improved material management along the material chain can play.

Articulating a methodology that captures the carbon impacts (and other environmental impacts) of material flows through the entire material chain and seeks to develop preferred futures at this scale remains a pressing need. Other authors have studied flows in the material chain for copper for different motives. For example Zeltner et al. (1999) and Ayres et al. (2001) construct dynamic material flow models to predict likely future demand and the quantity of future supply available in landfills in the USA. Graedel et al. (2004) consider a snapshot of the geographical location of stocks in various countries in 1994, and also aggregated at different scales.[2] Reuter (1998) links flows and environmental impacts in the context of ISO 14000 standards to process and recycling efficiency for multiple material chains. Verhoef et al. (2004) have developed sophisticated system dynamics models to describe metal ecology for connected cycles incorporating tacit process knowledge. In contrast to modelling the links between cycles as a basis for understanding the interconnection of cycles and informing policy, this paper puts a focus on the decision-making actors in the metals cycle to explore the role that collaboration along the material chain will have in cycling metal in society with a reduced impact.

Our paper develops technology-specific models of material flows across the value chain, which are linked to environmental impacts. Implicit in the modelling approach is the consideration of actors in the material chain and the system variables they control, enabling us to explore preferred future configurations of the value chain with less environmental impact and evaluate the progressive transition to such preferred futures.

Consequently, the overall aim of this paper is to determine: what metal cycle configurations in the USA could meet a 60% reduction in CO_2 emissions by 2050?[3] Related questions are then: what are the trade-offs in other environmental impacts associated with such configurations; and, which actors are responsible for changing key system variables – both supply side and demand side – to implement transition paths. Such questions are a first step in prompting the industry to consider the implications for the role and quantity of metals in a sustainable society and how their circulation in the economy should be managed.

To begin addressing these questions, this paper models metal flows across the value chain to a level of detail that allows identification of trade-offs in performance across system attributes for various future metal cycle structures (i.e. combinations of technologies, spatial locations and logistics). The focus is on targeted reductions in global warming impact (carbon footprint) and local ecotoxicity impacts. These dynamic mass flow models are coupled with environmental life-cycle-type indicators for mining, refining and recycling phases of the metal cycle (i.e. environmental impacts of all stages except consumption are modelled).[4] Identification of key variables through a sensitivity analysis and an assessment of each actor's ability to change key variables informs the backcasting of plausible future scenarios to meet environmental targets. This approach is demonstrated with a case study for the copper metal cycle in the USA.

2. Methodology: reducing the impacts of metal cycles

2.1. Characterising metal cycles

2.1.1. Metal cycle components and system boundary

A generic representation of a metal cycle is given in Fig. 2. Here, we consider the cycle as a network of connected nodes with material flows between each node. Fig. 2 shows a 'closed loop' material value chain for one metal, which means that all material recycled returns to the same value chain. This is not always the case. For example, consider the potential recycling of zinc, not in

[2] The zinc cycle has been studied in a similar way (Gordon et al., 2003) as part of the Stocks and Flows project at Yale University seeking to map the stocks and flows of major metals and recognising that metal-in-use stocks, largely concentrated in cities, represent valuable future resources.

[3] This target has been chosen to represent an ambitious reduction in the carbon intensity of the copper cycle to illustrate where such drivers could direct the industry. For countries seeking to meet economy-wide cuts in CO_2 of 60% by 2050, it is recognised that not all sectors (e.g. industries linked to the copper cycle) would reduce emissions by the same amount and that other sectors including energy and transport would be a focus for economy-wide emission reductions.

[4] The aim of this work is to understand and reduce impacts associated with brining metal to market (either from primary or secondary resources). Copper metal goes into a variety of uses from wires, to pipes, to electronic goods each with differing impacts, which are not modelled in this work. This work provides a basis for the future consideration of acceptable uses and impacts for copper-containing products informed by the impacts of production.

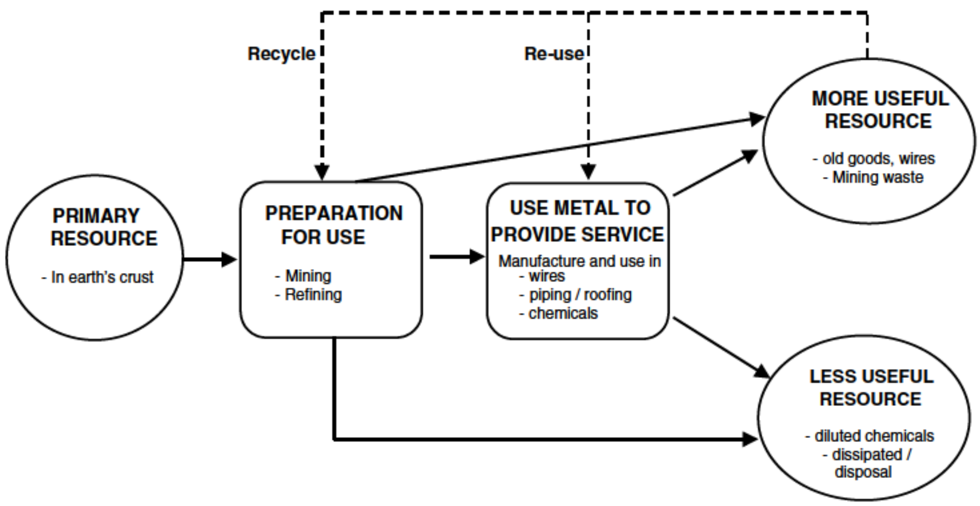

Fig. 2. Aggregated generic representation of a materials value chain as a network of five aggregated nodes (with examples for copper) (Giurco, 2005).

the zinc value chain to make zinc again, but in the copper value chain as an additive to make brass.[5] This would be termed 'open loop' recycling – namely, where a metal leaves its value chain to enter the value chain of another metal.

Using copper as an example, Fig. 2 includes qualitative descriptions for each node, which may represent either resource stocks (ovals: ○) or aggregated processing activities (boxes: ▭). 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 were centred on ore extraction (Cowell et al., 1999). Consequently, it challenges the industry to adopt a new, expanded focus around which to pursue performance improvements, both within and between nodes of the metal cycle – this also comes with requirements for new tools to map performance and assess related impacts. The material chain representation in Fig. 2 is a highly aggregated representation to simplify explanation of the concept. A more detailed material chain representation is shown for the case study in Fig. 6.

'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).[6] 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 deliver metal product as represented in Fig. 2. Mining may either be underground or open cut, depending on the metal and type of ore deposit. For the copper industry, a variety of technologies are then used to concentrate and refine the metal to a pure product (see Giurco et al., 2001 for further details). 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' as shown in Fig. 2.

Recent industry initiatives (MMSD, 2002) have recognised the need for longer term thinking and new institutional arrangements to 'bridge the discrepancy between the multigenerational time frame of indigenous people and the short time frame of mining'. Often the focus has been on a thorough planning for closure at a mine, and developing capacity for a continuing economy beyond this. Whilst this thinking is necessary, it still only engages with part of the overall value chain. There is little guidance on how to answer the question of what technology combinations are suited to processing ore grades and secondary scrap resources of the future, which will be of different compositions as patterns of consumption and use change. 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 Fig. 2. 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, and
- 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

[5] 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 explored by Reuter (1998) and Verhoef et al. (2004) but is not the focus of the argument developed in this paper.

[6] Ocean resources are not considered further in this paper as they are currently impractical to recover for copper and do not contribute to the supply of copper metal to the economy, whilst remaining a resource in the longer term.

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 a sizeable 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). Others have pointed out that the recyclability of metals from non-dissipative uses, given appropriate energy inputs and technology availability, should focus attention on the operation of the value chain and less on the issue of resource scarcity within the value chain (Stewart and Weidema, 2005).

2.1.2. Analytical framework

The analytical framework (Giurco, 2005) depicted in Fig. 3 shows that the materials chain may be specified at a number of levels *vis-à-vis*: 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).

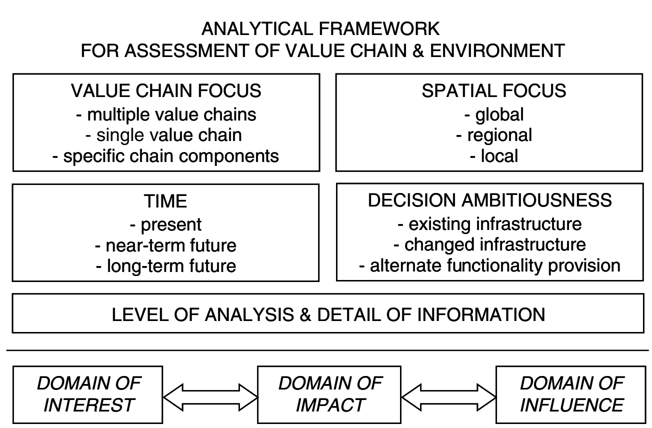

Fig. 3. Analytical framework for assessment of metal cycle and environmental impacts.

The ‘level’ at which each of these characteristics is specified constitutes the ‘level of analysis’ and each level of analysis will require differing ‘information detail’.

The analytical framework also considers explicitly the role and influence of actors or agents within any value chain network. It 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,[7] reducing externalities and providing information that allows better choices to be made with respect to the overall sustainability of the network. 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 spatial and value chain focus. For example, a multi-national mining company may have its domain of interest more 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 spatial and temporal scale at which environmental impacts manifest[8] 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 constituting a barrier to sustainable metal cycles (Giurco, 2005).

2.2. Modelling approach

The modelling approach links two sub-models developed in Visual Basic®. The first sub-model, the *material flows* model, tracks the *quality* and *quantity* of material flowing through the material chain. The model is defined in terms of material split functions between nodes, and 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.

An expression for the environmental performance of the material chain as a whole (or the parts of it for which there

[7] 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.

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

are process models) is represented as follows in Eqs. (1) and (2):

$$E(t) = \sum_{j=1}^{j'} f[P(j,t), m_j(t)] \quad \text{where } t_0 \leqslant t \leqslant t_{\text{final}} \tag{1}$$

$$m_j(t) = g[D(t), R(t)]. \tag{2}$$

$E(t)$ = 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 material 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 $E(t_{-1})$ or based on rules governing system behaviour through time).

First, a model of the status quo is constructed to determine baseline performance and links between actors and impacts. This baseline analysis also enables identification of critical parameters by means of a sensitivity analysis. Thereafter, use is made of backcasting and scenario analysis techniques to determine the range of environmental impacts associated with a set of alternate, but plausible futures (considering both technology choice and network configurations). Refer to Giurco (2005) for further details of the modelling approach.

2.3. Scenarios and future configurations of the material chain

There are several steps in considering future configurations of the material chain:

- identifying priority target areas from status quo analysis,
- identifying key variables, and actor influence over these variables, through a sensitivity analysis,
- forecasting system behaviour due to influence of external/exogenous variables,
- either exploring, from an actor perspective, performance improvements made by changes to actor-controllable (internal) variables, or
- backcasting a preferred future, and identifying how collaboration between various actors can help realise this future.

The functionality of the models allows the behaviour of individual actors to be explored within specific network development scenarios; i.e. focusing on 'cause' and measuring 'effect'; and, equally, simulating system changes (with associated collaboration between actors required) to achieve a particular network in terms of environmental impact profile i.e. focusing on 'effect' and identifying which 'causes' may give rise to this.

2.3.1. Status quo and sensitivity analysis and actor influence

An analysis of the status quo configuration and its environmental impact is performed first to develop a system baseline, supported by a simple sensitivity analysis where all control variables are changed by ±20% to assess their influence on each environmental impact category (see Giurco, 2005).

One then reflects on which actors can influence sensitive system variables as shown in Fig. 4. This is useful in two ways; firstly, in order to inform the exploration of future material chain scenarios, which can be achieved by single actors alone; secondly, it provides an audit trail for decision makers, by which the action of discrete actors can be followed during the roll-out of preferred future network configurations (themselves identified by a backcasting exercise).

A schematic representation showing the control of different actors over different system variables is given in Fig. 5. 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 and 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, 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 waste 1 contributes to impacts 1 and 2. Actor 3 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.

This conceptualisation is useful for understanding who the influential actors are, and what control variables may lead to overall system constraints, due to lack of individual actor control over them. This last situation may also suggest to decision makers at what level of concerted action by groups of network players is required to achieve a desired level of environmental performance. Both these situations are explored in the case study which follows.

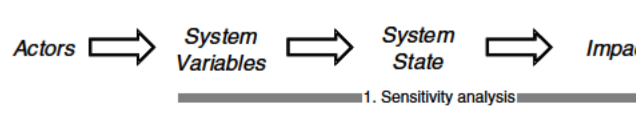

Fig. 4. Conceptual link between actors, variables, system configuration and impacts.

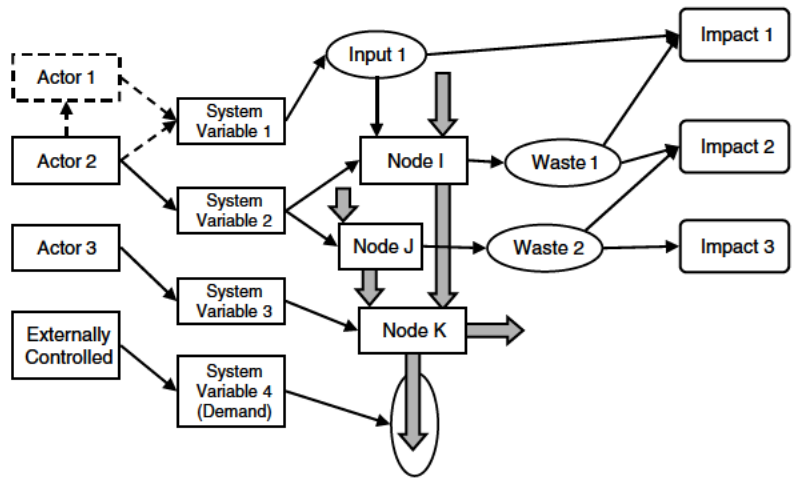

Fig. 5. Link between actor, system variables, system and impact.

3. Results of copper case study for the USA

This case study demonstrates the application of the methodology in Section 2 for the copper metal cycle in the USA over a 50 year time horizon. It explores changes to infrastructure to mimic 'decision ambitiousness' (see Section 2.1.2). Here we consider the introduction of new technology, not just new material flow patterns between existing technologies; however, no changes to product functionality are explored (e.g. the replacement of land-based communication networks with mobile telephony).

3.1. Model structure

A conceptual description of the model used to describe the value chain for the USA is shown in Fig. 6, 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 processing technologies.

Fig. 6 shows three technology options for processing primary ore bodies (T1, T2 and T3). There are also three technology options for processing secondary scrap (S1, S2 and S3), one unique technology for each type of scrap.[9] Very high grade No. 1 scrap (99% copper) is sorted and then re-melted. High grade No. 2 scrap (95% copper) is sorted and must then be re-melted 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 and 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 be explored, although this is not considered here. The environmental impact of the value chain can be tracked by summing the individual impacts of all stages in the chain (except the impacts from use which are not modelled). The residence times of 'copper in use' act simply as an available stock of secondary supply, and in this model a uniform distribution is used to model residence time.

[9] 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 the dedicated processing through secondary technologies.

3.1.1. Status quo characterisation

The baseline performance assessment for the USA value chain is based on Table 1, which lists key variables for resource quality, and the distribution of splits between technologies.

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 with 'old scrap', which is discarded after use by a consumer and which constitutes the secondary scrap resource considered in this case study.

The technology models developed in Giurco et al. (2001) 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 Fig. 7. This shows that the environmental impact associated with bringing metal to market in the USA is currently associated with primary processing – by some orders of magnitude. Total environmental burdens for each impact category are shown in Table 2, based on problem-oriented impact factors and indicators (PRè, 2000). The choice of impact categories was guided by the need to reflect global and local emissions, and focused on climate change, acid

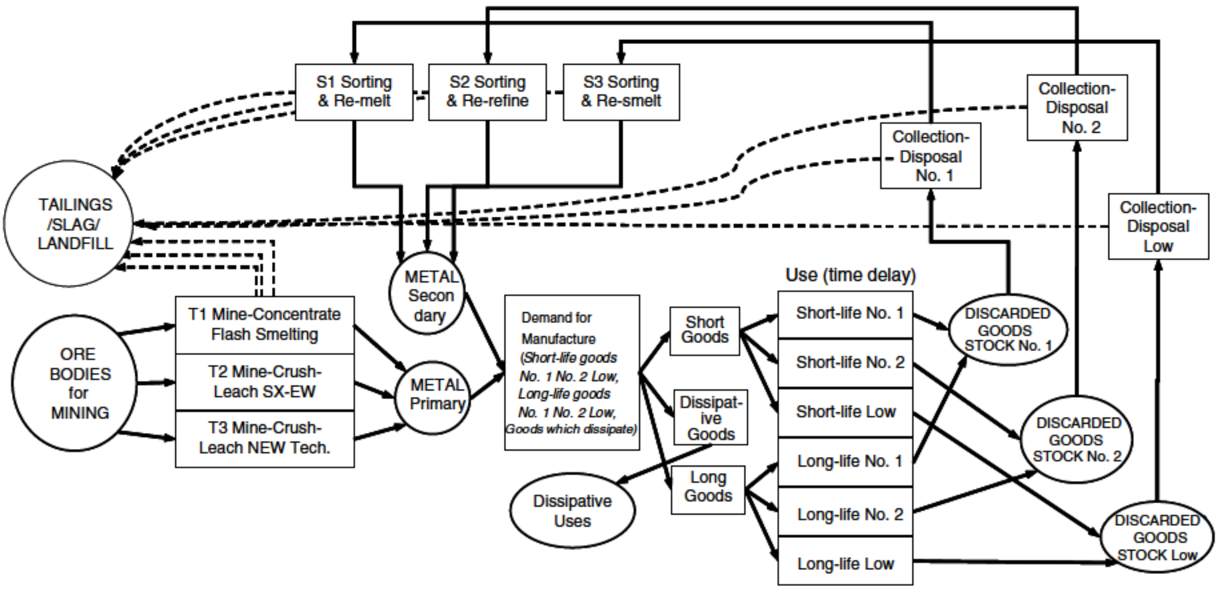

Fig. 6. Dynamic model of material flows in the value chain (stocks represented in ovals, processed in boxes).

Table 1
Assumptions for base case value chain configuration in the 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 'No. 1' scrap (99% copper)	25%
Secondary – high quality 'No. 2' scrap (95% copper)	37.5%
Secondary – low quality scrap (30% copper)	37.5%
Annual demand (*t*)	3,101,000
Imports/exports	Nil

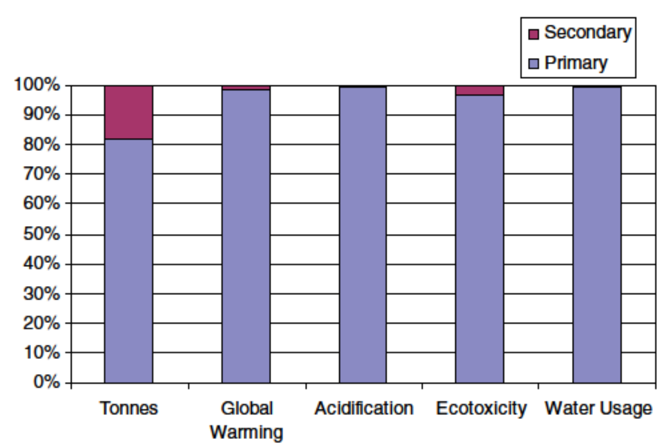

Fig. 7. Relative contribution of primary and secondary processing to impacts in the USA.

gas releases, ecotoxicity associated with liquid releases and water consumption. A more comprehensive accounting of environmental performance is possible, using a full life-cycle-impact-assessment methodology, but this was deemed unnecessary for the purposes of this case study.

The most sensitive variables for this system were identified as follows:

- demand,
- split between primary and secondary processing used to meet demand,
- ore grade and quantity,
- scrap quality and quantity,
- energy mix (e.g. coal, hydro, nuclear, gas and oil),
- recovery of copper in processing technologies,
- degree of open cut mining,
- primary technology choice, and
- secondary technology choice.

No single actor in the material chain (e.g. miner, refiner, recycler and consumer) has control over all variables. Hence, in order to proceed to a desirable environmental future, it is necessary to investigate scenarios in which some collective action involving several agents or actors is contemplated, and contrast these with scenarios in which individual action alone is envisaged. The latter correlates with the introduction of new processing technologies (as proposed by the Copper Technology Roadmap, see AMIRA, 2004) by individual

Table 2
Total environmental impacts for primary and secondary processing

	Greenhouse (kg CO_2 equivalent)	Acidification (kg SO_2 equivalent)	Ecotoxicity (Relative units)	Water consumption (*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

Table 3
Description of scenarios and key actor influences

	Description	Key actor influence
Scenario 1	Business as usual, with demand stabilising (consistent with conservative logistic growth model as shown in Fig. 8)	No action
Scenario 2	Scenario 1 plus introduction of new hydrometallurgical primary processing technology linked to hydro electricity	Miners/refiners
Scenario 3	Scenario 1 plus scenario 2 plus aggressive recycling (from 18% to 70%)	Miners/refiners/ secondary processors
Scenario 4	One percent annual reduction in demand plus new primary processing linked to hydro electricity (as per scenario 2) plus doubling of recycling (from 18% to 36%)	All actors in material chain

actors such as miners or refiners, whereas the former collaborative actions might include increased recycling or demand management. Four discrete scenarios were explored here.

3.1.2. Scenario descriptions

A description of the four scenarios is given in Table 3.

Demand forecasts for scenarios 1, 2 and 3 (it is set in scenario 4) are shown in Fig. 8, and ore grade forecasts for all scenarios are shown in Fig. 9. Fig. 8 shows that both logistic and linear models approximate the historical consumption data. In this paper, demand in the USA is assumed to follow a logistic model, which is 'best case' from an environmental perspective. The results in Section 3.2 show that even the 'best case' path still has significant challenges with respect to environmental impacts – should actual demand be closer to linear growth, the case for action to address the greater environmental burden associated with cycling copper in such a material chain configuration becomes even stronger.

The historical decline in copper ore grades is shown in Fig. 9, with an exponential trend line fitted over historical

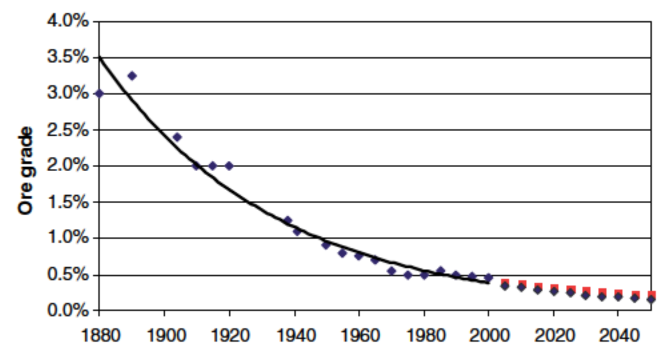

Fig. 9. Ore grade for copper in the USA (data from Ayres et al., 2001), predicted values based on exponential decline from 1880–2000 data shown as diamonds (ore grade A), predicted values based on 1950–2000 data shown as squares (ore grade B).

values, and future values shown as diamonds for an extrapolation of the trend line based on 1880–2000 data (ore grade A). Given the sensitivity of the model to ore grade, a second ore grade model was fitted to 1950–2000 data (ore grade B) to take account of the fact that there were smaller deposits of higher grade ores in the USA, but much larger deposits of lower grade ores, which have been mined since the middle of the last century. This would suggest a less rapid decline in future ore grade than that based on data from 1880 to 2000. The trend lines from both projections start to diverge significantly only beyond the year 2040.

Major variable values for each scenario are given in Table 4. Unless stated otherwise, linear interpolation is used between the years 2000 and 2050.

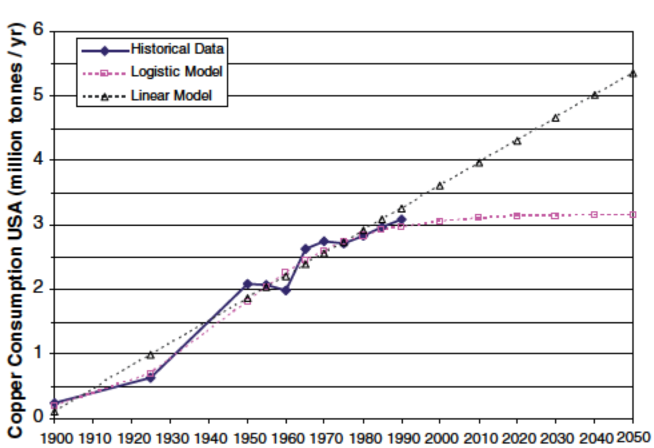

Fig. 8. Models of demand for consumption in the USA (data from Zeltner et al., 1999).

3.2. Results

3.2.1. Global warming potential

Each scenario is plotted in Fig. 10 for both ore grade models (ore grade A represented as connected solid shapes and ore grade B as hollow shapes with no connecting line).

The results for the 'business as usual' case (scenario 1), where growth in demand is stable to 2050, still results in

Table 4
Values of parameters for scenarios explored

Assumptions for base case	Base case in 2000	Scenario 1 2050	Scenario 2 2050	Scenario 3 2050	Scenario 4 2050
Ore grade	0.45%	Declines in all scenarios as predicted from Fig. 9			
Proportion of primary processing via flash smelting	65%	65%	20%	20%	20%
Proportion of primary processing via heap leach SX/EW	35%	35%	10%	10%	10%
Proportion of primary processing via new hydromet linked to hydro electricity or other low carbon energy	0%	0%	70%	70%	70%
Percent of total demand met via secondary scrap recycling, of which:	18%	18%	18%	70%	36%
Secondary – very high quality 'No. 1' scrap (99% copper)	25%	25%	25%	25%	25%
Secondary – high quality 'No. 2' scrap (95% copper)	37.5%	37.5%	37.5%	37.5%	37.5%
Secondary – low quality scrap (30% copper)	37.5%	37.5%	37.5%	37.5%	37.5%
Annual demand (*t*)	3,100,000	3,200,000	3,200,000	3,200,000	1,900,000
Imports/exports	Nil	Nil	Nil	Nil	Nil

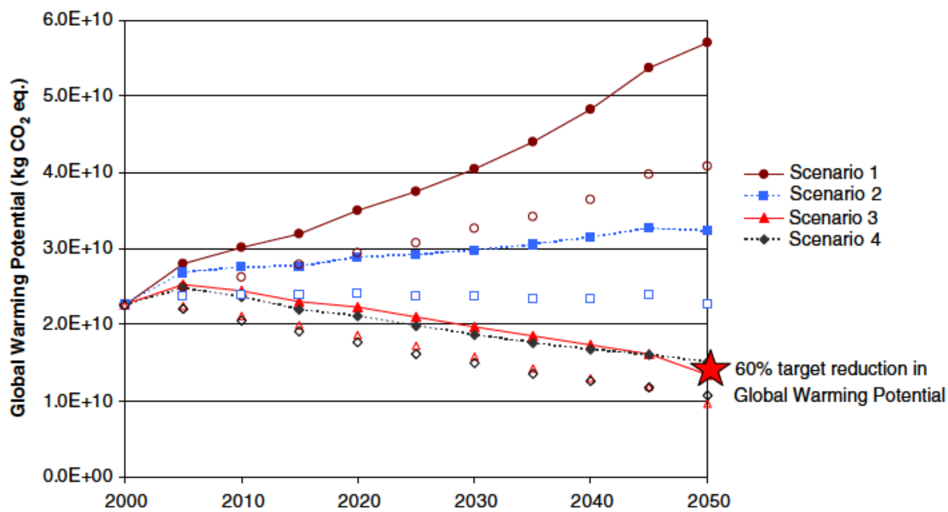

Fig. 10. Results for global warming potential.

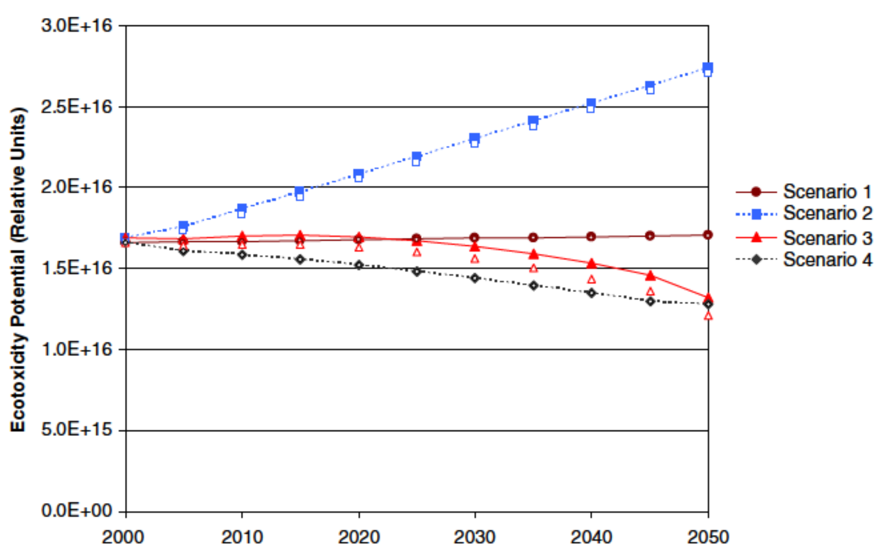

Fig. 11. Results for ecotoxicity potential.

an increase in global warming potential of between 1.8 and 2.6 times depending on the ore grade model as shown in Fig. 10. Note that this is with the assumption of a logistic demand-growth model for the USA. Should a linear growth model be adopted (which could be plausible from Fig. 8), the resultant increase in impact would be up to

8.8E + 10 kg CO_2 equivalent by 2050 – approximately four times the current impact.

Tellingly, the introduction of a new hydrometallurgical processing technology coupled to hydroelectricity (scenario 2) does not reduce the global warming impact of the material chain. This is because the declining ore grades and the limited recovery of hydrometallurgical technologies outweigh the gains made by the link with low-carbon energy for processing and refining.

The only scenarios to meet or exceed the target of a 60% reduction in global warming potential by 2050 are scenarios 3 and 4, both with a heavy emphasis on additional recycling. Scenario 4 has a less aggressive recycling approach, but introduces demand management. Note that with ore grade model B, scenarios 3 and 4 meet the 60% reduction target by 2030, rather than 2050.

3.2.2. Ecotoxicity potential

The corresponding impacts for ecotoxicity potential are given in Fig. 11. It shows that the increasing introduction of hydrometallurgical processing in scenario 2 actually increases the ecotoxicity potential of the system (due to lower recoveries in hydrometallurgical processing than for pyrometallurgical processing). Only through the introduction of increased recycling does the ecotoxicity potential diminish. Scenario 4, which includes reduced consumption, acts to reduce the ecotoxicity earlier.

4. Conclusions

This paper has developed an approach to modelling the impacts of metal cycles that provides a basis for exploring infrastructure configurations that meet targets for reduced environmental impacts.

Such an approach assists in making the case to move beyond compliance, to an integrated strategy for sustainable development of the mineral-to-metal-to product value chain, which moves beyond supply side initiatives (or a sole reliance on technological solutions) to embrace collaboration along the material chain. For the specific copper case study, such collaboration between network actors or agents can:

- increase the re-circulation of discarded copper sources from secondary scrap back into the economy, and
- explore demand management initiatives that either provide similar services with less metal mass, or longer lasting goods.

The case study for the USA demonstrated that a combination of increased recycling and demand management strategies will be required to deliver a configuration of the material chain that meets a 60% reduction in carbon footprint by 2050. New primary processing technologies – even linked to low-carbon energy sources – will play a limited role in achieving ambitious carbon-reduction targets. This is a highly significant assertion, and suggests that the current strategic planning focus of the industry (with its emphasis on technology road maps for primary processing) bears rethinking. Additional research into newer secondary processing technology is required.

A further challenge is that demand management is not on the horizon in the minerals industry, as it is in other primary resource sectors such as energy and water, where it has been implemented for some time. Certainly the challenge is greater for the minerals industry because of the greater scale and diversity of locations over which its resources are mined, refined and used. However, the scenarios explored here point the way toward modes of operation that will allow the industry to flourish within a material chain that provides services with a reduced material input, that fully account for the costs of carbon and other environmental impacts, and which potentially occur within a dematerialising economy.

In terms of the analytical framework in Fig. 3, the domain of interest (and accountability) for the industry is currently at the plant scale, yet its domain of impact from plant-based operations has ramifications along the entire value chain, and manifests itself in both local and global impacts. This suggests that more transparent decision making processes are required, within which the trade-off between performance in different impact categories (and their consequences for social welfare and development) are made explicit. Whereas the influence of single companies might well be limited in this regard, an 'ambitious' shared vision of collective action to transform material flows patterns and infrastructure is at least consistent with the intent of the International Council on Mining and Metals (ICMM). What is needed now is coordinated political and organisational will to make it happen.

The results of this work identify that collaboration between industry actors along the material chain is required to transition to a preferred future with less environmental impact. By demonstrating that the impacts for a 'business as usual' scenario are unacceptable, it makes the case for further research into innovative implementation strategies, including economic, voluntary and regulatory instruments, which may be used to drive transition to achieving a less impacting material chain configuration. Furthermore, this work establishes a basis for benchmarking the carbon footprint (together with other environmental impacts) for copper, which can be extended to other material chains. This assists the industry in better understanding its carbon-risk and the associated trade-offs in other environmental impacts that occur when choosing a low carbon trajectory. Such insights and assessments will increasingly be needed to justify industry's future 'licence to operate'; ensuring that it is consistent with societal values from the plant scale through to impacts on other parts of the material chain, the economy and the natural environment. Benchmarking impacts of other material chains also provides valuable information for fundamentally questioning the 'ethical uses' for different metals and the inter-connected material cycles in a sustainable economy. Debating what constitutes a range of 'ethical uses' and 'rates of use' for different metals should involve citizens, industry and policy makers. The debate must be informed by a clear understanding of the benefits and impacts of using metals and other materials to meet both the immediate and longer-term needs of society. By revisiting the *raison d'être* for metals with a focus on providing services in a sustainable economy, we can better articulate the roles of new technology, recycling and demand management in assisting our transition to a preferred future.

References

AMIRA, 2004. Copper Technology Roadmap. AMIRA International Ltd.

Ayres, R., Ayres, L., Råde, I., 2001. The life cycle of copper, its co-products and by-products. Mining Minerals Sustainable Development Project.

Azapagic, A., Clift, R., Perdan, S. (Eds.), 2004. Sustainable Development in Practice: Case Studies for Engineers and Scientists. John Wiley & Sons, Chichester.

Binswanger, M., 2001. Technological progress and sustainable development: what about the rebound effect? Ecological Economics 36 (1), 119–132.

Biswas, A., Davenport, W., 1994. Extractive Metallurgy of Copper. Elsevier, Oxford.

Bridge, G., 2004. Contested terrain: mining and the environment. Annual Review of Environment and Resources 29, 205–259.

CDP, 2006. Carbon disclosure project. Available from: http://www.cdproject.net/about.asp.

Cowell, S., Wehrmeyer, W., Argust, P., Robertson, J., 1999. Sustainability and the primary extraction industries: theories and practice. Resources policy 25 (4), 277–286.

Edelstein, D., 2001. Copper: Mineral Commodity Summary. US Geological Survey.

Gaines, L., 1980. Energy and material flows in the copper industry. W-31-109-Eng-38, Argonne National Laboratory, US Department of Energy, Illinios.

Giurco, D., 2005. Toward sustainable metal cycles: the case of copper. Ph.D. thesis, Department of Chemical Engineering, University of Sydney.

Giurco, D., Stewart, M., Petrie, J., 2001. Decision making to support sustainability in the copper industry: technology selection, 6th World Congress of Chemical Engineering, Melbourne.

Gordon, R., Graedel, T., Bertram, M., Fuse, K., Lifset, R., Rechberger, H., Spatari, S., 2003. The characterization of technological zinc cycles. Resources, Conservation and Recycling 39 (2), 107–135.

Graedel, T., Bertram, M., Kapur, A., Reck, B., Spatari, S., 2004. Multilevel cycle of anthropogenic copper. Environmental Science & Technology 38 (4), 1242–1252.

Henstock, M., 1996. The recycling of non-ferrous metals. The International Council of Metals and the Environment, Ottawa.

MMSD, 2002. Breaking New Ground: Mining Minerals and Sustainable Development Final Report.

OECD, 2001. Sustainable development: Critical issues. Organisation for Economic Co-operation and Development, Paris.

Petrie, J., 2007. New models of sustainability for the resources sector – a focus on minerals and metals. Transactions of the Institution of Chemical Engineers Part B 85 (B1), 88–98.

Petrie, J., Cohen, B., Stewart, M., 2006. Decision Support Frameworks and Metrics for Sustainable Development of Minerals and Metals. Clean Technologies and Environmental Policy 9 (2), 133–145.

PRè, 2000. Simapro LCA Software. Available from: www.pre.nl.

Reskin, E., White, A., Kauffman Johnson, J., Votta, T., 2000. Servicizing the chemical supply chain. Journal of Industrial Ecology 3 (2–3), 19–31.

Reuter, M.A., 1998. The simulation of industrial ecosystems. Minerals Engineering 11 (10), 891–918.

Stewart, M., Weidema, B., 2005. A consistent framework for assessing the impacts from resource use: a focus on resource functionality. International Journal of Life Cycle Assessment 10 (4), 240–247.

van Deventer, J.S.J., Lukey, G., 2003. Sustainability in the minerals industry: threat or opportunity. In: Lorenzen, L., Bradshaw, D., (Eds.), XXII International Mineral Processing Congress, Cape Town, pp. 23–41.

van Schaik, A., Reuter, M.A., 2004a. The time-varying factors influencing the recycling rate of products. Resources, Conservation and Recycling 40 (4), 301–328.

van Schaik, A., Reuter, M.A., Heiskanen, K., 2004b. The influence of particle size reduction and liberation on the recycling rate of end-of-life vehicles. Minerals Engineering 17 (2), 331–347.

Verhoef, E., Reuter, M.A., Dijkema, G., 2004. Process knowledge, system dynamics and metal ecology. Journal of Industrial Ecology 8 (1–2), 23–43.

Warhurst, A., Mitchell, P., 2000. Corporate social responsibility and the case of Summitville mine. Resources Policy 26 (2), 91–102.

Willard, B., 2005. The Next Sustainability Wave. New Society Publishers.

Wrisberg, N., Udo de Haes, H., Triebswetter, U., Eder, P., Clift, R. (Eds.), 2002. Analytical tools for environmental design and management in a systems perspective. Eco-efficiency in Industry and Science, vol. 10. Kluwer Academic, Dordrecht, The Netherlands.

Zeltner, C., Bader, H.-P., Scheidegger, R., Baccini, P., 1999. Sustainable metal management exemplified by copper in the USA. Regional Environmental Change 1 (1), 31–46.