

# Decision Making for Sustainability: The Case of Minerals Development in Australia

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It is the stated aim of the mining and minerals industry to support sustainable development. This is borne out by a review of current corporate policies and research initiatives. The challenge to the minerals industry is to recognise the value it represents to society as a whole, and to recast its activities accordingly. The focus of the industry needs to shift from resource extraction to “added-value” commodities provision. What this requires, in practice, is for the industry to develop mechanisms by which the trade off between environmental, social and techno-economic objectives can be explored systematically, ensuring transparency, defensibility and accountability for decisions taken. This paper describes a decision support framework (DSF) to guide the industry towards sustainable resource processing. The development of this DSF is based on a first order assessment of the environmental performance of the Australian minerals industry, supported by tools of Life Cycle Assessment and Multi Criteria Decision Analysis.

## INTRODUCTION

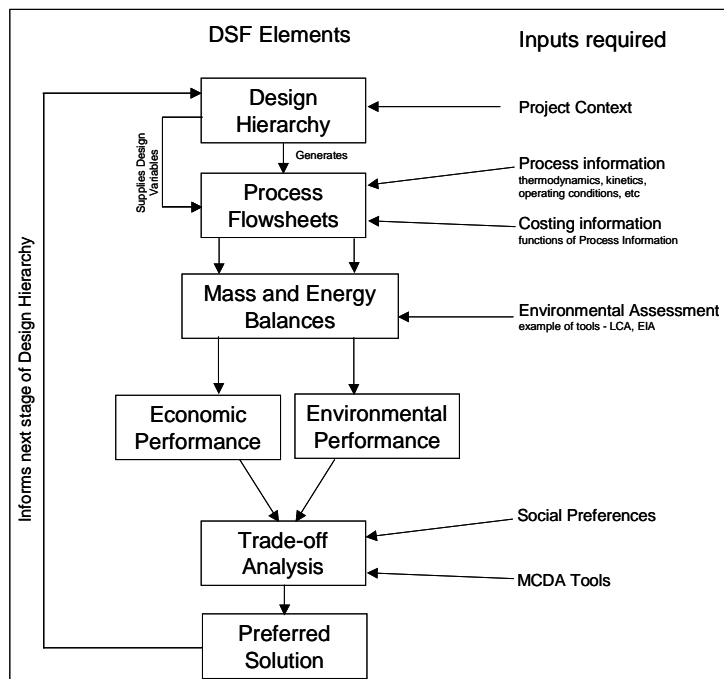
The mining and minerals processing industry requires assistance in decision making to support its drive to sustainable development. To this end, a decision support framework (DSF) has been developed, guided by the tenets of Sustainability. This paper describes this DSF and its various components, which include tools for the formulation of techno-economic, environmental and socio-political objectives, and other tools of Decision Analysis which assist in exploring requisite trade-offs between various objectives.

The DSF is based on detailed mass balance models of the Australian mining and minerals processing industry, reflecting the “status quo”. The methodology for developing these models, as superstructures, is described briefly. Though mass balance models have been developed for the entire industry, only the mass balance results obtained from the Australian copper industry are included here. These models have value in the context of the DSF as they provide a basis from which to explore various types of decision – from investment in new technologies, to improvements in existing process trains. The structure of the DSF facilitates comparison of options for continuous improvement. The techno-economic and environmental performance of the industry as a whole, as well as any particular sector of the industry, can be evaluated in this way. In this paper we offer some discussion on the methodology by which performance is assessed, considering all decision objectives, but, here, with a specific focus on environmental performance. A case study exploring the potential of the DSF to guide decision making around technology selection in the copper industry is included. This demonstrates both the value of the DSF, and highlights the use of the baseline assessment of the industry to inform decision making for Sustainability.

## DECISION SUPPORT FRAMEWORK

The decision support framework (DSF) presented here has been developed to assist the minerals industry in its transition to sustainable development. This DSF has been developed from the premise that the selection of “Clean Technologies” will support this shift to sustainability. Clift [1] defines Clean Technology as that which delivers goods and services valued by society while minimising the trade-offs accepted between techno-centric, enviro-centric and socio-centric concerns. To this end a consideration of environmental, social and economic effects is included in the DSF. The tools of multi-criteria decision making are used to determine and/or minimise the trade-offs between the different considerations (or objectives) within the DSF. The development of the DSF is discussed in [2, 3, 4, 5].

The structure of the DSF is illustrated in Figure 1. This figure demonstrates the way in which environmental, economic and social information sets are integrated into the overall analysis. It also shows that the framework is based on rigorous technical information for the industry. Figure 1 illustrates the DSF for design-level decision making. The reason for focussing on design is that it is the decisions taken during project selection and process design which define the environmental performance of a project to a great extent [6]. In this paper, the design process is viewed as an hierarchy of decisions through which flowsheets are developed with progressive articulation of detail, and reduced uncertainty. Further information on this evolutionary approach to design, based on the Douglas design hierarchy [7] is available in Stewart and Petrie [2].

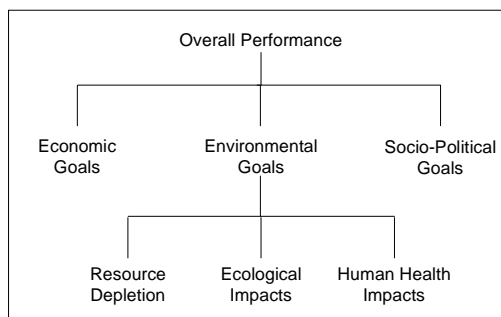


**Figure 1** Decision Support Framework for Process Design

A similar figure for decision making in the context of an operating process has also been developed by authors of this paper [3].

### SELECTION OF PREFERRED SOLUTION

The selection of process options to deliver outcomes consistent with a sustainable mining industry, requires simultaneous consideration of multiple objectives, each measured against acceptable performance criteria. The tools of multi-criteria decision analysis (MCDA) are employed here to facilitate the integration of multiple objectives within the DSF. As has already been stated, typical objectives include techno-economic, environmental, and socio-political considerations. An example of an objectives' hierarchy, reflecting the way in which different performance goals might be aggregated to provide an overall performance assessment, and within which only environmental objectives have been identified in any detail, is included in Figure 2.



**Figure 2** Example Objectives Hierarchy

The alternative which minimises the trade-offs between these different objectives which is acceptable to all stakeholders is the one which best supports the transition to sustainable development. However, it must be recognised that different value bases exist to inform this trade-off analysis, as evidenced by the fact that MCDA methods generally require some form of aggregation of performance measures, by use of a “weighting” protocol which reflect these value bases. Detail of different MCDA approaches, and valuation methods, can be found in Stewart [8] and Basson and Petrie [9]. The choice of particular method is informed by the decision context, the choice of criteria to articulate the objectives and level of information detail available.

### ARTICULATION OF ENVIRONMENTAL OBJECTIVES

Figure 2 provides the basis for the development of environmental objectives (note: the articulation of techno-economic objectives follows conventional process design approaches). The formulation of the environmental objective is based on an environmental profile of the industry, generated using the methodology of Life Cycle Assessment (LCA). LCA is attractive for a number of reasons:

- The boundary definition invoked in LCA ensures that all impacts associated with the extraction, production, use, recycling and disposal of a product/service are included.
- LCA is a form of environmental systems analysis, which facilitates its integration with chemical engineering design tools.
- LCA considers potential impacts only on a non site-specific basis, and thus has value at project selection and process design level where site-specific impact information is not available.

An example of environmental criteria developed using LCA methodology is included in Table 1, where units are normalised in terms of the functional unit of the study (e.g., per tonne of product).

**Table 1** Example of objectives hierarchy developed using LCA

Environmental Goal	Objectives	Performance Criteria	Units
Minimise Environmental Impact	Resource Depletion	Landfill Volume	m <sup>3</sup>
		Water Consumption	m <sup>3</sup>
	Ecological Impacts	Acidification	kg SO <sub>2</sub>
		Total Ecotoxicity	m <sup>3</sup>
		Greenhouse Emissions	kg CO <sub>2</sub>
	Human Health Impacts	Human Toxicity	kg/kg

However, the current state of development of LCA methodology limits its use for evaluation of mining and minerals processing operations. The two main deficiencies relate to its inability to:

- Consider the significant temporal and spatial effects which characterise resource extraction processes
- classify the impacts associated with products and wastes from minerals-based processes, including the fate and bio-availability of metals.

These shortcomings are, to some extent, being addressed in other work (see, for example [10,11]). However, LCA methodology does require further development if it is to reflect accurately the environmental performance of the mining and minerals processing industry [12].

### FIRST ORDER ASSESSMENT OF AUSTRALIAN MINING AND MINERALS PROCESSING

A generalised flowsheet for the Australian Minerals industry has been developed with a view to providing a base line assessment of the industry. This is included in Figure 3. This figure reflects a high level aggregation of all technologies in place in the Australian Minerals industry in the 1999 financial year. Models for each of the sub-sectors identified in this figure have also been prepared in more detail. These models can be used to provide mass and energy balance information from which the economic performance of the industry can be predicted, as per Figure 1. In order to demonstrate the degree of comprehensiveness which underpins the various sub-sections of this overall model, specific attention is given below to models developed for mining and minerals processing – as opposed to manufacture of final products.

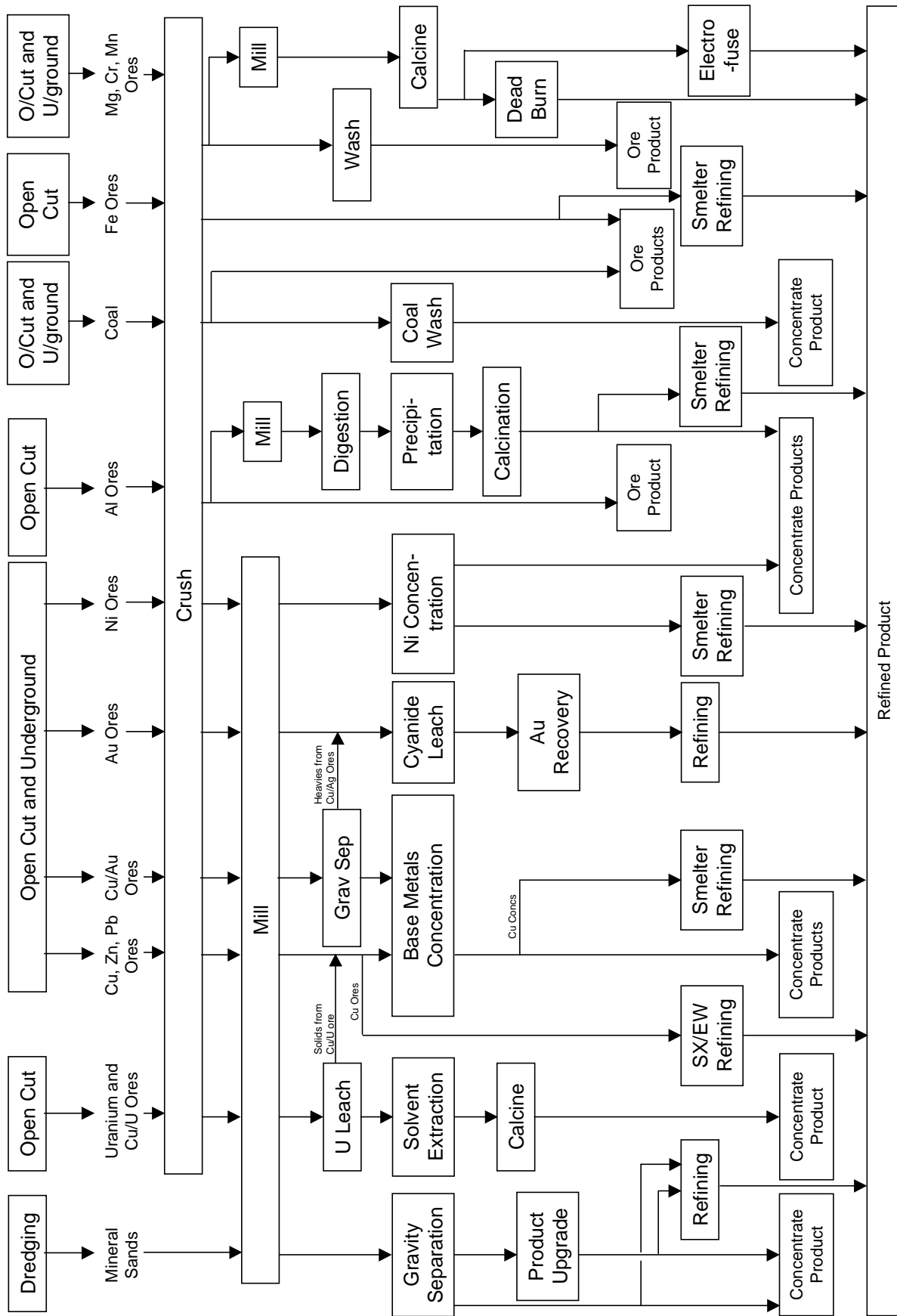


Figure 3 Overall Flowsheet for Australian Mining and Minerals Processing Industry

### Mining

Mining activities have, to date, been given scant attention by researchers involved in LCA or the development of other environmental impact assessment tools (beyond the obvious examples of EIA studies for specific mining projects in dedicated locations). This is, in part, a consequence of the difficulties already mentioned, but is also a consequence of the lack of awareness of the complexity of mining in its own right. The approach taken here is an holistic one, within which all mining stages, from initial exploration and mapping of a potential ore body, through site development and actual mining, to closure, and consideration of post-closure effects, are considered in a dynamic manner. A diagram of the process assessed for mining is included in Figure 4. The typical investigative boundary around the mine is shown to indicate how limiting such a view of the overall process really is. Within this framework, it is possible to observe the performance of the industry as a whole, or to reflect the performance of a single mine.

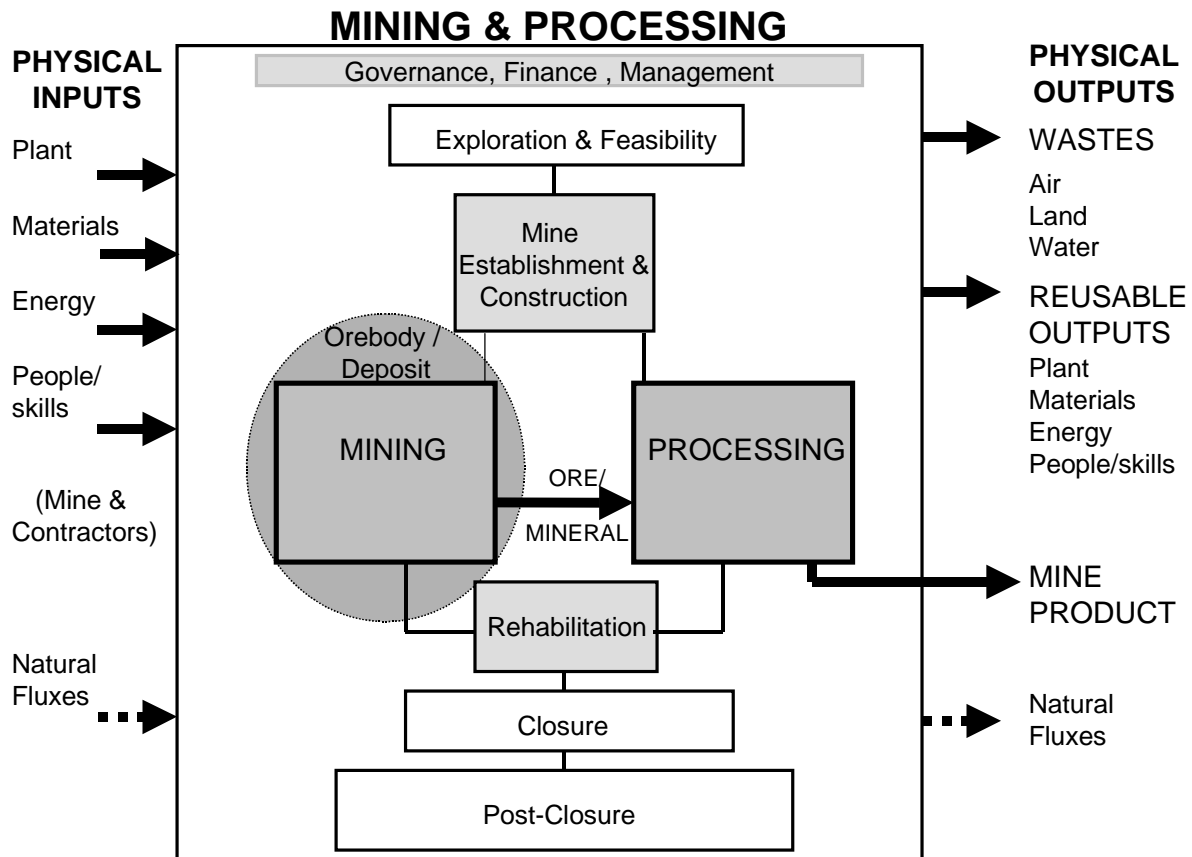


Figure 4 Diagram of the Mining Process

### Minerals Processing and Refining

Figure 5 exemplifies the level of detail typically available within the sub-system models of Figure 3. Though examining gold technologies only, this figure is indicative of the degree of specificity incorporated in the overall models. As a starting point, in order to produce a "base line assessment", the performance of each unit process is informed by a mass-weighted average of process plant performance in Australia (according to 1999 production statistics). Stream flows between unit processes are representative of mass flows through the industry. For further details on the modelling approach adopted see the work of Stewart and Petrie [12]. The baseline environmental performance for the industry as a whole has been determined using these mass balance calculations for the industry. These mass balances provide Life Cycle Inventories which can be mapped onto a set of Life Cycle Impact indicators, such as those included in Table 1. In the following section, we explore the use of these inventories in informing decisions using the DSF included in Figure 1, for the specific case of the technology selection in Australian copper industry.

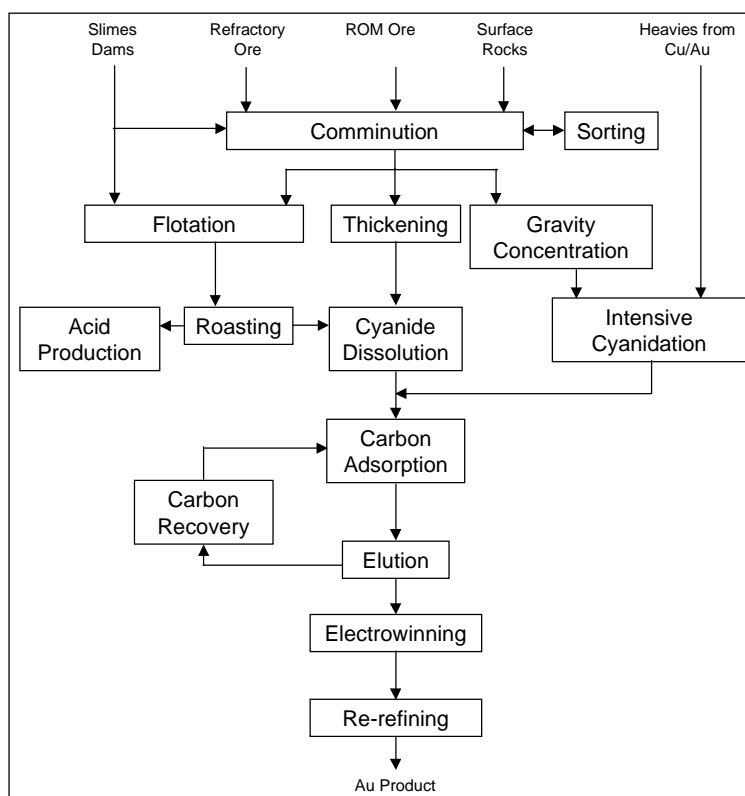


Figure 5 Generalised Flow Diagram for the Australian Gold Industry

### BASELINE PERFORMANCE OF THE AUSTRALIAN COPPER INDUSTRY

An hypothetical technology screening exercise for copper refinery technology selection (for a copper sulphide deposit) is explored in this section. Copper producers in Australia exploit two main types of deposits, those being base metals complexes, and copper/gold deposits. The majority of these ores are sulphides. In 1999, Australia produced 735 000 tonnes of copper. Of this figure, 417 000 tonnes was as refined copper, and the balance (318 000 tonnes) was as a “metal-in-concentrate”. Copper refining in Australia uses two different technologies; heap leach with associated solvent extraction and electrowinning of the copper from the leach solution; and flash smelting, which utilises the exothermic reaction of copper sulphides’ oxidation to smelt the ore. The generalised flow diagram for the Australian copper industry is shown in Figure 6. Referring to Figure 3 it can be seen that the added complexity of copper concentrates obtained from the Uranium/Copper industry has not been included explicitly in this figure (this requires that milled ores report to Uranium leaching before being directed to flotation). However, they have been accounted for in the inventory calculated for the industry.

Table 2 provides detail of the Life Cycle Impact Assessment categories developed in this exercise. These figures can be used to guide decisions taken to move the industry towards a more sustainable operating point.

Table 2 Impacts Associated with the Australian Copper Industry

Impact Category	Units	Total Contribution
Landfill Volume	m <sup>3</sup>	90 000 000
Water Consumption	m <sup>3</sup>	41 000 000
Acidification	kg SO <sub>2</sub>	75 000 000
Total-Ecotoxicity	m <sup>3</sup>	50 000 000
Greenhouse Emissions	kg CO <sub>2</sub>	6 000 000 000
Human Toxicity	kg/kg	37 000 000

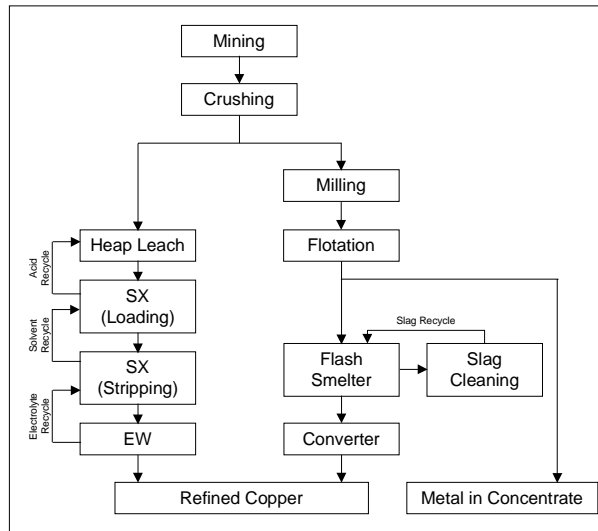


Figure 6 Australian Copper Industry Technologies in place 1999

### TECHNOLOGY SELECTION FOR THE AUSTRALIAN COPPER INDUSTRY

To demonstrate the use of the DSF model proposed in Figure 1, consider the illustrative case study below. Here, an hypothetical copper sulphide refractory ore body, with a grade of 0.5%, is available for processing. Technologically feasible options for processing such an ore body are included in Figure 7. Note: These are not necessarily those technologies which are most often used in the refining of such an ore body, but rather they are those technologies which are technologically feasible. A mine life of 20 years was assumed.

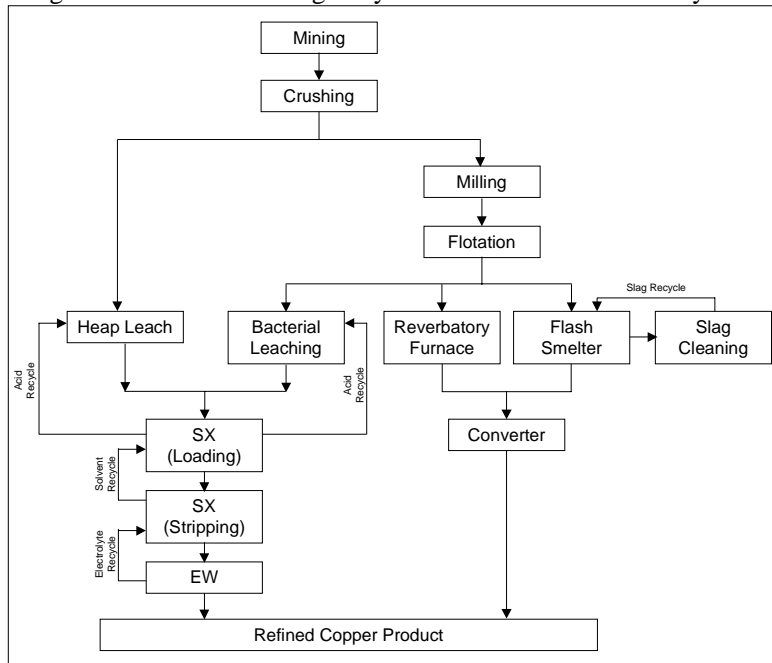


Figure 7 Technology Options for Refining Copper Sulphides

Essentially, there are four discrete process routes within this figure. They will be referred to as Bioleaching SX/EW, Heap Leach SX/EW, Flash Smelting and Reverberatory Smelting. These terms refer to the defining unit processes within each model. The value in developing flowsheets in this manner is that unit processes which are duplicated between different technology options (e.g., the converter), are modelled once only.

This hypothetical decision can be thought of as a technology “screening” exercise, in which the performance of the four options is developed according to environmental as well as techno-economic criteria. The information required at this stage is not very detailed, as the intention is simply to determine the technologies which are to be taken forward to more detailed process design, but with due regard being

paid to environmental performance “up front”. The environmental performance was informed by the LCA impact categories listed in Table 1, whilst the economic performance criteria used were capital and operating costs for the different options. These values are recorded in Table 3. All values are quoted per tonne of product from each process. This ensures that process efficiencies for each process route are accounted for in the final decision. Whilst there is significant uncertainty associated with these performance values, they are required for this screening exercise only to be indicative of average performance, not an accurate reflection of the actual performance of each technology. The propagation of uncertainty (both model and parametric uncertainty) through decision support frameworks, together with the evaluation of preferred alternatives within the context of these uncertainties, is being investigated within the authors’ research group [14, 15], and by others [16]. Our own results to date suggest that it is possible to both trace, and interpret, uncertainties within the DSF.

**Table 3** Performance of Copper Refining Technologies in different performance criteria

Performance Criteria	Units	Heap Leach SX/EW	Bioleach SX/EW	Flash Smelting	Reverberatory Smelting
Landfill Volume	m <sup>3</sup> /ton	140	130	230	230
Water Consumption	m <sup>3</sup> /ton	30	90	120	100
Acidification	kg SO <sub>2</sub> /ton	90	150	200	2 500
Total-Ecotoxicity	m <sup>3</sup> /ton	83	95	130	280
Greenhouse Emissions	kg CO <sub>2</sub> /ton	20 000	22 000	14 000	15 000
Human Toxicity	kg/kg /ton	100	100	86	110
Capital Cost	\$/ton	11 000	13 000	22 000	24 000
Operating Cost	\$/ton	170	300	230	230

From Table 3, the combination of Heap leach, SX/EW performs best with respect to water consumption, but not as well with respect to global warming potential (this is a function of the electricity used in the electrowinning of copper). MCDA tools are used to identify which technologies perform better than others with respect to the entire suite of criteria under consideration. The MCDA tool used here is a simple formulation of a *value function*. The aim of multi-attribute value function theory is to find a single mathematical value function, or index, that is the sum of the scores for each option in each of the given assessment criteria [17]. The overall value assigned to a given design alternative is then (in its most simple form) the additive weighted sum of the "scores" which the option achieves in each of the assessment criteria. These criteria can reflect any of the economic, environmental and social objectives or goals to be met by the preferred alternative. The overall value of an alternative (V(b<sub>i</sub>)) can be calculated using a simple additive weighting relationship as below:

$$V(b_i) = \sum_{r=1}^q w_r \cdot v_r(b_i) \quad \text{Equation 1}$$

where  $v_r(b_i)$  is the value of alternative  $b_i$  in criterion  $r$  (see Table 3) for a total of  $q$  criteria (illustrated in Figure 8)  
 $w_r$  is an indication of stakeholder preference for criterion  $r$

In order to render it possible for weightings in the value function equation to reflect the preferences of stakeholders, the scores of each technology in each criterion have been normalised with respect to the average sectoral performance as listed in Table 2. In so doing the significant orders of magnitude between the different criteria are reduced. In other words, a weighting of two on water consumption relative to a weighting of one on landfill volume can be interpreted as water consumption being twice as important as landfill volume. This highlights the importance of the baseline assessment conducted for the Australian minerals industry. The derivation of weights, or, as they are correctly interpreted in Value Function analysis, “scaling constants”, is the subject of considerable theoretical development [17,18]. A useful summary is given by Basson and Petrie [9]. Suffice it to say at this stage that weightings are meaningless if they are not associated with the range of performance scores for options in the set of criteria. A linear value function has been used here to demonstrate the approach. The formulation of a linear value function is illustrated for Water Consumption in Figure 8, where the “preferred” scoring position is the smallest possible value. The same holds true for the economic criterion where the best outcome will be to minimise the cost associated

with the preferred alternative. In order to eliminate residual order of magnitude differences, the value functions have been scaled to lie between “zero” and “one”, with “zero” representing best performance and “one” representing worst performance. Thus the alternative,  $b_i$ , which scores the lowest value of  $V(b_i)$  (from Equation 1) is the alternative which performs best across the suite of criteria.

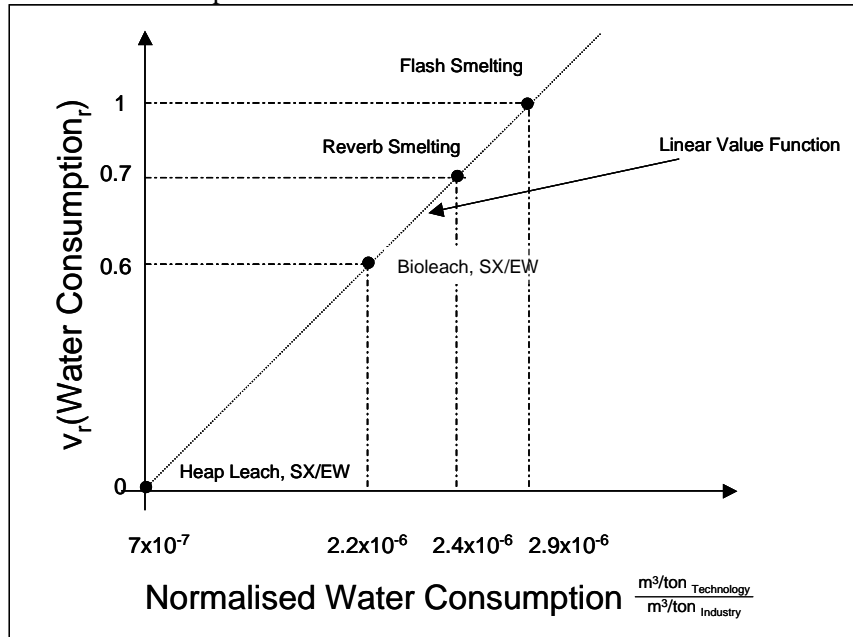


Figure 8 Example of Linear Value Function

Two different “weighting” regimes are explored in Table 4 below. In the first column, all criteria are assigned an equal level of importance, whereas the second column suggests a situation in which the aggregated environmental criteria are assigned an equal weighting to the aggregated economic performance criteria. In reality, the exact weighting distribution would be elicited by active participation of all stakeholders to the decision outcome.

Table 4 Performance of the Copper Refining Technologies

Technology	Equivalent Weighting	Sum of Environment equivalent to Sum of Economics
Heap Leach SX/EW	1.4	0.2
Bioleach SX/EW	3.5	0.9
Flash Smelting	3.6	1.0
Reverberatory Smelting	6.4	1.5

These results show that, when technologies are compared within the context of the environmental and economic objectives, the combination of Heap Leach, SX/EW performs best across the suite of objectives. Bioleaching and Flash smelting are difficult to differentiate at this level of detail, and Reverberatory furnaces perform relatively poorly. This pre-screening exercise would suggest that the performance of the Reverberatory smelter is too poor for this technology to be considered further, while the others are worthy of being carried forward to more detailed levels of design decision making.

## CONCLUSIONS

This paper has presented a Decision Support Framework for decision making in the mining and minerals processing industries. Its key objective is to promote decisions which are consistent with a path towards sustainable development. The DSF is based on a particular approach to flowsheet development and process modelling, incorporating key features of minerals processing projects, and supported by a generalised mass balance for the Australian mining and minerals processing industry. This mass balance forms the basis of environmental inventories evaluated for the Australian industry. The use of the DSF together with the inventory information is illustrated through a case study on technology selection for producing refined copper.

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