METALLIC RAW MATERIAL FLOWS – IMPACT ASSESSMENT

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Many potential environmental impacts considered in LCA and raw material flow studies vary considerably depending on the affected environment on both local and regional scales. Particularly metals being generally associated with large concentration processes at single sites, are covered insufficiently in generic inventories impact assessments. Thus an environmental information system (EIS) has been developed based on a geographic information system to analyse and quantify distinct environmental properties in the vicinity of any producing site considered.

The EIS was developed in the framework of a collaborative research programme aiming at the resource orientated analysis of metallic raw material flows. Firstly aluminium was taken as case study. The spatial database covers all present production sites of bauxite extraction, alumina refining and aluminium smelting. Environmental data for each location were derived from global digital survey data covering land cover, soils, morphology, climate, topography and population density.

The main application of this database is the characterisation of environmental safeguard objects which may be affected by the activity of concern. In combination with the technical inventory, it is possible to estimate site-specific in- and outputs such as land use, water consumption or emissions. Land use is weighted by the amount of dry substance not accumulated due to the activity. Water consumption is weighted with a site specific scarcity factor whereas emissions of acidifying substances are weighted by critical loads exceedance ratios.

The weighted impact scores can be interpreted on any desired aggregation level ranging from sites to technologies to countries or even global average values. Specific short term challenges can be inferred from scenarios. These weighting factors were developed for specific patterns of the primary aluminium production. Present research efforts focus on copper specific aspects.

THE ENVIRONMENTAL IMPACT OF PRODUCING NON-RENEWABLE RESOURCES: THE CASE FOR MINING WASTES

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Society is increasingly mindful of the environmental impacts of industrial activities, particularly those related to producing natural resources, mining, oil and forestry. In the effort to better evaluate these impacts, a number of methodologies are proposed. They generally use the amount of material used or disturbed as an indicator of impact.

These materials based environmental concepts or indicators include Material Flow Analysis (MFA), rucksack, Factor 4, Factor 10 and many others.

The objective of this paper is to evaluate in what manner and to what extent material based environmental concepts and measures reflect the specific ecosystems interactions and impacts of the production of the different resources streams, particularly for minerals.

The most active ecosystems are generally found at the interface between air, land and water. In the early stages, mineral production takes place at this interface, at the surface of the earth. Soon however, the bulk of the production activity will move to depth or inside mountains where the interaction with ecosystems is generally not as direct. As well, the impact on ecosystems of the placement of material may not be well correlated with the amount of material moved due to stacking and other practices. Finally, most national jurisdictions have now established strict remediation requirements for mining activities. How can the impact of remediation be factored when using measurements based on the amount of material moved?

THE ROLE OF TIME DEPENDENT ANALYSIS TO IMPROVE ENVIRONMENTAL MANAGEMENT SYSTEM IN MINE CLOSURE PLAN IN OPEN PIT MINE

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In the last two decades, Mining Industry has been ever exposed to environmental concern requiring all companies to adhere to a more stringent material and spiritual compliance in its operation. In another words, it is no longer enough for companies to comply with written regulation only. This environmental concern also applies to Indonesia, as Indonesia is known as one of the richest mineral deposits region in the world. This growing concern has forced the Government of Indonesia, to make best mining practice policy including regulation of Mine Closure Plan.

One of the important points in the Mine Closure Plan is how to ensure physical features such as embankments, pits, excavated slopes, and overburden dumps as well as tailing dam in open pit mines remain stable upon the mine closure. In fact, weathering process in Indonesia has been one of the most determining geomechanical factors influencing the stability of the above-mentioned physical features. The geomechanical factor that is considered essential but has not been included in stability analysis of the physical features is creep phenomenon or time dependent analysis.

Apart from the administrative and formal procedure, long-term stability of the physical features need to be understood, particularly from the geomechanical point of view. This paper therefore outlines the role of time dependent analysis parameters to improve environmental management system in open pit mine closure plan.

HOW FAR SHOULD WE IMPROVE IMPACT ASSESSMENT METHODOLOGY FOR METAL MINING? ILLUSTRATED WITH A BIODIVERSITY LCIA METHOD

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Presently, LCA is felt to address issues related to mining processes only poorly (see the MMSD workshop in New York on the application of LCA to Mining, Minerals and Metals, august 2001). Some impact categories are inadequately addressed, there seems to be ambiguity related to value-based aggregation of information, there is concern about the lack of metal-specific information, and site-specific impacts can not be addressed. On the other hand, LCA could support (product) system environmental improvements through prospective decision making, enhancement of the quality of metals supply chain management, and addressing issue on future markets and consumption patterns. It seems that the pro's of LCA do not come without the cons. The benefits of LCA relate to its ability to condense information in a consistent manner to a level where it can be consumed by decision makers, but for players in specific parts of the life cycle this information condensation can be perceived as information loss. Information aggregation is inevitable for LCA, but should be based on as much specific information as is available.

This principle is illustrated with the development of a new land use impact assessment method. This TNO land use impact assessment method includes methodological proposals from Switzerland, Denmark, the Netherlands and the SETAC WIA subgroup on Resources & Land use. It includes (1) a distinction between occupation and transformation, (2) the impacts of renaturation processes after extractions, (3) biodiversity indicators consisting of ecosystem- and species level factors, (4) an average and a maximum reference state to obtain relative biodiversity scores related to different value systems, and (5) biomass indicators as a proxy for impacts on the life support system. Inventory data have been gathered for various extraction processes including aluminium, aggregates and wood, average industrial processes, roads and railways, housing and waste disposal. The method allows the use of regionally differentiated land use data by giving the land use type and a country code. Even a design has been made how to include desiccation impacts with the same biodiversity indicator.

Thus, the method attempts to include as much methodological issues and specific information as is available, but to remain within the scope of LCA. Limitations due to the rough spatial detail, data gaps and attribution and interpretation issues will illustrate where we should seek a balance in the above dilemma on information aggregation. This might give insight in where to improve further on the quality and use of LCA.

NATURAL RESOURCE DEPLETION INDEX

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Impact assessment associated with the inputs to a product system in the Life Cycle Assessment (LCA) process, is not as well understood as for the assessment of system outputs. In particular, there is still ongoing debate concerning the significance and measurement of mineral resource depletion independent of fossil fuels. Some practitioners argue for exclusion implying that there is such an abundant supply that depletion has a negligible effect on LCA results and that extraction rates for specific elements will be ultimately regulated by economics, metal recycling and material substitution. On the other hand, there are compelling arguments to include resource depletion in LCA studies. Resource reserves are considered an important component of a nation's wealth and are normally reported in annual mining industry summaries. Policies encourage the careful use of resources, and developments in (metal) recycling technology not only reduce material flow to waste disposal facilities, but also minimize resource extraction rates. Standard LCA methodology still calls for the inventory and impact assessment of product system inputs, and LCA's would be considered incomplete without addressing depletion. Resource availability also lies at the heart of the sustainability issue. Therefore, it seems important to include the treatment of mineral depletion in the context of Life Cycle Impact Assessment (LCIA) and develop an acceptable measurement index.

Several approaches to the resource depletion issue have been proposed. The **use-to-stock ratio** relates the depletion index or characterization factor to annual extraction (use) rates and a reserve base. The **exergy method** is another way to characterize mineral depletion wherein the consumption in the amount of exergy to transform an ore into a usable material can be a measure of damage. In the **sustainable process method**, it is argued that a reduction in resources can be represented by the environmental interventions of a sustainable, theoretical extraction process, where current resources are treated as untouched, and the metal quantities extracted are assessed on the basis of theoretical emissions from the treatment of common rock (average earth crust). A **virtual impact method** has also been proposed which relates additional "virtual" interventions, associated with the surplus energy required to treat ores in the future with reduced mineral concentration, with current extraction.

A number of complexities are associated with each method, and the establishment of a universal baseline index to express natural resource depletion for minerals remains a challenge. Issues discussed are the characterization of resource reserves, the impacts of material substitution and metal recycling, and the use of intricate models to support certain methods.

NATURAL RESOURCES DEPLETION INDEX

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INTRODUCTION

There is still room for discussion about the significance and the need for a measure of natural resource depletion or long-term availability in LCIA studies. Natural resources for the purposes of this discussion refer to naturally occurring minerals which are extracted or transferred into the possession of humans as an input to a process or function in the economy independent of fossil fuels. Mineral sources would include the earth's crust as well as the metallic values contained in water. A measurement index or weighting factor should ideally focus on metal scarcity, depletion rate, reduction in the amount of usable material or availability, but could also be equated with other environmental interventions such as land alienation, energy use, human toxicity or ecotoxicity if resource depletion analysis was simplified.

Some argue that resource depletion is not a clear physical entity and should not be considered a damage to nature. Others consider exclusion from LCA studies since there are still growing reserves and the abundance of existing sources in the earth's crust and water bodies is so massive that availability for future generations is not a serious issue. Furthermore, recycling, substitution and technological advances could more than compensate for the scarcity of any particular mineral and thus metals might be considered infinitely finite. It can also be argued that restrictions on the availability of fossil fuel resources is such a dominant sustainability factor that the supply of mineral values is a non-issue.

On the other hand, there are compelling arguments to include resource depletion in LCA projects. Standard LCA methodology calls for the inventory and impact assessment of product system inputs and studies would not be considered complete without addressing depletion. Resource reserves are considered an important component of a nation's wealth and are normally reported in annual mining industry summaries. Government and industry policies encourage the careful use of resources and metal availability is a major concern of the public. Emphasis on increased recycling efforts is not only promoted to reduce material flow to waste disposal facilities but also to minimize resource extraction rates. Mineral extraction is a major and very visible industrial activity and there is a sense that there will be ultimate limits to viable sources in the future. Thus, it seems important to include the treatment of mineral depletion in the context of LCIA assuming an acceptable measurement index or weighting factor can be developed even if they might equate to zero impact on LCIA results.

Guidelines for the development of an index come from the recommendations in ISO standards. The impact categories, category indicators, and characterisation models should be based on an international agreement or approved by a competent international body. The value choices and assumptions made during their selection should be minimal and the characterisation model for each category indicator should be scientifically and technically valid, based on a distinct identifiable environmental mechanism and/or reproducible empirical observation, and be environmentally relevant.

SUMMARY OF EXISTING PROPOSALS

Several approaches to the resource depletion issue have been proposed and reported in the literature. Brief summaries follow.

STOCK-USE RATIO METHODS

Indicator weighting factors are based on measures of world production (U) and/or reserve base (D)

a) inverse of reserve base

The indicator is expressed as a fraction of reserves and the weighting factor is given as 1/D. This method addresses the depletion of reserves and the size of the reserves but does not address the period the resource will be available or the rate of depletion.

b) inverse of remaining years of use (defined as the reserves divided by world production)

The weighting factor is the inverse of the remaining years of use (U/D). It represents the number of years for which current reserves will suffice at the present extraction level but does not correctly account for the size of different reserves.

c) inverse of remaining years of use and reserve size

The factor is expressed by the inverse of the product of reserve base and remaining years of use (D*D/U) or U/D^2. The method addresses both problems mentioned in a) and b). (This approach was used in the Ni industry LCIA, see below)

Besides the problems noted with these approaches in a) and b), a well recognized difficulty with all of the methods lies with the uncertainty of values selected for the reserve base of mineral resources. Resources can be classified according to geologic or physical/chemical parameters, (grade, tonnage, thickness, and depth) or by a profitability analysis based on the costs of extraction and marketing resultant products. Consequently, different types of reserves have been defined which can lead to a large variations in values selected for reserves. In the limit, reserve base (D) could be equated to the crustal abundance of a particular metal in which case the result would be that current world-wide extractions for most minerals could be supported for millions of years and there would be no need to develop an LCIA method to treat them.

Additionally, the methods given above (as well as the methods to be discussed below) do not consider the importance of substitution and recycling which can have a strong influence on mineral resource depletion rates.

EXERGY CONSUMPTION METHOD

The exergy method is another way to characterize mineral depletion wherein the consumption in the amount of exergy to transform an ore into a usable material can be regarded as a measure of damage. The total chemical exergy calculated for an ore (in MJ per kg of pure ore) is simply taken as the sum of the chemical exergies of the various minerals contained in the ore. The reduction in this amount of exergy when the ore is transformed into a usable product would then be a characterization weighting factor for the extraction of a particular metallic element.

A problem with this approach is that most of the exergy in many ores is often concentrated in components that are not used or discarded. This will result in a gross overstatement of exergy loss to the product metal and a false calculation of weighting factor. Allocation of the exergy loss of the specific mineral to the corresponding metal product would result in a very low exergy loss relative to the exergy of the fuel used for mining, extraction and smelting, thus , the mineral contribution to a weighting factor would be negligible.

The method also refers to the production of a metal followed by dissipation after use and consequently does not consider the importance of recycling.

SUSTAINABLE PROCESS METHOD

In the sustainable process method, it is argued that a reduction in resources can be represented by the environmental interventions of a sustainable, theoretical extraction process, where current resources are treated as untouched and the mineral quantities extracted are weighted on the basis of calculated, theoretical emissions from the treatment of common rock. It basically assumes that ultimately mankind must extract minerals from average earth crust material and resource depletion is weighted on the basis of the comparatively large theoretical emissions of a sustainable process alternative exploiting the almost unlimited availability of common rock for materials.

This method weights present day extraction with the energy requirements that would be needed in the far future using current technology giving no indication when this need might occur which could be in the millions of years. It can be considered an extreme case since ores of average earth crust will never be used for actual mining. Again, metal use is considered dissipative and no account is made for substitution or recycling.

VIRTUAL IMPACT METHOD

A virtual impact method has been proposed which equates the additional environmental interventions to the surplus energy required to treat ores in the future having reduced mineral concentration as a result of the current mining of higher grade ores. Present mining practice represents the real situation whereas the future mining of lower grade ores represents the virtual situation. The current extraction of higher quality resources can therefore be charged with the surplus energy required for the future extraction of lower grade ores. Models are available for calculating surplus energy requirements for processing ores with decreasing metal content and coupled with geostatistical models for predicting future ores grades can produce figures for expected energy use for metal mined at a future time. Thus, the scarcity of currently used high grade ores can be reflected in LCIA studies by weighting the ore quantity actually used in the present LCI by the ratio of surplus energy to current energy use.

It is interesting to note that by using a simplified approach, and if the world reserve base index (current yearly extraction divided by the reserve base, U/D), is considered greater than 100 years, it was reasonable to assume that the availability of currently used ore grades is so good that the average grade mined would essentially remain constant for many hundreds of years. Therefore, the corresponding surplus energy for future mining would be negligible and the current weighting factor would approximate unity. This situation has been reported to apply for the most important minerals suggesting that the scarcity should not play a significant role in LCIA studies.

The difficulty with the virtual impact approach is that three complex models are required to estimate; future ore grades, the surplus energy to mine these grades and the virtual interventions associated with the surplus energy to be attributed to current extraction. Once again, dissipative metal use is considered and no account is made for substitution or recycling.

NICKEL INDUSTRY COMMENTARY

The natural resources depletion index was calculated in the recent Ni LCI study using the stock-use ratio method c) given above. It was done to establish a baseline index using methodology reported in other LCA studies. It must be noted however that the Ni industry does not support the use of this index as related to Ni and other recyclable metals nor does it support any other current methodology. It is argued that Ni and other metals can be extracted from the earth’s crust and used in a variety of applications including some dissipative uses. However, Ni and other metals cannot be destroyed and in this context, it is not appropriate to refer to metals as being depleted. Rather, a concentration in nature (ore deposit) is depleted and a concentration is established in society. Thus, the natural resources depletion index is somewhat misleading when applied to Ni and other metals. The index can only reflect a level of what remains to be mined under conditions of varying and complex geological and economic assumptions. It does not give insight into the amount of Ni and other metals that can be “surface mined” by future generations from the large and growing inventory in society. A major challenge for the metals industry is to increase the efficiency of process technology and enhance metal reuse and recycling in the context of sustainable development.

CONCLUSIONS

There are a number of complex issues associated with each method used to describe resource availability or depletion and the establishment of a universal baseline index to express resource depletion remains a challenge. Current model and data uncertainties are very difficult to assess in detail. Indeed, the very value and use of a depletion index warrants further discussion. How to deal with substitution and recycling adds further complexities to an already complex problem. More effort and dialogue are required to development methodology consistent with ISO standards and acceptance by the LCA community.. It is hoped that advances can be made at the International Workshop on Life Cycle Assessment and Metals (April 2002).

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April 08, 2002

Salinity and Metals' Impacts of Solid Waste Management Practice in Mining and Minerals Processing

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The environmental impacts of solid waste management in mining and minerals processing is due to the leaching of salts and metals, and their subsequent migration into the environment. The resultant elevated environmental concentrations of metals and salts may lead to eco-toxicity and human toxicity effects due to contamination of surface and ground water. Formative Life Cycle Impact Assessment methodology considered only the volume or mass of waste generated as a proxy indicator. Current methodologies include more realistic indicators, using multi-media fate and transport models to evaluate the deportment of waste constituents to various environmental compartments. Toxicological information is then used to relate environmental concentrations to effects. However, drawbacks to these approaches still abound. These relate to loss of spatial and temporal information, and the poorness of the method to reflect metals behaviour in the environment due to a lack of thermodynamic information on speciation and mobility.

In this work we retain a focus on improved characterisation of environmental exposure of salts and metals released from solid waste impoundments. A waste deposit is viewed as an integral step in the technology train, which provides a direct linkage between waste characteristics and upstream technology or process performance. This is of immediate value in prospective LCA studies. Leachate generation is modelled dynamically, accounting for all biophysical sub-processes, including speciation. The time-dependent concentration profile of mobile constituents at the interface between the deposit and the surrounding environment is linked to plume dispersion modelling tools to determine the fate and transport of leached components, predominantly salts, into groundwater. Metals mobility in groundwater is examined in conjunction with salts mobility, accounting for processes such as competitive adsorption in soils. In this way, it is possible to predict time dependent concentration isopleths for species of interest. With some *apriori* knowledge of what constitutes acceptable risk to the environment (based on proxy metrics such as water quality standards) it is possible to derive a measure of the land mass impacted by pollution plumes emanating from a waste deposit. This time-dependent 'impacted land mass" footprint has value as a mid-point indicator for LCIA studies. This methodology is demonstrated for wastes from the ferro-alloy and coal based power generation industries, both of which are relevant to many product LCAs. It is hoped that this work can be extended to produce characterisation factors for common metals species released from solid waste impoundments for specific industry sub sectors.

INVENTORY AND IMPACT ASSESSMENT UNCERTAINTY IN COAL-BASED POWER GENERATION

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This paper presents a detailed life cycle inventory and impact assessment profile for coal based power generation in South Africa. These profiles are supported by rigorous process models for the range of technologies in place within the industry, and can therefore be used to support both “attributional” and “consequential” decision making within the industry. Both types of decision context are demonstrated.

A framework has been developed to include all relevant sources of uncertainty in these LCA models explicitly, where empirical parameter uncertainty, model parameter uncertainty and model form are investigated in a looped fashion, using a combination of probabilistic and sensitivity analysis tools. Rank order correlation analysis is used to focus the analysis on those parameters with high uncertainty importance (which is a function of the decision context in which the LCA information is to be used). Principal components analysis (PCA) is used to provide an enhanced interpretation of the very large information sets resulting from the incorporation of uncertainty analysis at both inventory and impact assessment stages of LCA.

It is apparent that there are many decision making situations within the industry where the increased uncertainty in moving from inventory to impact assessment obscures the decision. In these situations, it remains possible to make informed decisions using inventory data alone. This is demonstrated for a specific case of technology choice for combustion of discard coal.

MINERALS RESOURCES AND DEPLETION

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While future mineral scarcity has all but disappeared as an issue among specialists in the field of mineral economics, it remains an important touchstone among environmental and population activists, as well as those concerned with the inequality between industrialized and developing countries. Many minerals are simply abundant, including those of greatest economic importance. Other mineral commodities can be classified as abundant, not because of their geologic reality, but because they can be manufactured. Of course, many commodities are more geologically limited, but even in these cases production continues to increase, and while depletion would be a serious blow, given current technology, it will not come any time soon. Geologic reality is not the only residence of mineral commodities. Materials exist for potential use throughout the anthroposphere. The most obvious supply is embodied in infrastructure, durable goods, and other stock-in-use, but minerals also exist in overburden and tailings from extraction, emissions (especially to land and water) from processing and use, and middens of final deposition.

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METALS USE IN RELATION TO AGGREGATE MATERIAL FLOWS AND SUSTAINABLE DEVELOPMENT

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This paper examines all the material flows used for physical goods in the US for the entire twentieth century, and compares these flows with both population and economic growth. Metals from both primary and secondary resources are then the compared with other materials that compete in many similar markets.

For the more recent, twenty-five year, past the processed flows of all material used for food, energy, and physical goods in the US are considered. Included with the processed flows is an examination of the hidden flows generated during their extraction and processing. The processed and hidden flows for a variety of metals are then examined separately. Next, the trends in the global use of specific metals are examined. The per capita relationship of overall global use to that in the US is also addressed.

Sustainability is considered by examining the trends in recycling for various metals, both in the US and globally. The ultimate fate of a number of metals is examined as an indicator of environmental impacts along with emissions associated with the recovery of metals from primary resources. Finally, based on recent work with the World Resources Institute, the aggregate material flows associated with mature industrial economies are briefly discussed as they relate to long-term sustainability.

EXTRACTION OF METALS FROM BEDROCK

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As a basis for finding characterization and weighting methods for metal ore flows in LCA, a study was made to investigate the extraction of metals from bedrock. The main goal of the study was to determine cost relevant parameters for using bedrock to create a concentrate similar to ores that are mined today. The cost for producing such concentrates would tell us something about the value of present ores to future generations. The efficiency of various sustainable or near sustainable extraction processes and their need for chemicals and energy is to a high degree determining this cost.

Leaching experiments were made with different strong acids on ground granite, granodiorite and basalt. Hydrogen chloride was found to be most efficient and extraction rates were determined for several metals of interest. These varied from a few % to almost 100%. It was concluded that extraction of metals from bedrock is from a technical standpoint possible and may in the future also be economical, in particular when it is combined with a high degree of metal recycling in the society. Therefore, the resource consumption of these types of extraction processes is of interest to use in characterization and weighting methods in LCA.

SUSTAINABLE DEVELOPMENT IN THE MINING INDUSTRY

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Sustainable development has become a driving force in how the mining industry approaches all existing and future activities. Progress has been made to advance environmental performance and stewardship and provided benefits to civil society. Technologies are now in place to open, operate and decommission a mine property in an environmentally acceptable manner, both in the short and long term. This can have a major impact on new mine financing and development. Moreover, mining companies, governments and consultants have acquired a great deal more capability to deal with environmental and societal issues such as water contamination from mine wastes, including acid generation.

The long history of mining in Canada has resulted in a number of abandoned and orphaned sites. Research and compilation regarding abandoned and orphaned sites is ongoing, and is necessary to provide relevant information to government including the location, environmental issues, potential ownership and resulting liability. The presentation includes issues related to abandoned and orphaned sites and their rehabilitation to ensure long-term protection of land and watercourses impacted by past mining activities.

Acidic drainage is one of the most significant environmental issues facing the mining industry. The Canadian Mine Environment Neutral Drainage (MEND) initiative was the first international multi-stakeholder program to develop scientifically-based technologies to reduce the effect of acidic drainage. A toolbox of technologies that is available to all stakeholders was developed. Case studies depicting Canadian full-scale applications of various technologies will be presented.

The strategies mentioned above are consistent with the environmental protection goals of ensuring biodiversity and sustainable development. The results that have been achieved, the lessons learned, and the opportunities for future actions will be discussed. Through these efforts a significant advancement in the environmental management practices is achieved and thus has contributed to the long-term sustainability of the mining industry.

TOWARDS IMPROVED ENVIRONMENTAL INDICATORS DURING THE MINING LIFE CYCLE

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This presentation will focus on the environmental impacts of mining throughout the mining life cycle: exploration to post-closure. Each stage in the life cycle will be touched upon. Specific attention will be paid to the various facilities associated with a mine during the operating, closure and post-closure stages. These include: mine pit or underground mine, tailings disposal facilities, waste rock disposal facilities, heap leach facilities, and infrastructure. Long-term chemical stability issues such as acid drainage and/or metal leaching will be discussed separately. While the presentation will concentrate on metal mines, reference will be made to coal and industrial minerals.

Mines are developed where ore is found. Site climatic, topographic and other physical conditions determine the potential environmental impacts of the mine during the mining life cycle. It is true that large-scale open pit mining disturbs the natural terrain in the vicinity of the mine and changes the landscape, however it is possible that the post-mining land use may be as productive, or even more productive, than it was before mining. There may also be ongoing reclamation efforts that reduce the effective overall area of disturbance.

Technological advances and improved understanding of natural processes have contributed significantly to reducing environmental impacts at modern mines. However, there is a wide range of design and operating conditions at mines around the world. Some abandoned, or orphaned mines, also cause environmental impacts.

Mining environmental impacts are site specific and it is incorrect to assume that all mining will impact the environment equally. Even at the site level different large volume waste facilities will result in different impacts: waste rock disposal facilities may occupy large areas but these facilities can provide stable foundations for light structures or other land use. It is more difficult to create the same stable surface conditions on a slurry deposited tailings impoundment soon after construction. The presentation will discuss these issues.

Towards Improved Environmental Indicators for Mining Using Life Cycle Thinking

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Introduction

Life-cycle thinking is the broad basis for the life cycle approach and life cycle analysis (see Figure 1). Environmental impact is often used to compare different options in Life Cycle Assessments, e.g. the use of metals vs. plastics, or different processes for recovery of metals. Improved environmental indicators can be developed by considering a life cycle approach to environmental impacts of mining throughout the mining life cycle, i.e. exploration to post-closure.

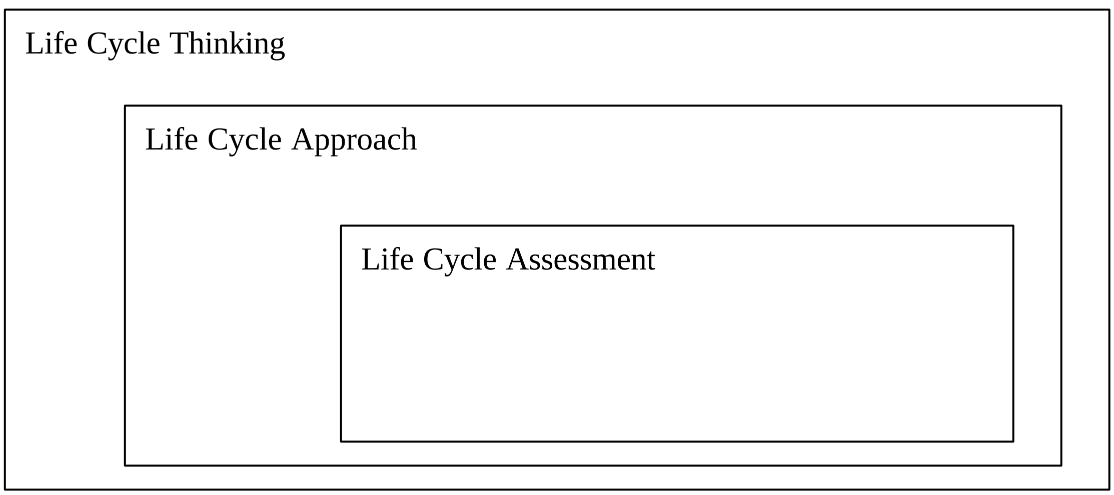

Figure 1. Life Cycle Thinking, Approach and Assessment (Frankl and Rubik, 2000)

The number, extent, and conditions of facilities at mine sites change during the life cycle of a mine. The various facilities associated with a mine include: mine pit or underground mine, milling and processing, tailings disposal facilities, waste rock disposal facilities, heap leach facilities, and infrastructure. Long-term impacts from mine sites are typically associated with chemical stability issues such as acid drainage and/or metal leaching.

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Mining environmental impacts are site specific and it is incorrect to assume that all mining will impact the environment equally. Even at the site level different large volume waste facilities will result in different impacts: waste rock disposal facilities may occupy large areas but these facilities can provide stable foundations for light structures or other land use. It is more difficult to create the same stable surface conditions on a slurry deposited tailings impoundment soon after construction.

Mine Life Cycle

Every mine goes through the same stages of the life cycle, however the site-specific characteristics are different. Figure 2 shows a typical mine life cycle. The major life-cycle stages are: exploration, mine development, operations, closure and post-closure. It is also possible that the mine may close temporarily because of low metal prices, labor disputes, etc. and then re-open operations. Following closure the mine may also re-open when new technologies or higher metal prices make it possible to have a profitable operation. Future land use for the mine site may not include mining at all but may be for industrial such as placing solid waste in the mine pit or residential purposes such as building homes on waste rock disposal facilities.

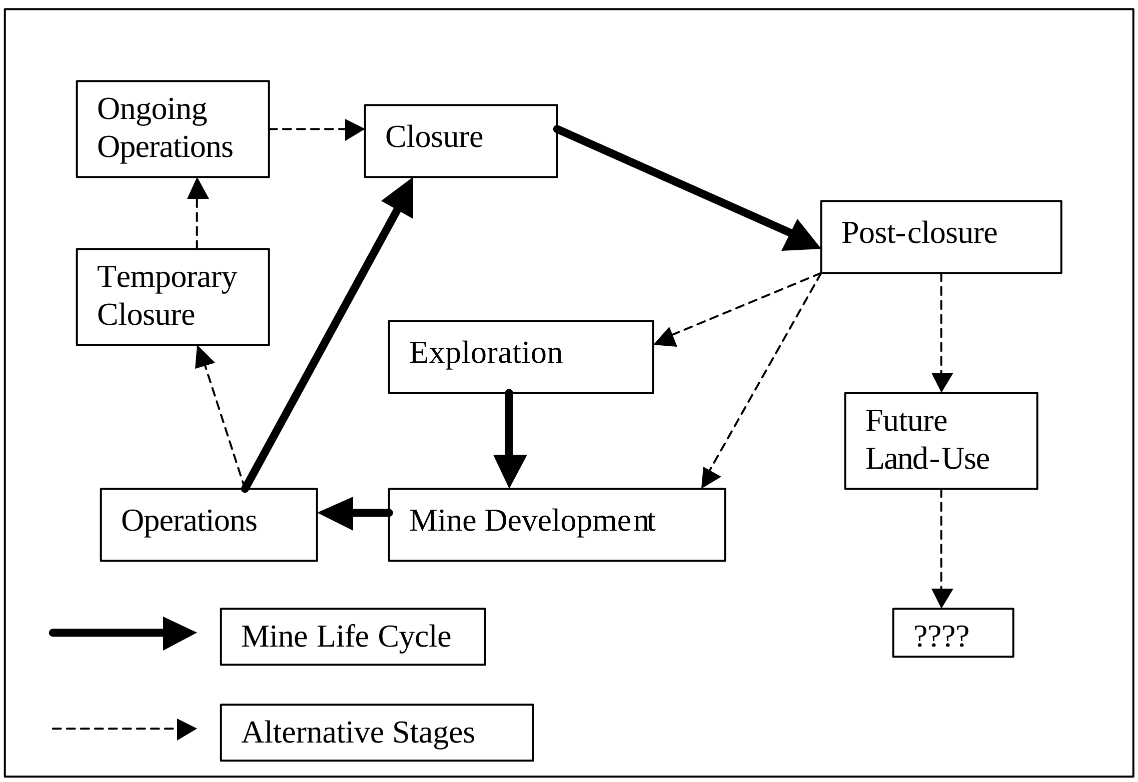

Figure 2. Mine Life Cycle Stages

It must be noted that the timelines associated with each of the stages of the mine life cycle vary from site to site. There are mines with operating stages as short as 3 to 5 years, while others have operating lives of over 100 years. It is clear that the mine life cycle is not a linear process, many things can happen during the various stages that changes the outcomes in terms of longevity and future land use, it may be more appropriate to refer to the mine life spiral where the intent is to improve the environmental and social conditions in the community as a result of mine development (MMSDNA, 2002).

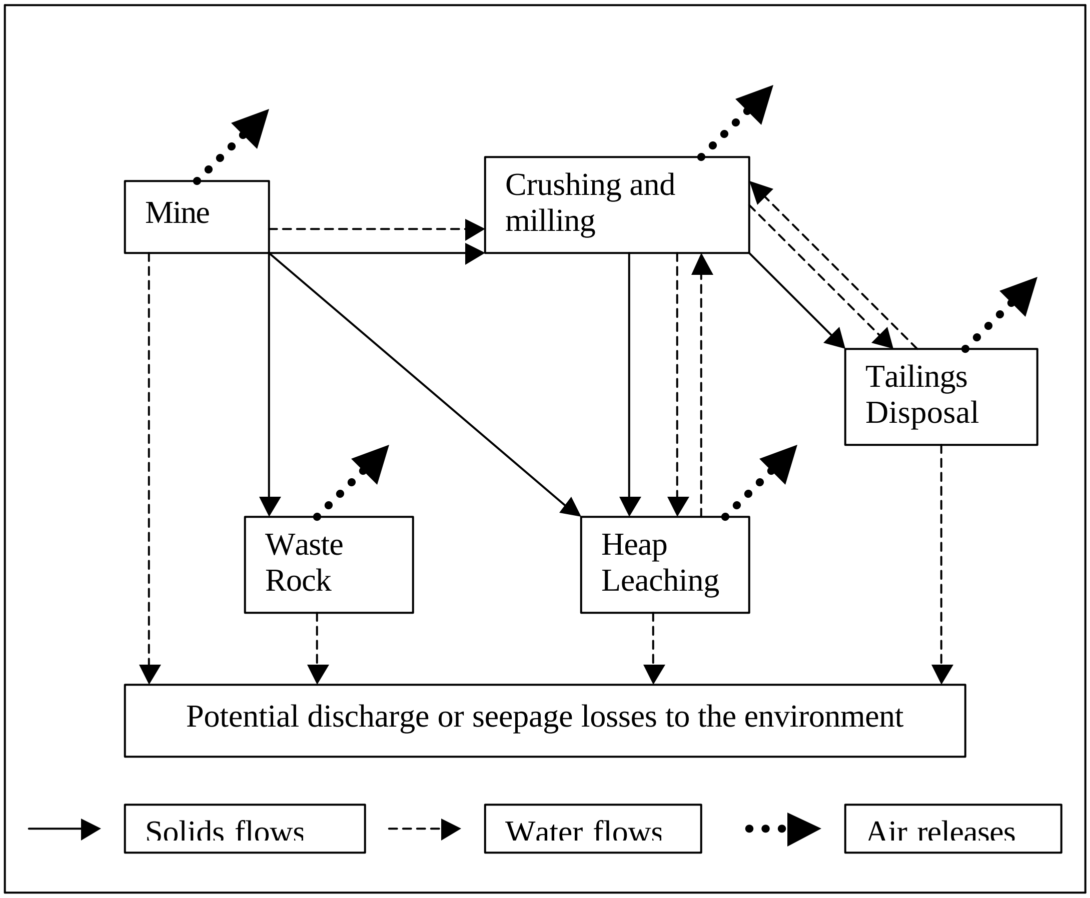

Figure 3. Mine Solids and Water Flows and Air Releases During Operations

Mine Site Solids and Water Flows and Air Releases

The solids and water flows on a mine site during operations are very complex. Figure 3 provides a schematic of typical solid and water flows as well as potential water and air releases at a mine site during operations. Rock is removed from the mine and processed through milling or heap leaching to recover the metal of interest. Various solid and water waste streams are present and air releases may occur at various facilities. Not all releases (such as to the air or water to the environment) necessarily cause negative impacts; the constituents that are released, their concentrations and magnitude will determine the impact.

Potential Environmental Impacts and Indicators

Figure 3 is specifically focused on the operating stage of the mine life cycle. In keeping with the life cycle thinking this section will highlight some qualitative considerations for the other stages of the life cycle.

Mining is a land use that causes disturbance in the vicinity of the mine. Land use is considered as an environmental impact of mining. Land use can be the land directly occupied by the activities during the specific stage of the mine life cycle. Table 1 provides a qualitative evaluation of the relative area of land use through the mining life cycle.

Table 1. Relative Areas of Land Use During the Mining Life Cycle

Life Cycle Stage	Relative Area of Land Use
Exploration	Small
Development	Increasing
Operations	Highest
Closure	Reducing
Post-Closure	Very small

The impacts to water use and water quality are important environmental considerations at mines. Table 2 provides a qualitative analysis of the relative quantities of water used during each stage of the mining life cycle as well as the potential for contamination.

Table 2. Relative Water Use and Potential for Water Quality Impacts during the Mine Life Cycle

Mine Life Cycle Stage	Water Use	Potential for Water Quality Impacts
Exploration	Low	Low
Development	Increasing	Increasing to high
Operations	Highest	Highest
Closure	Reducing	High
Post Closure	Very low	High to low?

The source of water quality impact also changes during the various stages of the mining life cycle. Water quality impacts can be related to the geological characteristics of the ore and waste rock (resulting in acid drainage or metal leaching) as well as the chemicals used during metal extraction (cyanide, sulfuric acid, organics, etc.). Table 3 provides a summary of the sources of impacts and its time dependence.

Table 3. Sources and Time Dependence of Water Quality Impacts

Source	Mine Life Cycle Stage	Potential for Long-Term Impact
Process chemicals	Operations to post-closure	Yes to maybe
Geologic characteristics of the rock	Exploration to post-closure	Definitely when it occurs

Integrating Over All Stages of the Mine Life Cycle

While it is clear that improved environmental indicators are required to express the environmental impacts of mining, it is also clear that it is a very complex problem. A Life Cycle Assessment (LCA) is done at a specific point in time. The metal or mineral of interest may be produced at many mines in the world in different climatic conditions, different geologic settings, and with mines at different stages of their life cycle. The latter is shown in Figure 4. An LCA performed at time A will have to consider a different mix of mine stages than one performed at times B or C. For example at time A: one mine is in the exploration stage, two are in the development stage, two are in the operations stage and one is in the closure stage. It is necessary to take into account the relative environmental impact of each mine at its specific stage in the mine life cycle and add it all together. Only considering the environmental impacts of mines in the operating stage of the life cycle does not provide a complete analysis.

```
Mine 1: |--exploration-|- development---|---operations-----------------|closure-------

Mine 2: |expl |development | operations|---closure---------------|post-closure|

Mine 3: |--operations-------------|-closure-------| post-closure-----------|

Mine 4: |--closure--------------------|----post-closure----------------------------------

Mine 5: |development|----operations---------------------------------------------------

Mine 6: |operations----------------------------------------------------------------------
               ||                          ||                          ||

Times:         A                           B                           C
```

Figure 4. Mine Life-Cycle Stages for Six Mines Along a Linear Time Line

Conclusions

Application of Life Cycle Thinking results in a more complete view of the environmental impacts of mining. This approach will also allow the evaluation of potential positive contributions of reclamation[1] or other long-term uses of the land. More work is required to operationalize this concept and to make it tractable as a tool for professionals working in Life Cycle Assessment.

It can be concluded that using average values for land use and other environmental impacts derived from a review of a few mines to evaluate the environmental impact of whole sectors cannot be correct. Such oversimplification will lead to incorrect conclusions. It is important to recognize the site-specific differences between mines, in some cases regional similarities may be recognized. Sectoral analyses must recognize the impact of mines at life cycle stages other than operational.

References

Frankl, P. and F. Rubik (2000) Life Cycle Assessment in Industry and Business, Springer-Verlag, 280 pp.

Mining, Minerals and Sustainable Development North America (2002) Seven Questions to Sustainability – How to Assess the Contribution of Mining and Minerals Activities, 54 pp, www.iisd.org/mmsd (accessed July 6, 2002).

[1] Note that there is much local context to the use of terms such as reclamation, remediation, rehabilitation, restoration and even renaturation that the author prefers to refer to all these as "R" and let the readers make their own judgment on what term to choose.