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Mining Life Cycle Modelling for Environmental Control and Waste Minimisation

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ABSTRACT: Life cycle assessment methodology has been applied to mineral processing cycles considering as inputs the volume of materials used and the energy consumed in the process to compare the economic benefits and the waste production for different metals. However, a holistic life cycle assessment system for the extractive industries, which accounts for all stages of minerals production, from exploration and development of a mineral deposit to mining, processing, waste disposal, remediation, decommissioning and aftercare has not yet been developed. Currently, a large European Commission funded project is developing an LCA methodology to minimise the "full life-cycle" impact of metalliferous mining projects, adopting an integrated approach to production and process design, and the costs involved. This paper presents the main principles used in designing the mining production and solid waste handling LCA developed in this project. The methodology developed for the life cycle database is illustrated using examples from the model.

1 INTRODUCTION

Notwithstanding their economic importance, the mineral's extraction and processing industries are considered to have significant impacts on the surrounding environment. In recent years modern mines have implemented the best available technology in environmental management and monitoring with a view to control and minimise their impacts on the surrounding environment. In addition, modelling of the monitored parameters has now started to provide scientifically proven indicators about the state of the environment around these operations.

Over the past 20-30 years, life cycle assessment (LCA) has been widely used by many organisations. Beginning in 1990, the Society of Environmental Toxicology and Chemistry (SETAC) and from 1993 the International Standards Organisation (ISO) began promoting consistency in the design of LCA systems. These efforts produced a number of guidelines and draft standards on different aspects of life cycle assessment, with varying degree of success. The development of LCA methodology in Europe has been further promoted by the Society for the Promotion of LCA Development (SPOLD) and a number ot EU initiatives such as the European network for strategic life-cycle assessment research and development (LCANET). In the minerals industry, life cycle assessment has mostly been applied to mineral processing cycles (Pétrie & Clift, 1995; Stewart & Petne, 1997; Hake et al., 1998; Bruch et al., 1995a, b).

The methodological framework of conventional life cycle analysis can be described in four phases: i) goal and scope definitions, ii) inventory analysis, iii) impact assessment and iv) interpretation. However, it is clear that for any product, process or service, in addition to the environmental aspect considered in this conventional LCA framework, there is a strong interaction between the process and scientific development, legislative requirements and most importantly the economical viability of a project. This is particularly true for the minerals industry, which faces a serious challenge in combining good environmental practice and compliance with regulations, with issues of social acceptance in the local communities and financial feasibility.

Conventional life cycle assessment focuses on relative comparisons of whole systems with respect to resource use and emission loadings in relation to defined functional units. This reveals the contrast between LCA and other environmental impact assessment tools (e.g. pollution dispersion models) which work with absolute measures without normalisation by functional units. Additionally, LCA generally has no spatial or temporal resolution (Barnhouse, et al., 1998), so that emissions, wastes and resource use are combined over time and from different sources. Furthermore, environmental processes may display thresholds or non-linear dose-responses, however, LCA generally is based on assumptions that no threshold exists and that a linear response exists between the system loading and the environment (Fava, et al., 1991). Research described in this paper is part of a larger project aiming at addressing these issues:

- by developing a complete LCA framework for a cradle-to-gate assessment of minerals extraction projects,
- by developing a modelling system that will integrate the LCA framework with the quantitative environmental impact assessment models and financial models,
- by accounting for the financial costs and benefits of alternative mining scenarios within the LCA model,
- by accounting for the long-term effects of alternative mining scenarios examined by the LCA model to be developed.

One of the main drivers of the research described in this paper is the fact that an increasing number of new environmental permits issued require the long term monitoring and control of the waste disposal sites, such as tailings dams and waste dumps, after mine closure. In some cases, the specified monitoring period is longer than the productive life of the mining operation itself. Therefore, the main project emphasis is on minimising the waste disposal requirements, through the application of '"design for decommissioning" concept. The partner industrial sites were selected with a view to facilitate the development of a range of case studies, emphasising waste minimisation through engineering design and life cycle modelling. Mining operations considered as the basis for LCA development fall into three categories:

- Greenfield sites where provision for minimising the impact of mining on the environment can be an integral pan of the mine design.
- Redevelopment projects where mine design is constrained by old surface and/or underground operations and their existing impacts.
- Ongoing investments in active operations where fundamental modifications to the existing mine design may not be practical or may even be counterproductive.

2 THE MINING LCA MODEL

The first step in mining LCA model development involved the definition of the system boundaries for the complete system and for the functions of the different sub-systems within the LCA model. The region in which the mining activities take place is considered as the system, which is enclosed by the system boundaries (Fig. 1). The region surrounding these boundaries is the system environment. In relation to the environmental impacts, the life cycle impact assessment (LCIA) system boundaries were defined as the effective impact radius around a minerals extraction operation.

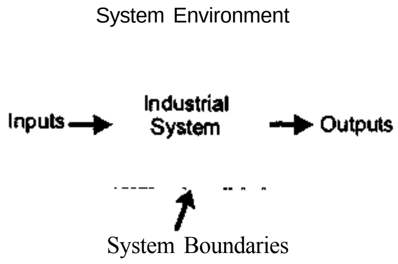

Figure I : Mining LCA system boundaries.

In order to describe the mining system sufficiently, and to include enough detail to enable quantitative assessment of its performance during the modelling stage, the overall system was divided into subsystems (phases) that will be linked to each other by flows in the LCA system. Figure 2 presents the three main subsystems identified: extraction, processing and waste disposal and rehabilitation, as well as the energy, material and emission flows and the waste streams. Special emphasis was given to mapping the waste streams. These subsystems were further broken up to sub-subsystems. During this second classification, three types of subdivisions, meaningful in the way of the stream flow, were identified: *operations, processes* and *activities.* While an operation is a planned action to achieve something in terms of physical changes, a process is a series of actions carried out to achieve a particular result and include chemical changes. An activity only implies 'doing' something. Operations and processes would be relevant when dealing with mass flow, whereas activities would be relevant when dealing with cost flows.

The system was then broken into components such that each subsystem corresponded to a small convenient size function, suitable for the technical, economic and mathematical purposes and needs and for ease of use. This small convenient function will be referred to as a *functional unit.* The mining phases indicated in Figure 2 link with the functional units through the structure: *Phase - Process - Functional Unit.*

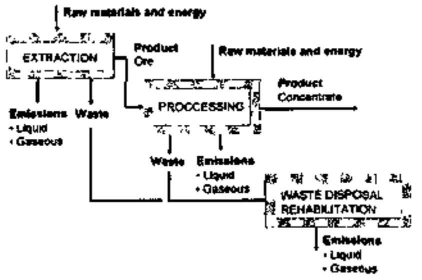

Figure 2: Schematic representation of the Mining LCA system.

Inputs

1. Energy

2. Materials
   - a. Main process
   - b. Secondary process
   - c. Services

3. Costs

Outputs

1. Product

2. Discharges
   - a. Emissions to aJr
   - b. Effluents to surface waterfgrojjdwator
   - c. Solid waste
   - d. Energy
   - e. Other

Figure 3: The inputs and outputs of functional units.

As a result, once the physical, real life aspects of the mining phases are described, each and every phase can be represented by an appropriate number of unit processes. For every process assigned, the relevant characteristics that define the specific function are attributed to the process as *variables,* which relate to either the inputs or the outputs. The flows of mass, energy and costs are allocated to each process and the relationships between inputs and outputs are identified and described. Figure 3 illustrates the types of inputs and outputs for each functional unit. The variable related to each input and output are generic type variables that may be related to any process, be it extraction, processing, waste disposal and rehabilitation, in the mining life cycle.

Once the functional units were characterised, their inputs and outputs were identified and classified, as illustrated for a rope shovel in Figure 4. Only after this process it is possible to relate the inputs and the outputs and express them as mathematical functions of quantities that may be modelled. The tabulated example in Table 1 illustrates the above concepts for a functional unit from the production operations, namely a truck, which transports the extracted ore to the process phase. The truck in this example uses diesel fuel and the emissions to the atmosphere due to combustion are considered as environmental outputs.

A functional unit was also declared in terms of the product for each subsystem. Thus the functional unit for the extraction system was chosen to be one tonne of dry ore extracted, while the functional unit for the mineral processing system was one tonne of concentrate produced. The extraction and mineral processing functional units are related as a mass fraction ratio.

The definition of such functional units for the waste disposal subsystem was a more complex issue. It was decided that for the backfill plant, the functional unit should be 1 tonne of backfilling material, while for the water treatment plant the functional unit would be 1 Mm^1 of treated effluent discharged.

2.1 *Mining LCA inventory system*

The structure of the system developed was reviewed and revised a number of times in order to organise, manage and utilise most efficiently the information required to describe all the phases, processes and functional units within the mining LCA system. The inventory system analysis work carried out led to the decision to structure the database in specialised compartments. This structure was designed to enable faster data access and update capabilities for the detailed models, while providing the platform for the LCA model.

Functional Unit: **Rope shovel**

CHARACTERISTICS
Dimensions ? units
Life span: ? years

INPUTS
Energy
Type Electric
Power requirement 500 kW
Material
Type ROCK
Volume 20 cubic yards
Costs
Type Purchase
Price 3 700 000 €
Type Spare parts
Costl 25 91 €/hr
Type Maintenance labour
Cost2 21 59€/hr
Type Electric power
Cost3 29 64 Ohr
Type Lubncants
Cost4 10 57€/hr
Type Operator wage
Costs 23 18€/hr
Other Freight and installation
Cost6 *1*

OUTPUTS
Products
Type Rock
Volume 20 cubic yards
Discharges
Air emissions Airborne particles
Composition Silica
Concentration 2 000 mg/mVhr
Max Permitted level
Potential impact Hazardous to health
CAS 7 631-86-9
Ld50
NIOSH TWA 6 mg/m'

Ftguie 4- Chaiactenslics. inputs and outputs of the 'rope shovel' functional unit.

Table 1: 'Truck' as a functional unit and associations amongst the relevant defining variables.

TRUCK	Description	**Formula**	Units
Inputs			
Energy	due to fuel	$\text{Eji}_{ese}\vert$ = f (Truck_power_requirements. time) E	kW
Ma.\.\	of ore to transport	More = f (Truck_capacity)	tonne
	of consumed fuel	Mdiesel = f (Mass_consumed_per_unit_time)	1
Ca.\t.\	of machine	^machine = depreciation + maintenance + consumables + interest	**e**
Outputs ' >			
Protluit.\	mass of transported ire	"lore = ^{M}ore	tonne
Dı.\ıharge.\ tıs emissions to the atmosphere	mass of naphthalene	^{m}nanhthalene = ^{f}\ (Mjiesel- truck_engine_efficiency)	g/m'
	mass of benzene	'"benzene $^{=}$ *2 (Mdiesel- truck_engine_efficiency)	g/m'
	mass of ethyl-benzene	'"edivl-benzene = *h* (Mdieseb truck_engine_efficiency)	g/m'
	mass of toluene	'"Minene = f4 (Mdiesel. truck_engine_efficiency)	g/m'
	mass of xylene	'"xylene = fs (Mdiesel. lruck_engine_efficiency)	g/m'
	mass of SO_x (and/or N„ CO. CO?)	'"gas = ffi (Mdiesel- truck_engme_efficiency)	g/m'

As described earlier, the mining LCA system was divided into three phases (mine production, processing, waste disposal and rehabilitation) reflecting the types of operations, processes and activities in each phase. The waste composition, structure and the volume generated from processing are largely influenced by the ore mineralogy, the physical and chemical processes used and the reagents consumed. On the other hand, the type and amount of waste generated from mine production is influenced by the geological setting which would also dictate the choice of suitable mining method to extract a specific ore deposit. In terms of the mining methods available, the two broad categories considered are surface mining and underground mining. Their use and the choice of a specific production technique depends, to a great extent, on the deposit type.

The volume and complexity of the information required to design and populate the mining LCA inventory system necessitated that each of the three main subsystems is first studied separately. The design process followed for each subsystem was essentially the same as described in the previous section. The first step was to create the conceptual framework, break down the system into components, then identify activity functions and finally assign material, energy and emission flows according to each function. Tables 2-3 illustrate some of the subsystems/sub-activities defined for surface mining production phase and for waste disposal and rehabilitation phase for a surface mining operation respectively.

Two inventory forms were created for the extraction subsystem based on the detailed system structure, one for surface and one for underground mines. The inventory forms were populated with information provided by industrial partners of the project and from the literature. The LCA inventory database was designed following a hybrid format under the object-relational model. The backbone of the database consists of six object tables designed to store technical information regarding:

- the geological setting (depth, geometry, etc)
- inputs (primary supplies, energy, etc)
- outputs (amount and composition of solid waste, effluents etc).

Table 2 Sub-systems/sub-activities defined 1ll surface mining production phase

Surface mining production phase

Geological settings	*Pre-production work subsystems sub-activities*	*Production work subsystems /sub-activities*
• Deposu ch.ır.ıcter-ısıICS • Ore/counhy rock strength • Ore tonnage and grade	• Site clearing (removal of vegetation, levelling ot land) • Construction of access roads • Construction ot surface infrnstruclures (buildings, waste disposal facilities) • Surveying • Primary supply need • Personnel requirement during pre-production • Pre-pioduction scheduling	• Dense vegetation removal • Cyclic overburden removal • Drilling • Blasting • Loading • Cyclic ore extraction • Drilling • Blasting • Loading • ln-pit crushing and material transport • Auxiliary operations • Pit dewalenng • Dust suppression

Table .V Sub-systems/suh-activities defined in the waste disposal and rehabilitation phase for a surface mining operation.

Waste disposal phase

Solid waxte disposai sub'Systems/sub-activüies
- Top soil storage
- Overburden and mine ladings disposal
- Aggregate processing
- Primary supply need
- Personnel requirement

Rehabilitation and maintenance phase

Mine rehabilitation and maintenance sub-systetns/sttb-activities
- Sue reclamation
    - Demolition and salvage of surtace infrastructures
    - Backfilling and grading of spoil
    - Revegetation ot the mine site including wasie disposal sues
- Monitoring
    - Air quality
    - Groundwater quality
    - Surface water quality
    - Soil and herbage quality
- Primary supply need
- Personnel requirement

The object tables were developed in Oracle Release 2 (8.1.6) for Windows NT. The methodology used to create the LCA model object tables is as follows:

1. Entities and entity relationships were identified; the main entities became objects, and the entity relationships became references. All main entities were complex object types, therefore simple object types were identified as building blocks for each complex object type.
2. The simple object types were defined for each complex object type. Then, a set of attributes for each simple object type was specified.
3. According to the level of dependency, the object types were used to create object tables, nested tables or object referred tables.

Table 4: Primary supplies values inserted in the relevant nested table for the production subsystem.

Daily supply requirement	Quantity	Cost. (C/hr)
Diesel fuel	1,470 l/day	0 65
Electricity	160 I/day	0 08
Bulk ANFO	890 kg/day	100
Caps	72 units/day	0 20
Detonation cord	730 units/day	0.20
Drill bits	1.4 units/day	0 10

Once the object tables are created, values were inserted into object tables, nested tables and referred object tables, as instances of specific objects. Table 4 illustrates an example of the values inserted in a nested table, which stores information relevant to primary supplies. The relationship among entities was tested, through SQL (Structural Query Language) queries. The objective of such queries was to navigate through the whole data structure and test reference links, object availability, access time and abstraction conceptualisation. Finally, data in the object tables were allocated to parameters and used to perform calculations, using PL/SQL (Procedural Language extensions to SQL).

The database was designed to provide calculation methods for variables required to run the LCA model. These procedures were coded as subprograms together with the relevant object table and can calculate, for example, the amount and composition of waste, blasting fumes and gaseous emissions from fuel combustion to compliment the available data in assessing a mining scenario.

Table 5 presents the object-relational representation of the sub-activity object table. For example, in the case of gaseous emissions, the equations developed by the European Programme on Emissions, Fuel and Engine Technologies (EPEFE) research programme (Camarsa, 1996) were used to estimate the volume of exhaust emissions from vehicles used in a mining system. The EPEFE equations combine both engine technology and fuel properties and cover gasoline, light duly (LD) and heavy-duty (HD) diesel. The example in Figure 5 illustrates the output of the relevant calculations in the LCA model developed.

Table *5:* Object-relational representation of the sub-activity object table

Subactno	Subactivityname	Startmgdate	Duration	Machineuntts_ntab	Prjmarysupplyunits_ntab	Contractorcost	A£tmty_ref
NUMBER (•1,0)	**VARCHAR ßS)**	**DATE**	**NUMBER** *(1.1)*	NESTED TABLE Machınelınk_ntalıtyp	NESTED TABLE Supplieslmk_ntabtyp	NUMBER	**REFERENCES Acf«rcty_objtyp**
PK							FK

```
MEMBER FUNTION Macmne_gaieoiM_emission(Gasa!k VARCHAR2) RETURN NUMBER
MEMBER FUNTION Bla«ina_PM.suet(Choict NUMBER) RETURN NUMBER
MEMBER FUNTION Total_SuspeniiedJ˃arMUates(Event NATURAL, Parameterl NATURAL. Parameter! NATURAL Parameter NATURAL)
  RETURN NUMBER
MEMBER FUNTION PMJ0(Event NATURAL. Parameterl NATURAL. Parameter NATURAL. Parameters NATURAL) RETURN NUMBER
MEMBER FUNTION C02_Blastmg(E!tplosive NATURALN) RETURN NUMBER
MEMBER FUNTION Bla«Ms_fumes(Fumein NATURALN, Watercon NUMBER, Fuelcon NUMBER) RETURN NUMBER
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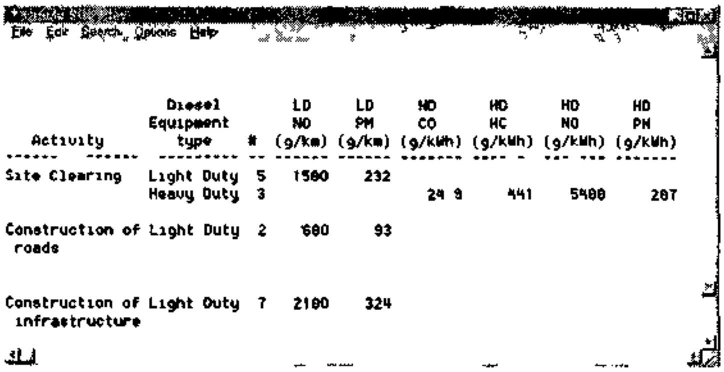
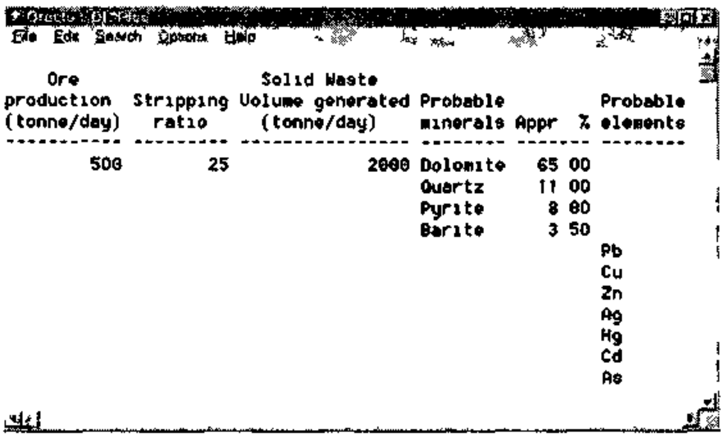


```
                    Diesel           LD      LD      HD      HD      HD      HD
                    Equipment        NO      PM      CO      HC      NO      PM
  Activity            type     #  (g/km) (g/km) (g/kWh) (g/kWh) (g/kWh) (g/kWh)
------  ------  ---------- -- ------ ------ ------- ---- - --- --- -------
Site Clearing    Light Duty  5   1500    232
                 Heavy Duty  3                  24 9     441    5400     207

Construction of Light Duty  2   600      93
 roads


Construction of Light Duty  7  2100     324
 infrastructure
```

f-ı^uıı. i Gaseous Linissinns Mom dıesLİ equipment USLCI in eaelı ot the jLlmties ifuiing IllL piL piodiiLtion stagL



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   Ore                       Solid Waste
production  Stripping Volume generated Probable              Probable
(tonne/day)   ratio      (tonne/day)    minerals Appr  % elements
----------- --------- ---------------- -------- ------- --------
        500        25             2000 Dolomite   65 00
                                       Quartz     11 00
                                       Pyrite      8 80
                                       Barite      3 50
                                                           Pb
                                                           Cu
                                                           Zn
                                                           Ag
                                                           Hg
                                                           Cd
                                                           As
```

FiguiL 6 Volume and pıobabİL Loınposıtıon ol solid waste geneiattd dunng SUIİJLL mining

Fıguıc 6 piescnts the output ol the algorithm which calculates the volume and composition ot the solid waste generated using mining and ore grade data entered in the LCA database In doing so, the piogiam navigates through a number ot object tables, including the surface mining extraction phase and oi e grade tables

The emissions and waste stieams wcie allocated in a two step piocess as suggested by Knoepfel (1994)

1 The direct allocation step (based on engineeiıng knowledge) An exhaustive analysis ot the sub systems was earned out until the mam lelcvant activities and/oi processes weie identılıed and their functions descıbed Chemical and physical causes tor emission and waste geneıatıon weie charactensed loi each activity and/oi piocess accoiding to then functions Emissions and waste weie allocated directly As an example the emission categories allocated to the activity blasting aie gı\en in Table 6
2 The geneial allocation step is based on mass units The remaining encigy and matenal Hows were allocated according to mass tractions of the ore extiacted, oıe piocessed and waste stream composition

Table 6 Emissions categoues allocated to the ac lıvıty blasting in the exiiaclion sub system

Cause	Emission
Chemical	CO_2
	CO
	NO
	NH_3
Physical	PM10
	TSP

2 2 *The Life C\cle Impact A\iestment i\ stem*

The next stage in lite cycle assessment is to assess the outputs of the lite cycle inventory (LCI) analysis stage from an environmental perspective using impact categories and category ındıcatoıs connected with the LCI icsults The **LCIA** phase also provides mtoimalion lor the hie cycle interpretation (ISO 140042 2000(E)) and is composed of three mandatory elements: the impact category selection, the classification and the characterisation. There also are optional elements for normalisation, grouping or weighting of the indicators resulting from the mandatory steps. Current research at Imperial College involves the implementation of ISO guidelines in developing the LCIA model as the last phase of this project.

3 CONCLUSIONS

This paper presented the modelling framework used in the development of a mining life cycle model at Imperial College.

During the initial stages of model development, the LCA system boundaries were defined for the complete system and for the functions of the different sub-systems. The region in which the mining activities take place was defined as the system, enclosed by the system boundaries. Beyond these boundaries is the system environment. In relation to environmental impacts, the LCIA system boundaries were defined as the effective impact radius (being dependent on the impact category) around a minerals extraction operation.

A data inventory was designed and coded in an object-relational database model. The calculation procedures accounting for the input/output balance of the alternative scenarios for mining production, processing, waste disposal and rehabilitation were programmed into a software system. In developing the LCA system the following assumptions were made:

- the mine, the plant and the waste disposal areas are located in close proximity of each other,
- final product (metal) use by the downstream industries and end users are not considered. In this context, the model presented in this paper is a cradle-to-gale, rather than cradle-to-grave LCA model.

The LCIA model development, which is the last phase of this research project, is currently being undertaken by the authors.

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