Life Cycle Inventory of Molybdenum Products

INTERNATIONAL MOLYBDENUM ASSOCIATION

1.

Summary Report

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Introduction

Life Cycle Assessment (LCA) has become one of the most valuable environmental tools for assessing the environmental footprint of a product or process. LCA provides quantitative and scientific analyses of the environmental impacts of products and their associated industrial systems. Because it assesses each stage of the life of a product, LCA offers valuable information for a product's supply chain and helps to identify environmental attributes and weaknesses of a product.

Over the past 10 years, the non-ferrous and ferrous metals industries have adopted LCA as an environmental tool of choice to supply environmental information to customers, help identify areas for process improvement, and measure environmental performance. In 2000, the International Molybdenum Association (IMOA) completed a Life Cycle Inventory (LCI), the first part of an LCA, for three molybdenum metallurgical products: technical grade molybdic oxide (tech oxide), ferromolybdenum, and tech oxide briquettes (this study is hereinafter referred to as the "original LCI"). At that time, the original LCI provided the molybdenum community and data requestors with robust, current data on the cradle to gate production of these molybdenum feedstock products.

In 2006, IMOA commissioned Four Elements Consulting to update the original LCI since it has been more than five years since the production of the original LCI - an ideal timeframe to revisit processes and data as well as invite other molybdenum producers to join the study.

Goal and Intended Uses

The aim of this study is to provide the molybdenum industry with a current LCI of three molybdenum products, using current, robust data on molybdenum production. The three products studied include:

a) Tech oxide in powder form;

b) Tech oxide in a briquette form; and

c) Ferromolybdenum in chip form.

The LCI is cradle-to-gate, which encompasses the processes that include extracting resources from the earth through the point at which the molybdenum products are ready for shipment to customers. The LCI is based on current data on process technologies, energy and materials consumed, and environmental outputs. The geographical scope is western world production of molybdenum excluding China, Mongolia, and CIS (former USSR).

The study results may be used by the molybdenum industry members in the evaluation of the potential impacts of molybdenum products and their applications. The results may also be used with other appropriate methodologies for industry benchmarking and management of environmental improvement programmes. The results to this study will be furnished to the iron and steel industry, plus other interested parties, for use in other LCI studies.

This project adheres to the LCA guidelines summarized by ISO, which are the most widely accepted worldwide standards for performing LCA. The requirements in this study are summarized in the following:

- ISO 14040:1997(E), the International Standard of the International Standardization Organization, Environmental management – Life cycle assessment – Principles and framework.
- ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines.

This study aims to meet the essential requirements formalized by these ISO standards. Specifically:

- The project aims at taking an inventory of the environmental inflows and outflows associated with the cradle-to-gate production of a product;
- The goal and scope of the project are precisely defined at the beginning of the project;
- Assumptions are clearly stated, and the methodology is as transparent as allowed with protection of confidential data;
- System boundaries, functional unit, and allocation rules are rigorously defined and described;
- Pertinent data are collected and their quality is rigorously assessed; and
- Reporting requirements are stated.

Four Elements worked to ensure that the major LCI-related methodological decisions (allocation rules, etc.) were consistent with EUROFER and other stainless steel-related LCI studies that have been peer reviewed, to the extent that the confidentiality of all studies has been respected.

The LCI will be the most comprehensive, current record of environmental inflows and outflows associated with molybdenum production. However, it should be borne in mind that this LCI, like any other scientific and/or quantitative study, is not completely free from some margin of error due to various limitations such as unavailability of some potentially relevant data.

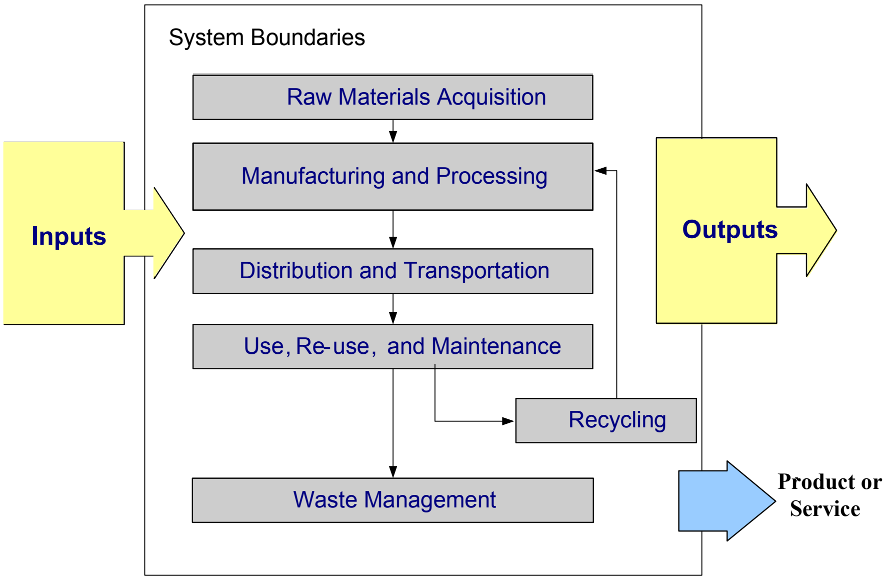
Scope Definition and Methodology

This section presents the project scope and describes the general methodology used. Additional details related to the methodology and the life cycle stages are presented in further detail in the Modeling section.

Life Cycle Assessment Principles and Terminology

LCA is an analytical tool used to comprehensively quantify and interpret the environmental flows to and from the environment (including air emissions, water effluents, solid waste, and the consumption/depletion of energy and other resources) over the life cycle of a product or process. The life cycle includes production and extraction of raw materials, manufacture of intermediate products, transportation, distribution, use, and end-of-life management (e.g., recycling, reuse, and/or disposal). The system boundaries for the product or process being studied are illustrated in the figure below.

Figure 1 System Boundaries



An LCA involves three main phases:

1. Life Cycle Inventory (LCI), the "phase of the LCA involving the compilation and quantification of inputs and outputs, for a given product system throughout its life cycle." The three major steps in an LCI include defining the project system boundaries as specified by the goal and scope of the project; collecting data required for each step included in the system, and calculating the inventory.
2. Life Cycle Impact Assessment (LCIA), the part of the LCA "aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system." The LCIA stage involves categorizing inventory flows and characterizing those flows according to their overall impact to the category. This is explained in more detail later in the report.

3. Life Cycle Interpretation, the LCA phase in which the "findings of either the inventory analysis or the impact assessment, or both, are combined in line with the defined goal and scope in order to reach conclusions and recommendations." Examples of life cycle interpretation include contribution analyses and scenario analyses, both of which are used to help understand the results of this study.

ISO's interpretation of LCA actually indicates a four-stage process, with the *Goal and Scope Definition* preceding the LCI. Individualizing the *Goal and Scope Definition* as a separate stage is not a key methodological issue, but is specially intended as a reminder that the key project objective parameters should be carefully established and clearly stated at the outset of an LCA, and that they guide the subsequent stages. All stages of an LCA should be scoped by the particular use or uses for which the study is intended, and that the use of the results may entail some results interpretation.

Function and Functional Unit

The function of this study system is the production of three molybdenum products. The functional unit, or reference flow, is **one kilogram of molybdenum in each product studied**, i.e., one kilogram of molybdenum in the tech oxide, the briquette, and the ferromolybdenum chip.

The molybdenum products studied are "average" to the industry, and not "typical". Studying an average product enables the span of technologies and material inputs to be taken into account in the analysis, yet specific characteristics of *actual* products are lost (i.e., exact product density, molybdenum content, etc.). Thus the resulting product represents not a typical or actual product, but instead an average, accounting for components of the whole industry – this is a critical aspect of the goal of the study.

Transportation of upstream materials and energy to the facilities are accounted for, but transportation of the finished product from the shipping dock to a customer is not, as downstream production stages, such as stainless steel manufacturing, capture this data in their own upstream material transportation data. Final product packaging is included.

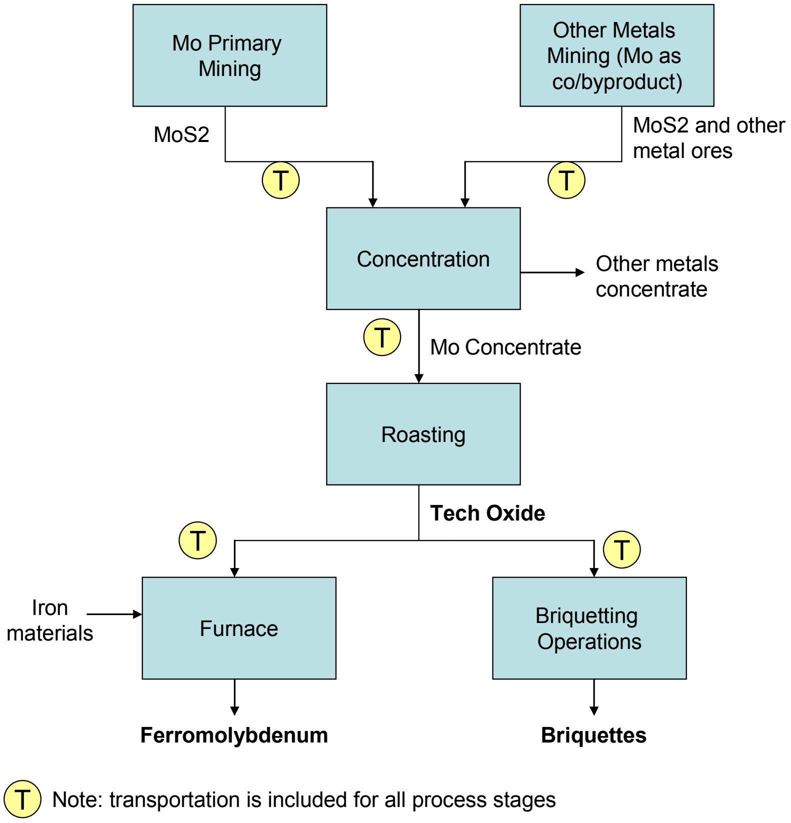
System Boundaries

General Process Overview

This study covers five major unit processes that have been defined for molybdenum metallurgical production:

1. Mining, including both primary and byproduct mining;
2. Concentration (milling);
3. Roasting into tech oxide;
4. Briquette production; and
5. Ferromolybdenum production.

Figure 2 Overall metallurgical LCI system boundary



Cut-off Criteria

Cut-off Criteria Goal

In LCA, a cut-off criterion must be defined for the selection of materials and processes to be included in the system boundaries. Only the first of the decision rules defined by ISO 14044, the mass criterion, was used, implying that materials and processes to be included in the system boundaries were chosen based upon their contribution by mass to the production processes. It was decided that a cut-off criteria of 99.5 percent of the mass of inputs would be used to determine the inputs and outputs of each unit process stage.

Attaining the Cut-off Criteria

In order to attain this cut-off goal, the questionnaires to be completed by facilities already contained lists of key inputs expected for each specific process. Aside from the inputs presented in each process stage questionnaire, additional space was provided to encourage the site staff to fill in any additional inputs he/she determined to be within the mass criteria.

Three guidelines to determine inputs were used:

- All inputs that are known;
- Inputs that have a high purchasing price to the facility; and
- Environmentally relevant inputs.

Exclusion of Data from the System Boundaries

Two elements of the life cycle have been excluded from the system boundaries: capital equipment and human-related activities. This is standard practice for most LCAs and the reasons are described briefly below.

Capital Equipment

In LCA system boundary defining, one might include capital equipment such as the production and transportation of concrete and steel for facility infrastructure. However, capital equipment is generally excluded since its contribution to the overall life cycle is expected to be small. An exception to this is steel consumables such as liners and crushing/grinding media in milling/beneficiation.

Human Involvement

The humans involved in molybdenum production have a burden on the environment in driving to and from work, production of food they eat, etc. However, specific flows related to people and offices are not necessarily unique to molybdenum production. In addition, flows attributable to people and offices in the plant which may be difficult to separate from production process flows, such as electricity, are usually small in comparison to the production process flows, so may be left aggregated in the production process or may be excluded if they are not quantified with the production process data.

Data Categories

Choosing Inventory Flows

LCA methodology considers at the onset of a project the environmental inventory and impact flows that will most likely receive subsequent attention. While keeping the breadth of the life cycle approach, setting priorities in terms of data collection and relevant industry flows helps to focus the project and ease the subsequent use of data in decision-making.

Molybdenum LCI Data Categories and Inventory Flows

The data categories were based on the following criteria:

- Molybdenum industry environmental policies and priorities; and
- The flows identified by EUROFER for its LCI of stainless steel products.

The next sections outline the list of elementary inputs and outputs studied.

Energy and Material Input Category

The energy and material categories reported in the inventory are flows that have been traced to their elementary condition (generated after full aggregation of upstream data with downstream data). Consumables and fuels, therefore, do not show up in the inventory as they are found at the facility. The list of major raw materials inputs included in the results is found in Table 1.

Table 1 Raw materials inputs

Material and Energy-Related Inputs (units in kilograms)
Coal (in ground)
Iron (Fe, ore)
Limestone ($CaCO_3$, in ground)
Molybdenum (ore)
Natural Gas (in ground)
Oil (in ground)
Uranium (U, ore)
Water Used (total)

Air Emission Category

Table 2 presents the air emissions categories.

Table 2 Air emissions

Air Emissions (units in kilograms)
Ammonia (NH_3)
Carbon Dioxide (CO_2, fossil)
Carbon Monoxide (CO)
Hydrocarbons (unspecified)
Hydrogen Chloride (HCl)
Hydrogen Cyanide (HCN)
Hydrogen Sulfide (H_2S)
Lead (Pb)
Mercury (Hg)
Metals (unspecified, besides those listed here)
Methane (CH_4)
Molybdenum (Mo)
Nitrogen Oxides (NOx as NO_2)
Nitrous Oxides (N_2O)
Particulates (unspecified)
Sulfur Oxides (SOx as SO_2)
Zinc (Zn)

Water Effluent Category

Table 3 presents the water effluents.

Table 3 Water effluents

Water Effluents (units in kilograms)
Aluminum (Al3+)
Ammonia (NH4+, NH3, as N)
BOD5 (Biochemical Oxygen Demand)
Cadmium (Cd++)
Chlorides (Cl-)
Chromium (Cr III, Cr VI)
Copper (Cu+, Cu++)
Cyanide (CN-)
Fluorides (F-)
Iron (Fe++, Fe3+)
Lead (Pb++, Pb4+)
Manganese (Mn II, Mn IV, Mn VII)
Mercury (Hg+, Hg++)
Metals (unspecified, besides those listed here)
Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)
Nickel (Ni++, Ni3+)
Nitrate (NO3-)
Oils (unspecified)
PAH, unspecified

Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)
Silicon Dioxide (SiO2)
Sulfate (SO4--)
Suspended Matter (unspecified)
Zinc (Zn++)

Waste/Solid Material Category

The waste flows in this study are consistent with the EUROFER stainless steel LCI list of waste categories. Table 4 presents the waste flows in this study that are consistent with the EUROFER study, with the exception of waste rock and tailings, which are mining industry-specific categories.

Table 4 Waste categories

Waste (units in kilograms)
Waste rock
Tailings
Waste: non-hazardous, non-organic, to disposal
Waste: hazardous, non-organic, to disposal
Waste: hazardous, organic, to disposal
Waste: for incineration
Waste: oils
Waste: filters
Waste: slag
Waste: sludge
Waste (other): sulfur

Energy Accounting Category

The energy values represent a quantification of the total energy in the system. The Total Primary Energy category includes all energy-related inputs to processes in the system. Total primary energy is broken down into the following two categories:

- Fuel and feedstock energy, and
- Renewable and non-renewable energy.

Reporting Units

Final inventory results are reported in metric units. Data in the questionnaires were provided in English or metric units, and wherever necessary, the English units were converted to metric. The results are reported in the following units:

- Raw materials: kilograms (kg);
- Air emissions, water effluents, and solid waste: kg;
- Energy: Megajoules (MJ).

Data Quality Requirements

Source of the Data

Site data, also called primary data, are used for the main unit process stages of molybdenum production (mining, concentration, roasting, briquetting, and ferromolybdenum production), and were provided in either Microsoft Excel-based or Microsoft Word-based questionnaires. Each facility data set includes main and ancillary materials consumed, total production, waste, coproducts, and environmental emissions.

Secondary data have been used to model upstream materials production (fuel, auxiliary materials, electricity, etc.), transportation, and any other modeling or production data within the study boundaries not attainable by molybdenum production facilities. The secondary data sources include:

- The SimaPro 7.0 database which contains mainly European and North American data (www.pre.nl);
- The EcoInvent database (www.ecoinvent.org);
- The U.S. LCI Database (www.nrel.gov/lci/);
- Other bibliographic, publicly-available sources; and
- Engineer calculations.

Note that when data gaps and surrogate data are used, (such as from the sources listed above), these data might correspond to earlier or more innovative technologies. These aspects, as well as any other data uncertainties, are discussed in the Data Quality Evaluation section (page 25).

Geographical, Technological and Temporal Representativeness

Representativeness is defined by ISO 14044 Section 4.2.3.6 as a "qualitative assessment of degree to which the data set reflects the true population of interest", and includes geography (i.e., area covered), temporal data (i.e., the age of data and length of time over which data should be collected), and technological coverage (i.e., the technology mix) as defined by the goals and the scope of the project.

Geographical Representation

The primary molybdenum data collected and modeled for this study represents approximately 52% of the total molybdenum produced in the world and 74% of western world production, according to the IMOA website (2008). Facilities from the following countries reported data:

- Austria
- Belgium
- Canada
- Chile
- Mexico
- The Netherlands
- United Kingdom
- USA

Countries in the western world that did not contribute data include Iran and Peru. Missing production data (i.e., from plants within the geographical scope of the study that did not contribute data) is ignored in the weighted average results, and the aggregate of the facilities that were included in data collection are assumed to be representative.

Temporal and Technological Representation

Considered the most complete and accessible data at the time of collection, 2005 data was the data year chosen to represent current energy and material usage, technologies, and general plant design. Most of the data is based on 2005 yet some of the data comes from 2003 and some other data originate from the original LCI (with verification from the facility that no major changes took place from the time of the original LCI to 2005).

Technological Representation

Technological coverage, or the technology mix, may include a weighted average of the actual process mix, best available technology, or worst operating unit. The primary data collected on the metallurgical production processes are assumed to be representative of current technology and plants.

Other Data Quality Requirements

ISO 14044 Section 4.2.3.6 highlights other data quality requirements for an LCA, including:

- Consistency – the qualitative assessment of how uniformly the study methodology is applied to the various components of the analysis;
- Reproducibility – the qualitative assessment of the extent to which information about the methodology and data values allows an independent practitioner to reproduce the results reported in the study;
- Precision – the measure of the variability of the data values for each data category expressed; and
- Completeness – the percentage of flow that is measured or estimated.

These are described in the context of this study in the Data Quality Evaluation section starting on page 25.

Allocation

Co-products and the Allocation Procedure

Many industrial processes produce multiple useful outputs which are referred to as co-products. In LCA, the functional unit generally focuses on one main product, and co-product(s) are modeled with other product systems. This makes it necessary for multiple output systems to be divided into more than one process, fairly distributing the environmental inflows and outflows of the multiple output process between the main product and various coproducts. This is referred to as “allocation”.

When allocation is required, the key to robust modeling is to determine

(a) which are the co-products that need to be allocated, and

(b) on what basis should the allocation be made (e.g., on a weight basis, value basis, etc.).

Allocation Decisions Made for this Study

Both metal and non-metal coproducts are produced during molybdenum production. The general allocation rules followed for the study are:

1. Allocations were avoided wherever possible;

2. Allocations made on metal-containing products and coproducts are made on the basis of their mass of metal. The decision to use allocation by mass and by economic value was made primarily because the production of products is dictated by physical processes and because of the volatility of the metals market (if an allocation were performed based on market value, results would have to be generated often to reflect the volatility of the market).
3. Allocations are made by partitioning, not substitution (substitution is made by subtracting out from the system an alternative production of the coproduct, making the assumption that the production associated with molybdenum processes has offset that alternative production).

Both non-metal and metal co-products are produced during molybdenum production. The specific allocation rules for each are presented in the Process Stage Modeling sections.

Modeling

This section contains modeling descriptions of the following:

- Process stage grouping to define the questionnaires (page 10);
- Data categories modeling (page 11);
- Utilities modeling (page 14);
- Mining process stage modeling (page 15);
- Concentration process stage modeling (page 16);
- Roasting process stage modeling (18);
- Briquette production process stage modeling (page 18); and
- Ferromolybdenum production process stage modeling (page 19).

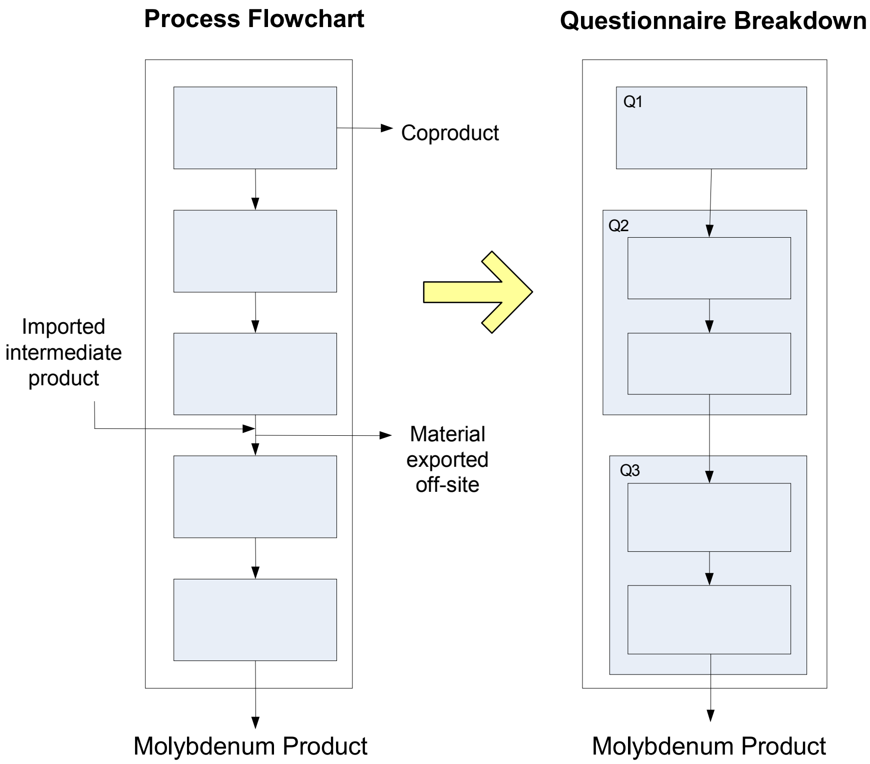
Process Stage Grouping to Define the Questionnaires

Each main molybdenum unit process defined in this study is made up of several smaller processes within the facilities. The ISO standards recommend a black box approach to data collection so that the highest level of data is generated and all inflows and outflows to a product system are included. While the highest level of a process is ideal for the black box, there are factors that require a process to be broken down into smaller boxes. These are:

- **Existence of co-products:** The mere fact that co-products are produced during the process (especially if they do not fall out near the end of the process) means that this process must be broken down to the point at which the co-product is produced.
- **Existence of imports or exports in integrated facilities**: If any intermediate material is transported off-site to be processed elsewhere, or an intermediate product comes onto the site to be processed further, then the two processes would have to be separated since the tonnage of product coming into the facility does not equal the tonnage leaving the facility.
- **Different level of plant integration**: Less-integrated facilities may not be averaged with fully integrated facilities.

These three possibilities are presented in Figure 3.

Figure 3 Flowchart-to-questionnaires



Following this methodology, five separate questionnaires were developed for each main unit process stage: mining, concentration, tech oxide production, briquette production, and ferromolybdenum production. Each black box/questionnaire produced a data set containing plant inputs, outputs, and transportation of materials. In addition, the questionnaire contained qualitative questions on shared utilities such as a wastewater treatment plant. A questionnaire completion guide (both an English and Spanish version) facilitated the data collection process.

Data Categories Modeling

This section describes specific modeling considerations for each black box (questionnaire) component.

Energy and Material Inputs

Refer to the Cut-off Criteria section outlined on page 3 that addresses the energy and material input considerations. A couple additional points to mention are below:

Electricity

Electricity grids specific to each country (or region, if country is not available) were modeled for each of the defined molybdenum unit process stages (by weighted average of the sites involved in the respective unit process stage). Any special energy type or grid that was used, such as a hydropower-only plant, was modeled. Grid mixes corresponding to each region are found in Table 5, with data as close to 2005 as possible:

Table 5 Country- and region-specific electricity grids

	Natural gas %	Coal %	Oil %	Nuclear %	Hydropower %	Other renewables %
Belgium	3	3	3	79	11	1
Canada	4	20	1	15	58	2
Chile (CIS)	23	12	0	0	65	0
Chile (SING)	71	28	0.2	0	1	0
Austria	10	51	2	29	2	7
Mexico	30	10	42	4	10	4
Netherlands	45	10	36	4	0.1	4.6
United Kingdom	39	33	2	23	1	2
US: Arizona	32	41	0	22	4	2
US: Pennsylvania	2	73	0	24	1	0
US: Iowa	2	74	1	16	5	2
US: Colorado	13	81	0	0	5	1
US: New Mexico	32	41	0	21	4	2
US: Idaho	11	34	0	4	49	2

Note: Percentages may not add to 100 due to rounding.

Sources:
Belgium: electricity grid data for France due to lack of available data for Belgium (http://www.eia.doe.gov/emeu/cabs/France/Electricity.html). The coal, oil, and natural gas were estimated. 2004 data.
Canada: data provided by U.S. Energy Information Administration (EIA) (http://www.eia.doe.gov/emeu/cabs/Canada/Electricity.html). The coal, oil, and natural gas were estimated. 2004 data.
Chile: data provided by Codelco. 2005 data.
Austria: electricity grid data for Germany due to lack of available data for Austria (http://www.eia.doe.gov/emeu/cabs/Germany/Electricity.html). 2004 data.
Mexico: data provided by U.S. Energy Information Administration (EIA) (http://www.eia.doe.gov/cabs/Mexico/Electricity.html). 2004 data.
Netherlands: data provided by Renewable Energy Policy Review, European Renewable Energy Council (http://www.erec-renewables.org/fileadmin/erec_docs/Projcet_Documents/RES_in_EU_and_CC/Netherlands.pdf). 2004 data.
United Kingdom: data provided by U.S. Energy Information Administration (EIA) (http://www.eia.doe.gov/emeu/cabs/United_Kingdom/Electricity.html). 2004 data.
U.S, states: data provided by the U.S. EPA Power Profiler (http://www.epa.gov/cleanenergy/powerprofiler.htm). 2004 data.

Facility Water Consumption

Only *net* consumption of process and/or cooling water (e.g., make-up water) was reported and accounted for. Recycled water from within the molybdenum system boundaries was not accounted for, nor was water coming from processes outside the study boundaries or mine water (unless mine water crosses the study boundaries and is not recycled internally). The inventory results provide this data as water as an input to the system, i.e., “water used, total”.

Material Inputs

All known materials used in the process were reported and accounted for, with the goal of 99.5 percent of inputs. For chemicals and reagents, the chemical composition of the compounds were supplied, and the amount was reported in pure terms (e.g., 100 percent of weight) in order to avoid over-reporting the use of that input.. For recycled materials, the percentage of recycled content was specified and modeled accordingly.

Air emissions

Process-related air emissions were reported (e.g., particulate matter, VOCs, ammonia, etc.). In cases where air emissions were not provided in the questionnaires, publicly-available emissions factors were used, especially as they related to fuel combustion related emissions. To ensure the soundness and completeness of the data and to avoid missing data points, facility staff provided the following information for each air emission:

Table 6 Air data collection

1) Value for the year 2005 (or closest year available)	**Facility data**
2) "Zero" for values of zero.	**0**
3) NA if not applicable.	**NA**
4) ND if no data are available	**ND**
5) If ND, is it expected to be at the site?	**Yes/No**

In addition, the following was reported for each air emission:

- Source, i.e., direct plant data or published sources;
- Type, i.e., measured, calculated, averaged, etc.;
- Year of the data.

Efforts were made to report total emissions (fugitive plus stack), but fugitive was not readily achievable for many facilities.

Water Effluents

Total wastewater and effluents generated by the process were reported. If the facility had an on-site wastewater treatment plant (WWTP), the effluents were reported as levels leaving the WWTP. For water effluents from tailings and the tailings pond, effluents were reported if any water leaves the "fence line" of the facility, i.e., leaks or releases to groundwater or surface water. Many facilities reported closed-loop, zero-discharge systems. Water effluent data points were treated with the same data quality as air emissions (Table 6).

Allocation of Effluent Data

Total effluent data released from the site (post-WWTP, where applicable, or direct discharge), was reported as allocated on a "shared" basis. That is, water flows and water effluents were allocated amongst the different relevant site processes. The steps of the physical partitioning allocation procedure are:

- Where indicated in the questionnaires, the site staff allocated the flows as percentages of each process stage on their site, according to their best engineering judgment; and
- Where site staff could not make an allocation, Four Elements made estimations based on physical relationships and knowledge based on similar types of plants.

Solid Materials (Waste and Recovered Materials)

Solid Waste and Residues

Any material that was not considered a recoverable or recyclable material was reported in its dry form as waste. The waste data were collected from facilities for the most part in terms of their physical characterization, not according to general categories, such as unspecified hazardous or non-hazardous waste. This strategy of waste characterization was made to avoid inadvertent mischaracterization of waste (e.g., one facility staff member might call a certain waste non-hazardous, while a staff member at another facility might call it hazardous).

Classification of the waste categories into EUROFER flows (Table 4) occurred after the waste was inventoried.

Solid waste for which the accumulated tonnage represented less than one percent (by weight) of total waste of the production process was not recorded due to the difficulty of reporting and/or tracking such small quantities. Fate (e.g., municipal landfill, non-energy recovery incinerator…) and transportation distance to the final destination were reported and modeled.

Recovered Material

Materials recovered included molybdenum-bearing or other materials produced as a byproduct and used in another process on or off the site. Recovered materials were reported as the following:

1. Recycled as a closed loop material: reused/recycled within the same process from where it came. When this occurred, only the net of its use was included in the model.
2. Reused/recovered/recycled in another molybdenum process; or
3. Reused/recovered/recycled completely outside the molybdenum system.

In points two or three above, when the recovered material was molybdenum- or other metal-bearing, allocations by mass of the metal content were applied.

Transportation

The distances and modes of transport of the raw materials, intermediate molybdenum inputs, and purchased fuels were reported and modeled. Transportation of waste shipped away from the site was also included. As a reminder, transportation of final molybdenum products, recovered material and coproducts is not accounted for in this study, as this is taken into account by downstream users.

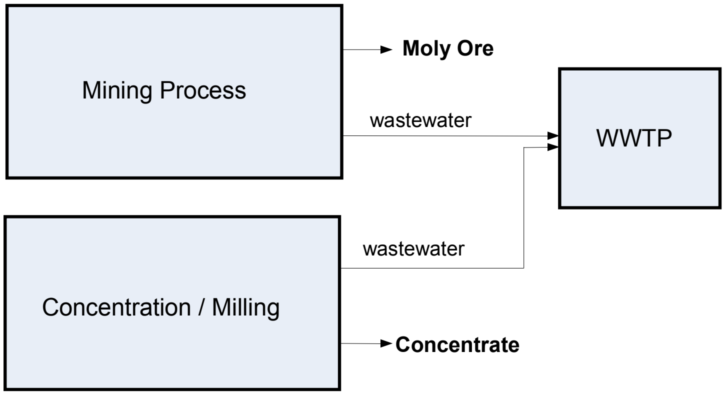
Packaging of the Final Product

Companies reported their packaging types used to ship to customers. Based on responses from the questionnaires, the two most common packaging types that were reported and calculated in the inventories included polypropylene “supersacs”, and 55-gallon steel drums. Other packaging materials such as pallets were not included.

Utilities Modeling

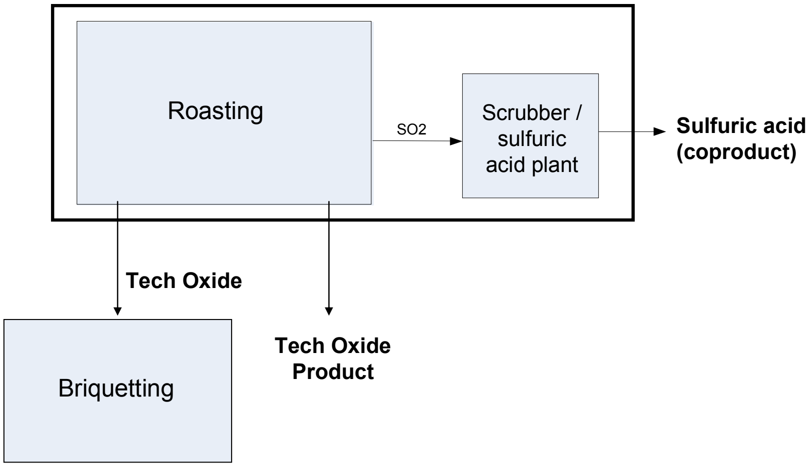
The questionnaires requested input and output data for on-site utilities, such as steam generation plants, sulfur dioxide scrubbers, and WWTPs. Utility data were collected as their own black box or as part of one of the metallurgical processes. For example, data for the WWTP in Figure 4 below was collected as a separate black box since both mining and concentration send wastewater there.

Figure 4 Utilities in the questionnaire (a)



However, in Figure 5, roasting is the only process using the sulfur dioxide scrubber, so all data for the scrubber is collected with the roasting questionnaire.

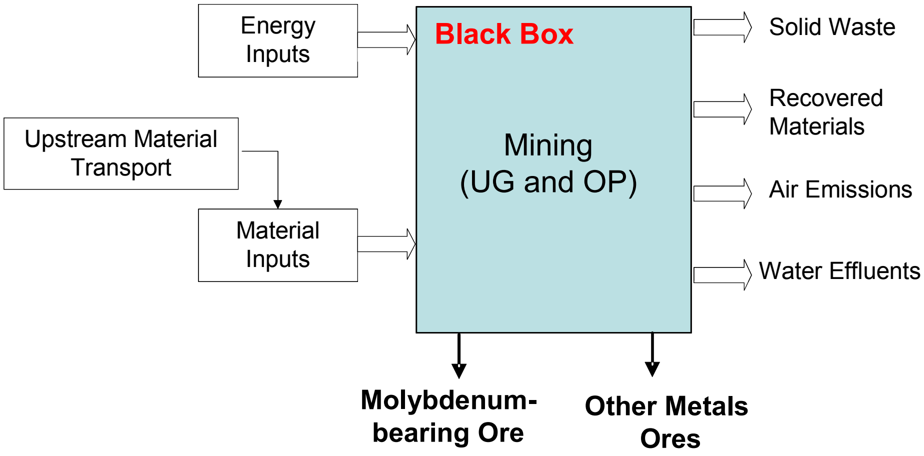
Figure 5 Utilities in the questionnaire (b)



Mining Process Stage Modeling

The mining stage of molybdenum production includes all processes to extract molybdenum ore up to the point of delivery to the concentrator. The mining data was collected as a black box that encompassed all mining operations such as overburden removal, blasting, and ore loading and transport. For some operations, grinding was included in the mining system boundaries, while in other operations, grinding is included in concentration / milling. Both underground and open pit mining were accounted for. In accordance with the overall goal of the study, (i.e., to produce an LCI of average molybdenum products), mining is averaged on a weighted basis for all of the mining facilities without distinction between the underground and open pit mining, or primary or byproduct mining.

Figure 6 Mining system boundaries



Coproduct Allocation

Data was collected from mine operations where molybdenum ore was both a main product and a by- or co-product of other ores. Metals were allocated based on their mass percentage, and the allocation was made based on the metal mass percentage of the *concentrate*. This was done in order to account for not the *potential* yield of the metal but what was actually recovered at concentration.

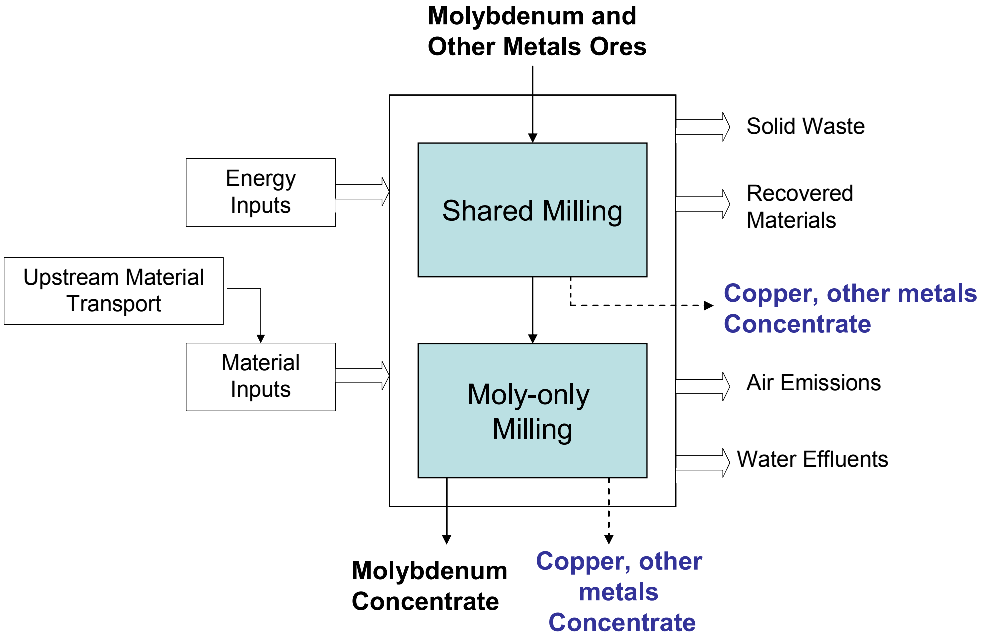
Mining Fuels and Air Emissions

Fuels for underground and open pit mining are primarily consumed in mobile equipment. In the questionnaire, the site staff provided data on how the fuel is used, i.e., either in trucks or other equipment, including heavy loaders or for drilling, blasting or hauling machinery. Fuel emissions factors were used for these applications. Publicly available emissions factors for dynamite and blasting were used where applicable (US EPA *AP-42 Emissions Factors* and Environment Australia, *National Pollutant Inventory: Emission Estimation Technique Manual for Explosives Detonation and Firing Ranges)*.

Concentration Process Stage Modeling

Concentration is the stage at which the ore undergoes crushing, grinding, flotation, and sometimes leaching to obtain an over 90% molybdenite concentrate. The concentration processes generally start at the primary crusher and continue to the point of delivery of concentrate to the roaster (but not delivery itself). Figure 7 presents an overview of the concentration (milling) system.

Figure 7 Concentration system boundaries



Questionnaire Organization

Concentration processes may produce copper concentrate or other coproducts at different stages. In order to correctly allocate environmental inflows and outflows to these processes across many facilities, two situations were defined for data collection and aggregation:

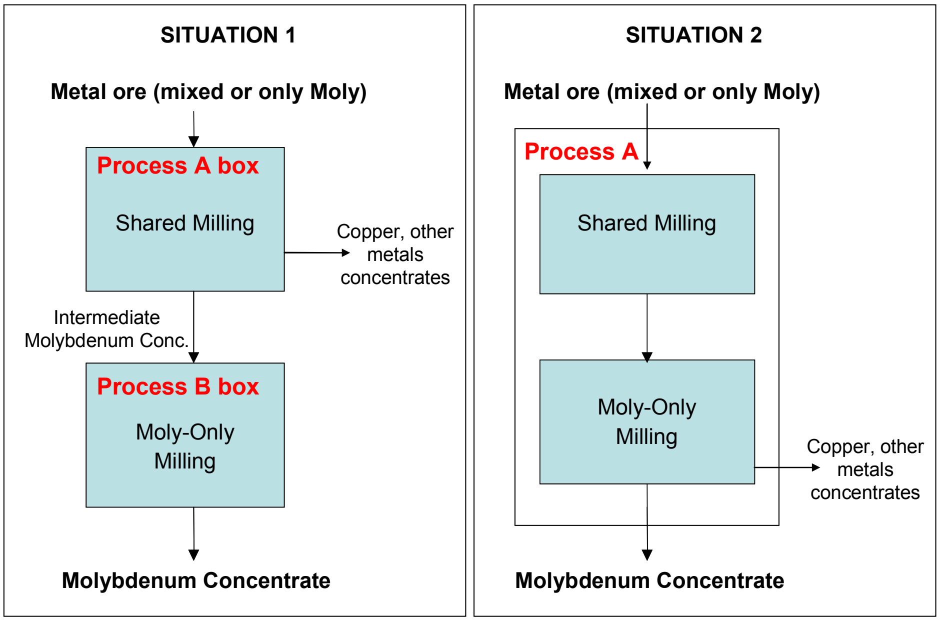
Situation 1: Two Black Boxes / Two Questionnaires

This situation was applied where copper (or other metal) concentrate is produced before the molybdenum concentrate is fully processed. Since subsequent moly-only milling processes may be energy intensive and may consume additional materials, it is necessary to break concentration down into two black boxes, with input and output data collected for both (i.e., Process A box and Process B box in Figure 8).

Situation 2: One Black Box / One Questionnaire

The processes for this situation can be put into one black box since the concentrate(s) that leave the concentration plant come out at the same time or are all mixed as one concentrate. In this case, only one set of inputs and outputs are collected in one questionnaire.

Figure 8 Concentration data collection situations



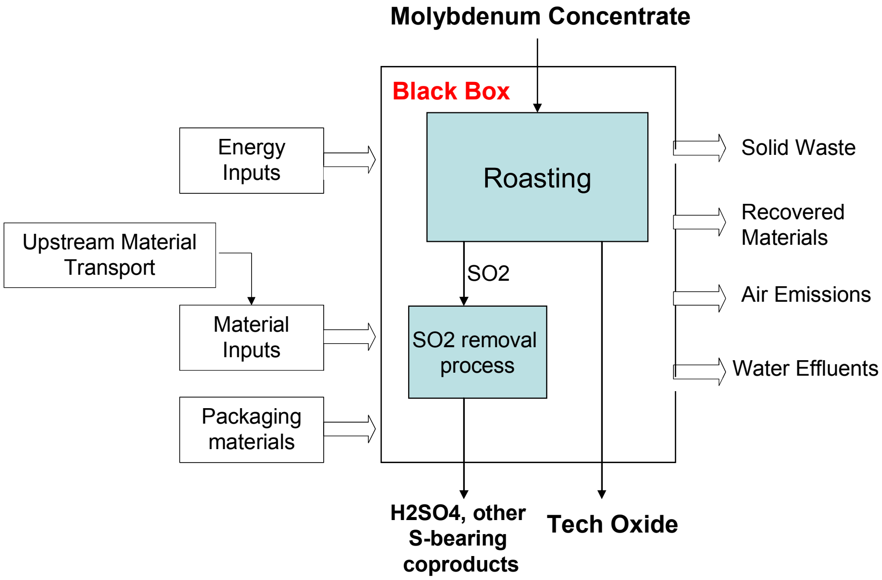
Coproduct Allocation

For Situation 1 in Figure 8, an allocation based on the metal mass in the concentrates was applied to the products from shared concentration (i.e., copper concentrate and the intermediate molybdenum concentrate), and generally no allocation was necessary for the moly-only concentration. For Situation 2, an allocation based on the metal mass of the concentrates produced in the Process A box was made if applicable.

Roasting Process Stage Modeling

Roasting is a pyrometallurgical process that converts the molybdenite concentrate into technical molybdic oxide as a final product (in powder form, going to customers) or as an intermediate product to be further transformed into briquettes or ferromolybdenum. Because the material is naturally sulfur-rich, many plants include sulfur dioxide abatement technologies that produce marketable products such as sulfuric acid. These processes are shown in Figure 9.

Figure 9 Roasting system boundaries



Allocations

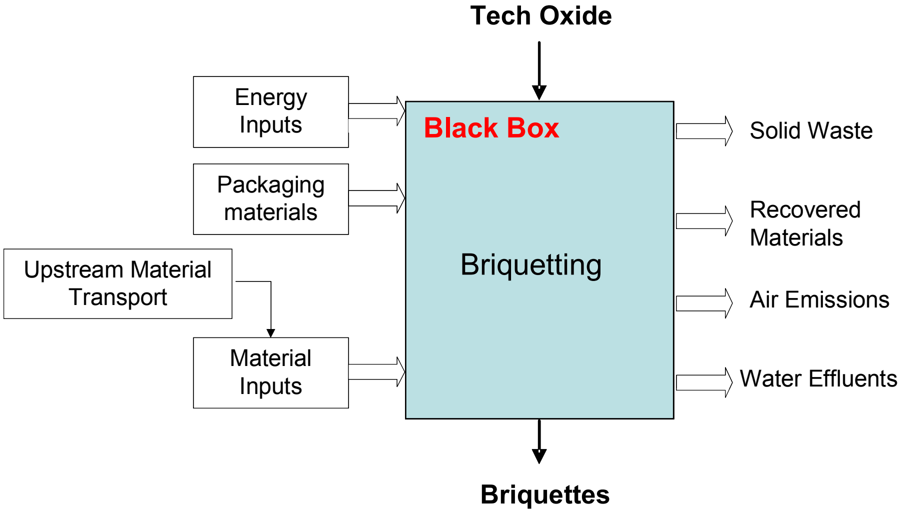
For metal coproducts, allocations were made based on the mass of the metal content of the coproducts. This applied to copper and a small amount of rhenium produced at some roasting facilities.

In the case of non-metal coproducts such as sulfuric acid, no allocations were made between the sulfur product and the metal-containing products. The reason for this modeling decision is that the sulfuric acid would not be produced if it weren't for the processing of the molybdenum concentrate. Furthermore, this is the most conservative, and least contentious, modeling decision, as the sulfur product does not take away any environmental burden from the tech oxide, and the sulfur plant's inflows and outflows stay with the molybdenum system. This modeling choice is also used by several molybdenum producers and other metal industries facing similar by/coproduct issues.

Briquette Process Stage Modeling

Briquetting includes the processes starting at the delivery of the tech oxide to the briquetting plant through the formation of briquettes to their point of delivery. Briquettes are pressed as either cylinders or pillows after application of a binder, typically an ammonium-based product. No coproducts were produced in the briquetting system. Figure 10 presents the briquetting system.

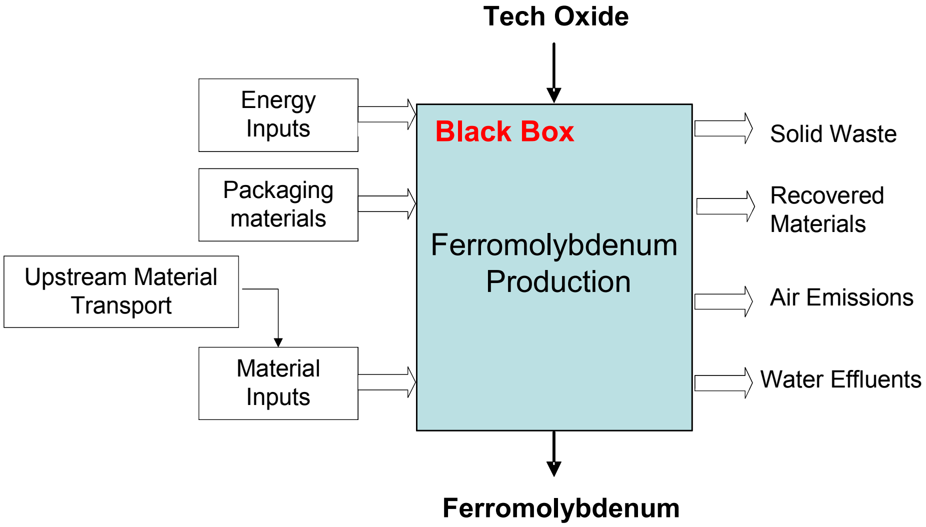
Figure 10 Briquette system boundaries



Ferromolybdenum Process Stage Modeling

Ferromolybdenum production includes the processes starting at the delivery of the tech oxide to the ferromolybdenum plant where tech oxide is reduced in the presence the iron sources, to the point of delivery of the finished ferromolybdenum. No coproducts were produced in the ferromolybdenum system. Figure 11 presents the ferromolybdenum system.

Figure 11 Ferromolybdenum system boundaries



Data Aggregation and Modeling

Preliminary Questionnaire Check

As questionnaires were returned to Four Elements, they were checked for overall completeness, from both a quantitative and qualitative perspective. Four Elements worked during this early stage to locate and correct possible discrepancies, errors and data gaps within each facility data set before aggregating them into data summary sheets (DSSs), the final averaging and aggregating step in the production of the average data set for each unit process stage. Specific checks included the following:

- Data tables, data quality indicator tables, and qualitative questions were checked for completeness;
- A molybdenum balance was calculated for each black box questionnaire to ensure correct balance of molybdenum inputs and products. Where there was an imbalance of greater than plus/minus 3%, the facility was contacted for verification;
- Energy sources at each facility were summed into a total energy value in order to compare the energy consumed for like process stages. Where energy consumption for a facility was not in the same order of magnitude of similar facilities, the facility was contacted for verification of fuel and electricity inputs;
- Utility repartitions were checked to be sure that the contributing processes added to no more than 100%; and
- Flows used or recycled internally and used in the metallurgical system were subtracted out of the system.

Facility-Level Aggregation

A typical questionnaire that was sent to each of a participating company's facility had one or more data black boxes plus black boxes for on-site utilities. For example:

Site Information for Questionnaire Data	
Site Name and location:	
Products Produced and Utilities:	molybdenum ore copper ore molybdenum concentrate copper concentrate WWTP

Most questionnaires had any combination of utility data, coproducts to allocate, and recycling loops to model. The following steps were taken to distill this complex relationship into raw data sets for each main unit process stage.

1. Utilities were allocated amongst the applicable processes;
2. Internal-loops were addressed;
3. Co-products and/or recovered materials not used in the molybdenum system were allocated or removed; and
4. Raw data sets were placed into separate DSSs for each unit process stage and the final DSSs were prepared.

Step 1: Utilities allocated between the products or processes

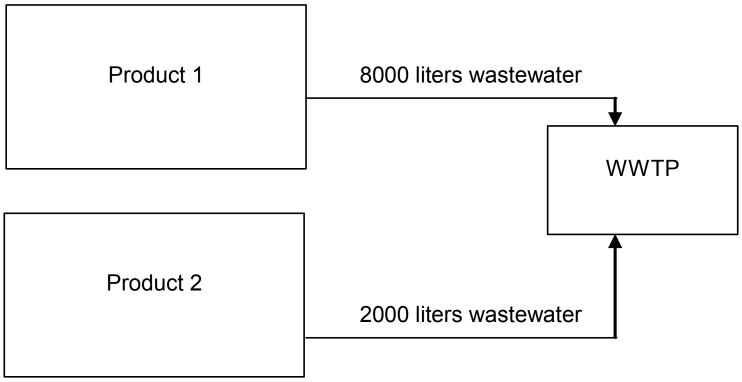
The facility staff provided allocation information for the on-site utilities, in a box like the one below.

Utility 1 (specify ___________)

Percentage allocated to various process stages:
_________%

Using this data, all inputs and outputs reported in the utility section were added to the appropriate metallurgical process boxes according to their use in the processes.

Figure 12 Allocating utility data



In the Utility section: % allocated to Product 1: 80%
% allocated to Product 2: 20%

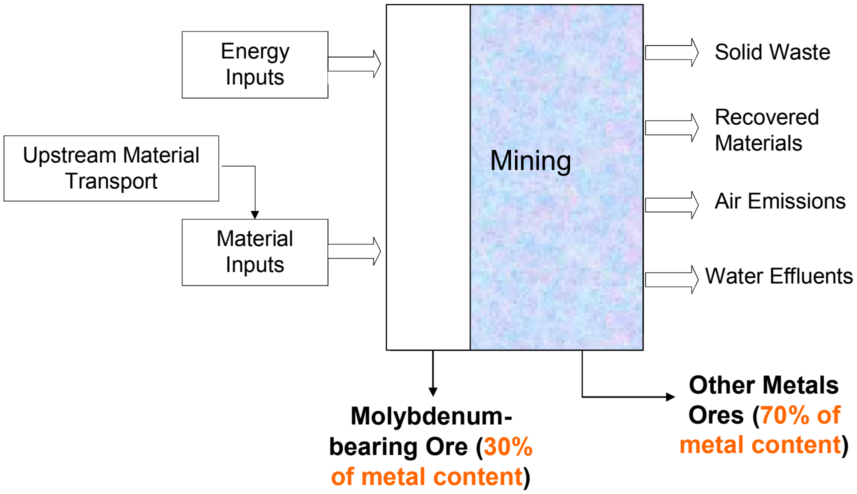
<u>Step 2</u>: Treatment of internal loops between metallurgical processes

Internal loop flows in a facility were subtracted out of each product's system as long as the input/output amounts were the same. For example, a facility produces sulfuric acid from the roasting process and sends it to the concentrator. If the output and input amount was the same, it was treated as a closed loop, with the environmental burden of production at roasting. If the amounts differed, then only the net amount was counted as an inflow to the process or as a coproduct.

<u>Step 3</u>: Treatment of co-products and/or recovered materials not used in the metallurgical processes

All coproducts and recovered materials were allocated away from the molybdenum systems according to their allocation rules. The coproduct allocation is illustrated in Figure 13 in which only 30% of the inputs and outputs of the byproduct mine are allocated to the molybdenum system.

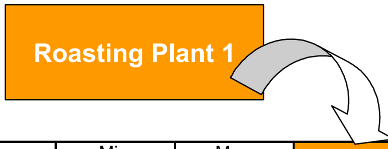
Figure 13 Coproduct allocation illustration



Step 4: Final preparation for DSS

At this point, the resulting product inputs and outputs are normalized to one kilogram of molybdenum in the unit process output and are averaged with other products, shown in Figure 14. The next section details the DSSs.

Figure 14 Aggregating questionnaire: step 4



Tech Oxide Production			Weighted Average	Min. Reported Value	Max. Reported Value	Roasting Plant 1	Roasting Plant 2	Roasting Plant 3
Moly product	Tech oxide	kg						
	Moly in Tech Oxide	kg						
Coproducts	Sulfuric Acid (H2SO4, 100%)	kg						
	Rhenium	kg						
	Copper in Cu coproduct	kg						
Energy In	Electricity (from off-site)	kWh						
	Diesel Oil	kg						
Material In	Total Molybdenum Mass in	kg						
	Moly In	kg						

Data Summary Sheets

As demonstrated above, fully aggregated data sets were placed into spreadsheets organized into individual unit processes. Table 7 presents part of a blank DSS, and the next sections describe each component.

Table 7 Blank DSS

Tech Oxide Production per 1 kg Mo			Weighted Average	Min. Reported Value	Max. Reported Value	Avg type - Only rpt'd?	# Sites who Reported	% of Sites	Comments
Moly product	Tech oxide	kg							
	Moly in Tech Oxide	kg							
Coproducts	Sulfuric Acid (H2SO4, 100%)	kg							
	Copper in Cu coproduct	kg							
Energy In	Electricity (from off-site)	kWh							
	Diesel Oil	kg							

Weighted Average and "Averaging Type"

A weighted average was taken for each unit process inflow and outflow. Two types of weighted averages were made: a weighted average of all of the sites together or a weighted average of only the sites that reported the flow ("*Avg. type – Only rpt'd?*"). The reason for distinguishing this is based on different representation in the industry. "No" to *Only reported* refers to a flow that is not necessarily found at all of the facilities, such as an obscure chemical used by only a few facilities. The flow would therefore have to be averaged over all sites since this is an industry average. However, an outflow such as ammonia to air might be expected to be emitted from all briquetting sites, assuming all facilities are using some ammonia-based products in the process. Therefore, if a briquetting facility does not report ammonia air emissions, then the average method for *only reporting sites* is used: the ammonia is averaged across only the sites that reported it, so as to not reduce its industry representation.

For the most part, an average was made over all sites for materials and energy in and the solid materials out of a unit process. Air and water outflows that were *expected* to be released were averaged for only the sites that reported data for them.

Minimum and Maximum Values

Minimum and maximum data values provided the variability of each data category as a means of checking the precision of the data. Outliers were double-checked by the site staff to determine whether they were valid and should be included in the average, and any number that could not be explained or validated was removed from the data set. Besides their use in identifying data deficiencies or outliers, there was no statistical or quantitative check for a margin of error.

Number of Sites, Percent of Total Sites

The number of sites that reported data and the percent of total sites that reported data provided an indication of data gaps (for such flows as air emissions and water effluents) as well as an indication of how representative that specific flow is in the industry (for flows like materials and energy).

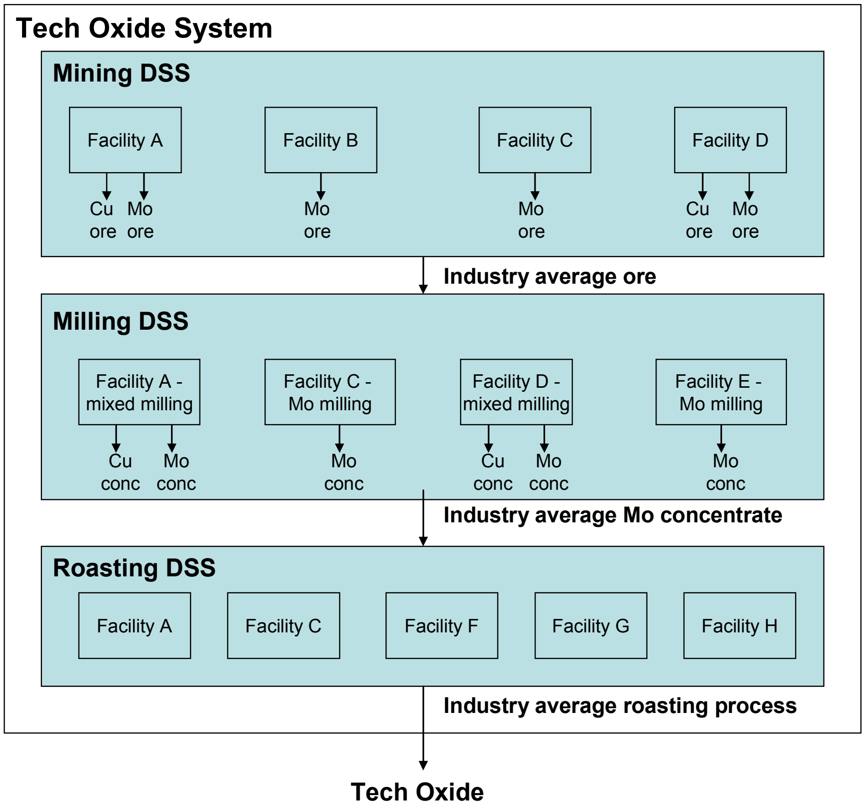
Comments

The comment section provided explanation where necessary, including stating which material input flows were not included in the model due to lack of available data.

Final Aggregation of Data to Produce the LCI

Figure 15 presents the overall process by which the individual data sets of each unit process are aggregated horizontally to produce one weighted average data set, which is then linked to the next unit process stage. In the figure, the mining, milling, and roasting are linked together in the LCA software to produce the LCI results for tech oxide.

Figure 15 Horizontal and vertical aggregation of data sets



Data Quality Evaluation

Evaluation of data quality is important not only to understand the reliability of the data, but also to properly interpret and/or use the results. This section summarizes the study's data quality requirements as listed on page 8:

Data Completeness and Representativeness

ISO 14044, Section 4.2.3.6, defines completeness as the "percentage of flow that is measured or estimated." One of the goals of the study was to increase the number of participants and include as many facilities as possible for the most representative LCI of these products. Even though this goal was met and more companies participated, a quantitative analysis on completeness for each unit process stage could not be performed to protect the confidentiality of the participants.

Representativeness is defined by ISO 14044 Section 4.2.3.6, as a "qualitative assessment of degree to which the data set reflects the true population of interest", includes geography (i.e., area covered), temporal data (i.e., the age of data and length of time over which data should be collected), and technological coverage (i.e., the technology mix) as defined by the goals and the scope of the project.

Geographical Representation

Data from facilities around the world were collected to represent the molybdenum industry. The primary molybdenum data collected and modeled for this study represents approximately 52% of the total molybdenum produced in the world and 74% of western world production, according to the IMOA website.

Temporal and Technological Representation

The primary data collection represents production for the 2003 or 2005 calendar year. A smaller percentage of facilities used their 1999 primary data, only after a very rigorous check on general facility processes, energy balances, and technological changes over the last eight years was made. Thus, technologically, it can be assumed that the data collected represents current technologies and practices. A summary of the data collection dates for molybdenum produced is provided in Table 8.

Table 8 Molybdenum production quantities represented in this LCI

	2005	2003	1999
Mining	44%	40%	15%
Milling/concentration	45%	39%	15%
Roasting	74%	13%	14%
Briquetting	100%	0%	0%
Ferromoly Prod	62%	0%	38%

Upstream Materials Production

The use of secondary data for production of non-molybdenum-bearing inputs (upstream materials) is an inherent limitation to the study because it may cover a broad range of technologies, time periods, and geographical locations. The use of secondary data is normal and necessary in an LCI, but measures are made to use the best data that available at the time of the study – as normal practice, Four Elements regularly maintains and updates the LCA database as more recent and/or better quality data become available. And when there is a choice between two data sets, the better quality data is used (more recent, more representative, etc.).

Cut-off Criteria

As is shown in Table 9, the inputs exceeded the cut-off criteria goal of 99.5%. Inputs of fuel and net water used were not included in this count.

Table 9 Cut-off criteria analysis

	Cut-off Results for Inputs excluding Mo-bearing & energy inputs	Comments
Mining	100%	No data for PETN (0.002%)
Milling/Concentration	99.97%	No data for undisclosed materials, xanthates, Mercaptbenzothiozol, MIBC
Roasting	100%	
Briquetting	100%	
Ferromoly Production	100%	

Consistency

Overall Consistency

Consistency is a qualitative understanding of how uniformly the study methodology is applied to the various components of the study. This quality of measure is one of the most important aspects for such a large-scale study with many facilities and questionnaires involved. A number of steps were taken to ensure consistency within this study and with the original LCI, including ensuring that the:

- Same methodologies and allocation rules were applied except where rules or scope changed;
- Same data categories were used and their information was collected in questionnaires;
- Questionnaires asked for the same qualitative data; and
- Same modeling was applied.

Consistency was maintained in the handling of questionnaires in order for the many individuals completing them to provide appropriate data in the appropriate manner. The questionnaires were distributed in electronic format with User Guide instructions on what type and form of data were needed, how data points should be reported, and how the data points were obtained. When questions arose, Four Elements communicated directly with the sites to resolve issues. When completed questionnaires were returned and rigorous data checking was completed, the data was linked to DSSs for further data processing and checking. This process was treated in the same, consistent manner for all questionnaires. With a common approach to data collection from the sites, communication with the sites, and data handling, overall consistency in the work was maintained.

Data Checking

Data Quality Indicators

The questionnaire included qualitative data quality indicators, including information on the time span of the reported data, the source of the data, and the type of data. Data source refers to where each data point originated. For example, the facility staff specified whether the data point came from the plant itself or from another source (other sites, published emissions, etc.). Data type refers to how each data point was obtained. Facility staff specified whether the data point was:

- Measured (e.g., electricity meter);
- Estimated (i.e., estimation had been established based on approximations, like transportation distance);
- Calculated (i.e., using emissions factors, mass balance, etc); or
- Shared or apportioned (i.e., data for two processes are estimated).

Data Availability

Particular attention was made to identify areas of the questionnaire that could potentially have data gaps, such as unknown or unmeasured air emissions and water effluents. Users were given specific instructions to fill out the air emissions and water effluents sections of the questionnaire (refer to Table 6, page 13). This was done to ensure that any blank cell in the questionnaire was not misinterpreted or misrepresented in the data set. This approach was used especially to assess whether the emission should be averaged over all of the sites or across only the sites that reported that data.

Reproducibility

Reproducibility is the qualitative assessment of the extent to which information about the methodology and data values allows an independent practitioner to reproduce the results reported in the study. The modeling and methodology are transparent enough such that an independent practitioner could reproduce the results.

Precision

Precision is the measure of the variability of the data values for each data category expressed. The minimum and maximum data values provided in the DSSs provide the variance of the data points.

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