European Commission
Horizon 2020
European Union funding
for Research & Innovation

PUBLIC REPORT ON TECHNOLOGY AND LIFE CYCLE ASSESSMENT

D7.5

PROGRAMME	H2020 – Environment and Resources
GRANT AGREEMENT NUMBER	689515
PROJECT ACRONYM	INTMET
DOCUMENT	**D7.5**
TYPE (DISTRIBUTION LEVEL)	☒ Public ☐ Confidential ☐ Restricted
DUE DELIVERY DATE	M36
DATE OF DELIVERY	31 January 2019
STATUS AND VERSION	0
NUMBER OF PAGES	26
WP / TASK RELATED	WP 7 / Task 7.1 & Task 7.2
WP / TASK RESPONSIBLE	CLC
AUTHOR (S)	CLC
PARTNER(S) CONTRIBUTING	CLC, TR, OUTOTEC, MINTEK, SOMINCOR, BOR, IMN, BRGM, IMNR, AGQ, MINPOL, KGHM
FILE NAME	D7.5 Public Report on Technology and Life Cycle Assessment

DOCUMENT HISTORY

VERS	ISSUE DATE	CONTENT AND CHANGES
0	31/01/2019	First issue

DOCUMENT APPROVERS

PARTNER	APPROVER
CLC	FRANCISCO SÁNCHEZ

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

AACE	American Association of Cost Engineering
CAPEX	Capital expenses
CLC	Cobre Las Cruces
EW	Electrowinning
IRR	Internal rate of return
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MSA	Methanesulfonic acid
NPV	Net present value
OPEX	Operation expenses
PLS	Pregnant Leach Solution
SX	Solvent extraction
TR	Técnicas Reunidas
WP	Work Package

1. INTRODUCTION

INTMET project falls under the PolymetOre (EIP-RM Awarded Commitment) umbrella aiming to develop a sustainable and efficient solution to process polymetallic, complex and low grade ores to allow exploitation of resources that are unviable today by conventional routes due to their complexity or low grade.

These are valuable resources which are abundant in some European mining regions as Spain, Portugal, Poland, Serbia, Sweden or Greece. INTMET opens up a new path to increase raw materials efficiency in EU mining business, since it will allow the unlocking of a substantial volume of difficult ores that are currently unviable to treat through conventional ways.

In this context, the main concept is producing bulk concentrates or middling concentrates that will be efficiently treated through tailored leaching technology approach to produce added value refined metal (commodities) like copper or zinc, other metals as lead and critical materials (e.g. silver, gold, indium or cobalt).

Most important objective of INTMET is applying on-site “Mine to Metal” through an integrated treatment of the produced concentrates, combining innovative hydrometallurgical processes (atmospheric, pressure and bioleaching), and novel more effective metal extraction techniques (e.g. Cu/Zn-SX-EW, chloride media, MSA, etc.). Additionally, secondary materials like mining (tailings) and metallurgical wastes are included for valorisation and metal recovery.

These hydrometallurgical processes were proved to have the potential to treat existing complex or low grade concentrates from current operating mines, opening the way to a new and profitable mining business model. Effluents from processes are reused and recycled, maximizing the recovering of dissolved metals.

Technical, environmental and economic feasibility of the entire approaches were weighed up in INTMET project to offer a real business solution, since the final goal is to ensure the economic viability of the entire INTMET process.

Work package 7 seeks to provide an overall assessment of the different technologies developed in the INTMET project from both economic and environmental perspectives. In this regard, several objectives were established in the proposal:

- Assessment and evaluation of the developed novel leaching technology capable to treat efficiently low qualified or low grade concentrates or polymetallic concentrates to yield high quality and added value metal products.
- Defining specific conditions and potentiality to apply the innovative developed technologies in existing hydrometallurgical plants or in new projects.
- Detection of potential synergies among industries to provide possibilities for integration of the technology in the existing plants.
- To identify and quantify the environmental burden due to the considered technologies, with a direct comparison of their global environmental performance by means of a life-cycle-Assessment approach.

Task 7.1 “Technology assessment and cost assessment” covered the engineering study and the techno-economic assessment of the proposed technological solutions. During first part of the project, a technical study was conducted on a conceptual level using data from lab scale tests, and supplemented with data from virtual simulations. An initial economic assessment, a preliminary estimate for operation and capital expenses, of the three proposed technological solutions was also performed at this stage. Technical, economic and environmental outputs from that first assessment helped to decide the most promising technology for each material. It also helped to design and determining experimental conditions at pilot plant scale in the second part of the project.

The second part of the project in task 7.1 encompassed the final assessment of technologies and INTMET project evaluation. It was accomplished after pilot plant operations, once the set of data produced after piloting provided more detailed technical information and process parameters in order to update previous technical and economic studies, including both, detailed mass balances and economic analysis for each technology. This final assessment only involved the most suitable material in each case:

- **Atmospheric leaching** applied to **Cobre Las Cruces (CLC) ore** (Spain).
- **Pressure leaching** applied to **the bulk concentrate provided by Somincor** (Portugal).
- **Bioleaching** process applied to **the concentrate provided by the BOR mine** (Serbia).

Task 7.2 “Life Cycle Assessment (LCA) for developed technological solutions” in WP7 aims at quantifying and analysing the environmental performances of the process chains in INTMET project by use of Life Cycle Assessment (LCA). Life cycle assessment (LCA) can be defined as a methodology for assessing a product or a process potential environmental burden along its life cycle from a “cradle-to-grave” perspective i.e. from the raw materials extraction to the end-of-life.

The standard for carrying out LCA implemented was ISO 14040 series by the International Organization for Standardization (ISO). In addition to these standards, the International Reference Life Cycle Data System (ILCD) handbook (JRC, 2010) was also used, such it provides a detailed guidance on LCA.

LCA framework includes four main steps:

- The goal and scope definition of the study comprising elements such as the decision context, the intended applications, the functional unit, the system boundaries, etc.
- The Life cycle inventory (LCI), which is the most demanding part of the LCA study in terms of duration and resources as it consists in the collection of data about the inputs and outputs relative to the system under study.
- The Life Cycle Impact Assessment (LCIA), which consists in the translation of the previously collected data inventory into impact calculations relative to different impact categories (e.g. climate change, ozone depletion, human toxicity, etc.)
- At last, comes the interpretation phase which “serves to steer the work towards improving the Life Cycle Inventory model to meet the needs derived from the study goal” to finally “derive robust conclusions and – often – recommendations.” (JRC, 2010)

It is to be noted that performing an LCA is an iterative process that allows refining the LCA study through its different stages (e.g. revision of the goal and scope, improvement of data inventory quality etc.).

Results and data gathered from tasks comprised in “Technologies assessment and Project Evaluation” work package are summarized and reported below, which constitutes the deliverable D7.5 “INTMET project assessment and LCA”.

2. LABORATORY AND PILOT PLANT RESULTS ACHIEVED

Tasks to design and integrate the hydrometallurgical technologies covered in INTMET project were developed in two phases:

1. Laboratory test works to study and proof the concept of selected technologies.
2. Integration and demonstration of developed technologies at pilot plant scale.

Polymetallic and bulk concentrates samples from four different mines have been delivered and tested: CLC, KGHM, BOR and SOMINCOR. Additionally, flotation tailings samples have been collected and analysed from CLC and SOMINCOR. Flotation laboratory test works for production of specific sample were performed.

Microwave radiation, electric-pulse fragmentation (EPF) process and high intensity grinding tests have been done to study their influence on efficiency of comminution processes, mineral liberation and metal recoveries. Conventional and new generation commercial collectors have been checked to maximize metal separation and recovery from polymetallic and complex ores in the flotation process. Process flowsheets and flotation protocols have been developed. Flotation Pilot Plant has been built and operated to produce bulk concentrate samples to develop the three hydrometallurgical processes at lab scale: Atmospheric / Pressure / Bio-leaching. In general, very positive results were produced in laboratory tests.

Related to pilot plants, they were designed, arranged and operated applying different technology approaches based on Atmospheric leaching, Pressure leaching and Bioleaching of bulk concentrate samples. Pilot plants results confirmed the expectations of previous laboratory tests, validating the innovative technological approaches.

FIGURE 1. CLC FLOTATION PILOT PLANT (LEFT). CLC ATMOSPHERIC LEACHING PILOT PLANT: REACTORS CASCADE AND FILTRATION (RIGHT).

FIGURE 2. TR LEAD AND SILVER LEACHING PILOT PLANT (LEFT). OUTOTEC LEAD PRESSURE LEACHING PILOT PLANT (CENTRE).OUTOTEC Cu SX PILOT PLANT MIXER SETTLERS (RIGHT).

FIGURE 3. BIO-LEACHING PILOT PLANT FACILITIES (MINTEK AND BOR INST).

Using obtained information from research tasks and piloting activities, a final assessment of the technology for process integration was performed showing very promising results. In addition to that, the preliminary results on LCA obtained from the different technologies indicate the sustainability of the technologies under development.

INTMET results will allow increasing the recovery efficiency of metals such as Cu, Zn, Pb and Ag in a range of 30% to 50% higher than conventional technologies based on selective flotation, and will allow recovery of some critical materials (e.g. In, Co, currently not recovered) from low grade, complex and polymetallic ores, as well as secondary materials from mineral and metallurgical processes. This will lead to a reduction of the energy consumption (20%), CO_2 (up to 36 %), lower SO_2 emission and the Product Life Cycle Cost.

3. TECHNOLOGY ASSESSMENT

INTMET technology assessment includes both, technical and economic development and analysis.

The starting point for the assessment was the grade of the samples obtained from WP1 and WP2. The following table summarise the base metals grades.

TABLE 1. SAMPLES MAIN COMPOSITION.

Sample	Cu (%)	Zn (%)	Pb (%)	Ag (ppm)
CLC	1.4	5.4	3.3	82
BOR	1.8	4.9	4.6	120
SOMINCOR	2.5	8.9	15.2	265

This final assessment was developed only for the most suitable material previously chosen for each technology:

- Concentrate from Cobre Las Cruces Mine for Atmospheric Leaching.
- Somincor concentrate for Pressure Leaching.
- BOR concentrate in case of Bioleaching process.

The technical study for each technology covered a block diagram definition and a basic material balance, accounting for the main metal values, in order to get a prospective of the flows and composition of the main streams, including residues and effluents, and estimate consumption of the reagents and utilities with impact on operational costs.

Regarding the economical assessment, the objective was obtaining a well-founded estimate of operational costs (OPEX), capital expenditure (CAPEX) of a greenfield plant and profitability and sensitivity analysis.

For CAPEX estimate, a proven methodology according to international guidelines has been applied: Methodology of Estimate Class: 5 - AACE recommended international practice number 18R-97 with an accuracy of order of magnitude estimate (typically -30% to +50%). Class 5 estimates virtually always use stochastic estimating methods such as cost/capacity curves and factors, scale of operations factors, Lang factors, Hand factors, Chilton factors, Peters-Timmerhaus factors, Guthrie factors, and other parametric and modelling techniques.

The profitability analysis was included with the objective of providing a more comprehensive economic evaluation. Internal rate of return (IRR), net present value (NPV) and payback were calculated for a capital budgeting estimate. Related to the sensitivity analysis, it reveals the impact on the total result of changes in individual parameters in order to identify those input parameters which have the greatest influence.

3.1 TECHNICAL ASSESSMENT

3.1.1 ATMOSPHERIC LEACHING

Bulk concentrate obtained from Cobre Las Cruces contains valuable metals as copper, zinc, lead and silver, as it was previously mentioned. In Atmospheric leaching hydrometallurgical process, the concentrate is leached as first step to recover those valuable metals. This process takes place at high temperature and atmospheric pressure. Sulphuric acid is used at this stage to adjust the pH, and oxygen is also fed as oxidant agent. Leaching reactions are helped by the catalytic effect of silver, which is recovered downstream in the lead and silver plant and recycled later to atmospheric leaching plant.

The aim of metals recovery and refining after atmospheric leaching is to extract copper and zinc from PLS and lead and silver from atmospheric leaching residue.

PLS will be fed to a set of treatments comprising: solvent extraction and electrowinning of both copper and zinc, melting and casting of zinc, neutralization and bleed treatment. This will be, in whole, referred to as “SX PLANT”.

Leaching Residue will be fed to a plant comprising a circuit of leaching and precipitation in a concentrated brine medium. This will be referred as “Pb&Ag PLANT”.

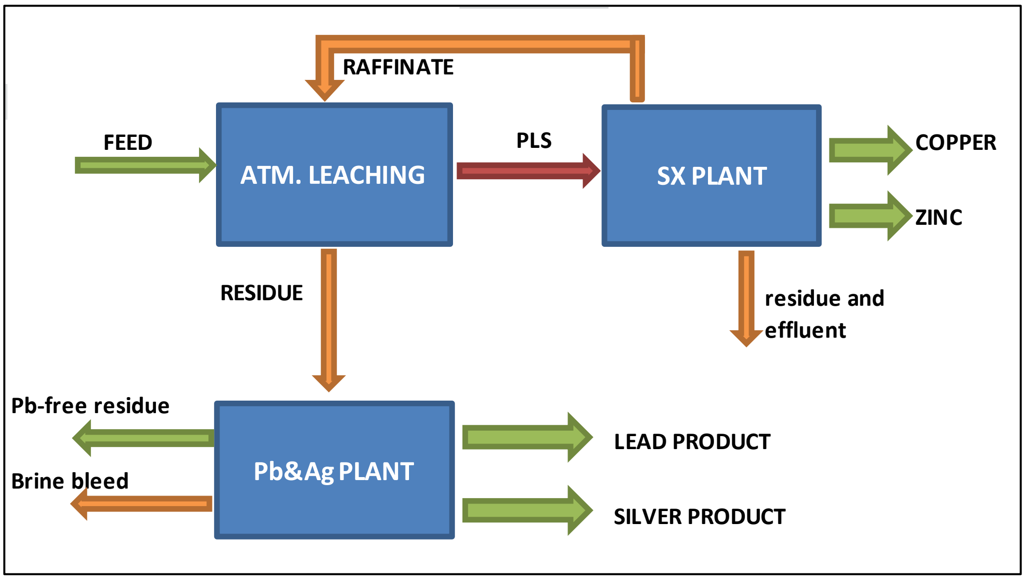

FIGURE 4. ATMOSPHERIC LEACHING SIMPLIFIED OVERALL PLANT.

Material balance was performed on the basis of the above block diagram, employing the simulation software METSIM®. Information provided by CLC has been used, along with TR’s testwork results, previous expertise and general bibliography. A set of consistent data related to the streams shown at the material balance is provided. Feed capacity established for calculation is 1,000,000 tonnes per year.

The following tables show the main streams depicted on block diagrams, with main metallurgical balance.

TABLE 2. MAIN INLETS AND OUTLETS AT ATMOSPHERIC LEACHING PLANT.

Plant Capacity		
CLC Bulk concentrate	tph	120
	Mtpa	1
Cu	ktpa	up to 13
Zn	ktpa	up to 50
$PbCO_3$	ktpa	up to 42
Ag	tpa	up to 59

3.1.2 PRESSURE LEACHING

Pressure leaching technology evaluation for INTMET project was based on Somincor concentrate. Main processing steps are: pressure leaching, neutralisation and iron removal, solvent extraction and electrowinning for both, copper and zinc. A separate lead recovery circuit is included for the pressure leach residue.

Pressure leaching is based on Pressure oxidation reaction, which is an exothermic reaction. It is cooled by means of water quench cooling and, by feeding of recycled process slurry. The leach residue is directed to lead recovery.

The leach solution from leaching is fed to the copper solvent extraction (SX) unit. Copper is extracted by an organic extractant from the leach solution. The organic flow is scrubbed and after that copper is stripped by a sulphuric acid solution. The strip solution is directed to copper EW unit where copper cathodes are produced.

Zinc recovery takes place by SX where organic extractant extracts zinc. After scrubbing, the organic stream is directed to zinc stripping where acid solution is used. The stripped zinc solution is pumped to the zinc EW unit where zinc cathodes are produced.

The leach residue from the pressure leaching is directed to the lead recovery section. The residue is treated to convert the lead jarosite to lead sulphate. Then, the converted material is fed to the leaching stage.

The block diagram developed for Somincor concentrate treatment is shown in next figure:

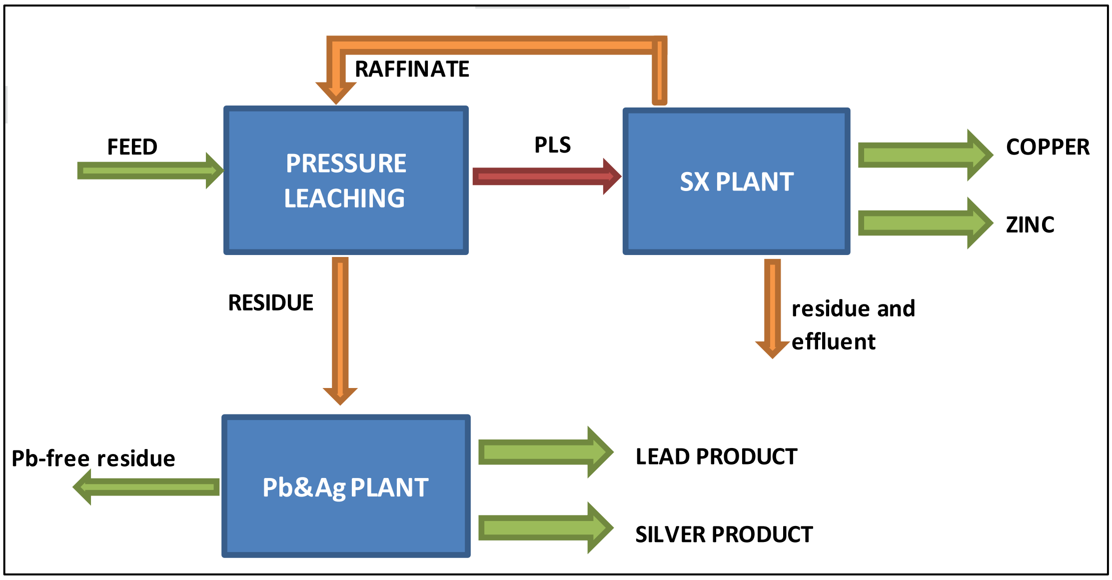

FIGURE 5. PRESSURE LEACHING BLOCK DIAGRAM.

The basis for the study was test work results of piloting applied in a flowsheet model using HSC Sim software. Concentrate feed and main metal production is given in next table. Annual operation hours (availability) are assumed to be 8.000 hours per annum (91%).

Feed of Somincor concentrate was adjusted to match an annual zinc production of 50.000 tonnes.

Mass and main elemental flows of main feeds and products are given in next table.

TABLE 3. PRESSURE LEACHING MAIN MASS FLOW RATES.

Plant Capacity		
Concentrate	tph	71
	ktpa	568
Cu	ktpa	13.6
Zn	ktpa	50.4
$PbCO_3$	ktpa	94.4
Ag	tpa	104

3.1.3 BIOLEACHING

BOR concentrate was the bulk concentrate which was chosen as feed material for bioleaching final evaluation.

Concentrate feed remained at 910.000 tonnes per year.

The entire bioleaching process comprises a number of different stages. Bioleaching is the main one and it is followed by iron precipitation and copper and zinc recovery. Leaching takes place at 45°C in presence of moderate thermophilic bacteria.

Slurry from oxidation is neutralised to precipitate iron. The mixture of iron precipitate and gypsum is contacted with cation-exchange resin to desorb value-metals that co-precipitate with the iron/gypsum mixture.

Zinc and copper are stripped selectively from the resin with acidic solution. The zinc solution is neutralised with magnesium oxide (MgO) to produce a zinc hydroxide product.

The second eluate contains copper and is fed to copper electrowinning (EW) where copper cathode is produced.

Block diagram is shown in next figure:

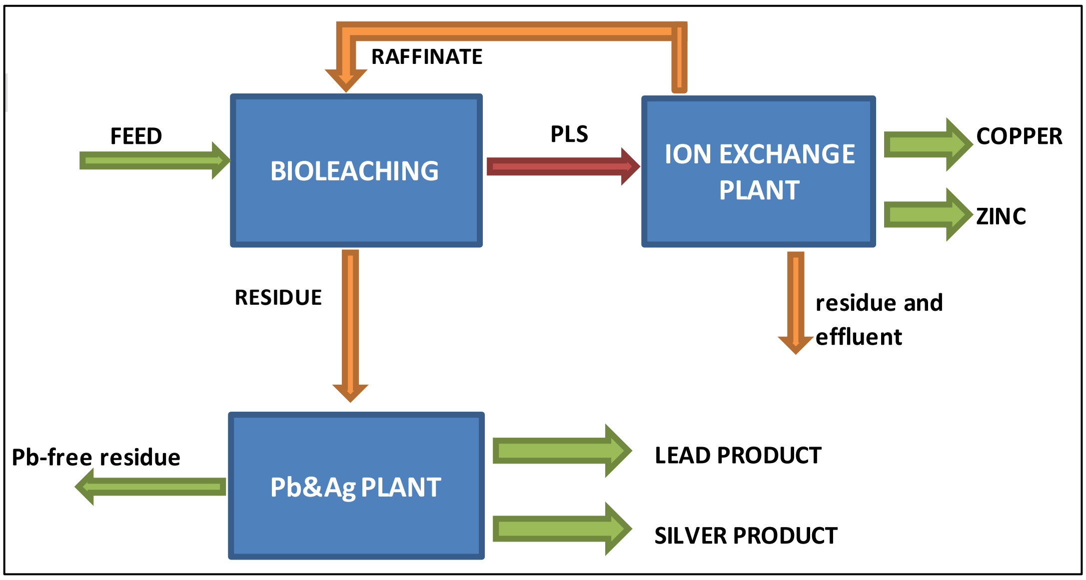

FIGURE 6. BIOLEACHING BLOCK DIAGRAM.

IDEAS process simulation software was used to model the complete bioleaching process. Further information of process streams was generated as output.

The mass and main elemental flows of main feeds and products are given in next table.

TABLE 4. BIOLEACHING MAIN MASS FLOW RATES.

Plant Capacity		
Ore	tph	104
	ktpa	911
Cu	ktpa	13
Zn	ktpa	28
$PbSO_4$	ktpa	55
Ag	tpa	75

3.2 ECONOMIC ASSESSMENT

Economical evaluation was made in terms of CAPEX and OPEX. Estimation of Capital Expenditure for the three different technologies was based on internal data bases and previous knowledge on similar projects. Equipment, bulk material, transport, installation, engineering services and first fill are included.

OPEX estimation was based on the following inputs:

- Estimation of unitary prices of reagents and utilities.
- Estimation of personnel requirements.

Technical assessment also included a profitability analysis in order to provide a more comprehensive economic evaluation. Internal rate of return (IRR), net present value (NPV) and payback were calculated for capital budgeting estimate.

Some assumptions were made:

- Ten years' service lifetime plant.
- Fixed metal prices were considered.
- Constant annual revenue and operational costs were established over time.

Final results from INTMET hydrometallurgical technologies under study revealed an internal rate of return, IRR, which varies from 14% to 27%, depending on metal production value. Net present value, NPV, ranges 125 million $ to 325 million $, depending on specific conditions.

Sensitivity analyses were also carried out in the economic study. These revealed the impact on the total result of changes in individual parameters and identified those input parameters with the greatest influence on the outcome. Metal prices, CAPEX and OPEX are the main parameters considered in the sensitive analysis. Outcomes are IRR and NPV. Sensitivity rate was fixed on ±25% for the analysis.

4. LIFE CYCLE ASSESSMENT

WP7 seeks to provide an overall assessment of the different technologies developed in the INTMET project from both economic and environmental perspectives. To do so, several objectives have been established, among which:

"To identify and quantify the environmental burden due to the considered technologies, with a direct comparison of their global environmental performance by means of a life-cycle-assessment approach."

To fulfill this latter objective, task 7.2 has been defined. This task aims at quantifying and analyzing the environmental performances of the process chains developed in the INTMET project, by use of Life Cycle Assessment (LCA).

LCA methodology

Life cycle assessment (LCA) can be defined as a methodology for assessing a product or a process potential environmental burden along its life cycle from a "cradle-to-grave" perspective i.e. from the raw materials extraction to the end-of-life.

A standard for carrying out LCA has been implemented by the International Organization for Standardization (ISO) through the ISO 14040 series. In addition to these standards, the International Reference Life Cycle Data System (ILCD) handbook (JRC, 2010) provides a detailed guidance on LCA.

Figure 7 describes the LCA framework, which includes four main steps:

- The **goal and scope definition** of the study comprising elements such as the decision context, the intended applications, the functional unit, the system boundaries, etc.
- The **Life cycle inventory (LCI)**, which is the most demanding part of the LCA study in terms of duration and resources as it consists in the collection of data about the inputs and outputs relative to the system under study.
- The **Life Cycle Impact Assessment (LCIA)**, which consists in the translation of the previously collected data inventory into impact calculations relative to different impact categories (e.g. climate change, ozone depletion, human toxicity, etc.)
- At last, comes the **interpretation phase** which "serves to steer the work towards improving the Life Cycle Inventory model to meet the needs derived from the study goal" to finally "derive robust conclusions and – often – recommendations." (JRC, 2010)

It is to be noted that performing an LCA is an iterative process that allows refining the LCA study through its different stages (e.g. revision of the goal and scope, improvement of data inventory quality etc.).

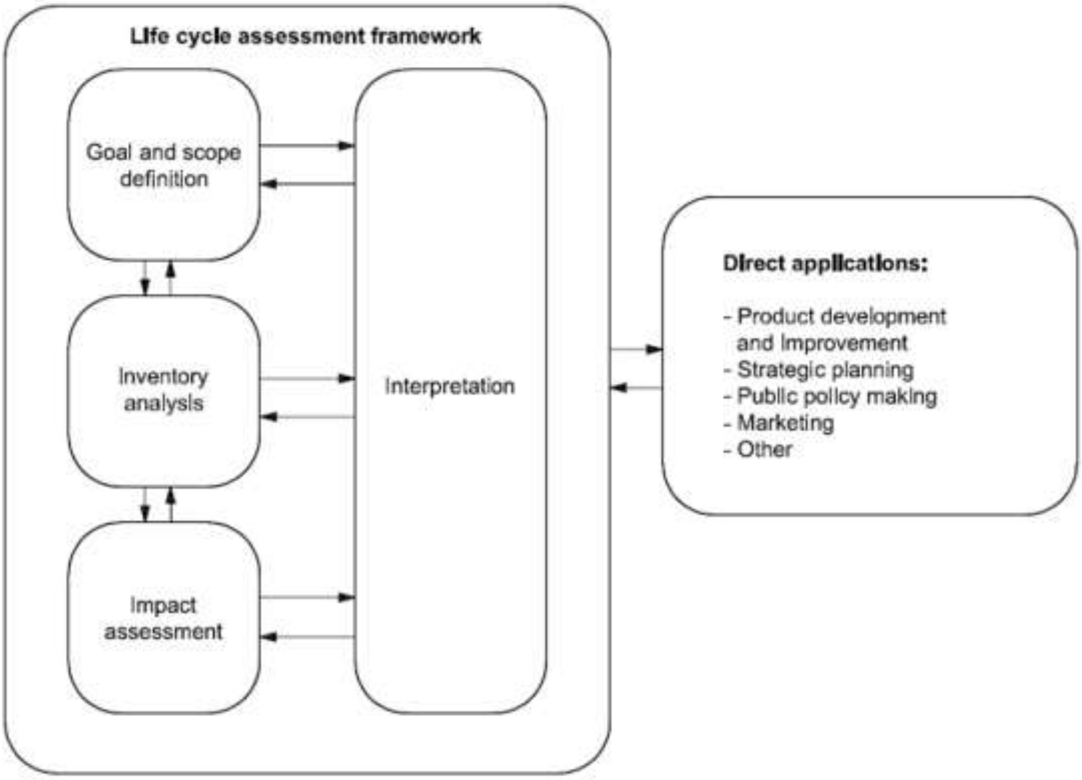

FIGURE 7. LIFE CYCLE ASSESSMENT FRAMEWORK (ISO, 2006A).

4.1 CASE STUDIES AND LCA MODELLING FRAMEWORK

In accordance with the piloting activities developed throughout the INTMET project, three LCA case studies have been defined:

- Atmospheric leaching applied to CLC (Cobre Las Cruces) materials;
- Bioleaching applied to BOR materials;
- Pressure leaching applied to SOMINCOR materials.

Details about these three case studies are provided in Table 5.

TABLE 5. DESCRIPTION OF THE THREE LCA CASE STUDIES

Technology	**Atmospheric leaching**	**Bioleaching**	**Pressure leaching**
Technology developer	Cobre Las Cruces (CLC)	Mintek	Outotec
Material feed	CLC ore	BOR concentrate	SOMINCOR concentrate
Metals recovered	Copper (Cu) Zinc (Zn) Silver (Ag) Lead (Pb)	Copper (Cu) Zinc (Zn) Silver (Ag) Lead (Pb)	Copper (Cu) Zinc (Zn) Lead (Pb)
Functional unit considered in the LCA[1]	The production of 1 t copper cathode along with 6 t zinc cathode, combined with the additional recovery of 2.65 t lead and 0.045 t silver	The production of 1 t copper along with 2.16 t zinc, combined with the additional recovery of 0.0076 t silver and 3.12 t lead	The production of 1 t copper cathode along with 3.71 t zinc and 5.71 t lead
System boundaries	Comminution Flotation Thickening Tailings disposal Atmospheric leaching Copper SX-EW Zinc SX-EW Pb/Ag leaching Silver cementation Lead precipitation	Regrinding Bioleaching Bulk Fe removal Resin adsorption Stripping Copper SX-EW Zinc precipitation Brine leaching – Silver recovery Lead recovery	Pressure leaching Neutralization Copper SX-EW Iron removal Zinc SX-EW Lead recovery
Foreground modelling	Pilot scale data from Cobre Las Cruces (CLC) and Tecnidas Reunidas (TR)	Pilot scale data from Mintek	Pilot scale data from Outotec
Background modelling	Ecoinvent v3.4 database		

The LCA modelling is performed by use of the Simapro v8.4 software, considering 9 midpoints environmental impact categories recommended by the ILCD guidelines (JRC, 2011):

- Climate change;
- Ozone depletion;
- Human toxicity, cancer effects;
- Human toxicity, non-cancer effects;
- Photochemical ozone formation;
- Acidification;
- Eutrophication, terrestrial;
- Eutrophication, aquatic;
- Ecotoxicity (freshwater).

4.2 IMPACTS ASSESSMENT AND IDENTIFICATION OF THE ENVIRONMENTAL HOTSPOTS

4.2.1 ATMOSPHERIC LEACHING: CLC ORE

The overall LCIA for the process chain developed by CLC (that is, including mineral processing, atmospheric leaching and further metals recovery) was performed, considering the contributions of the main process steps to the nine selected impact categories. In particular, “the production of 1 t copper cathode along with 6 t zinc cathode, combined with the additional recovery of 2.65 t lead and 0.045 t silver” generate 90,400 kg CO2-eq in a life cycle perspective (climate change indicator).

Among the different process steps considered in this assessment, four can be singled out as they significantly contribute to the environmental burden of CLC’s process chain:

- **Lead and silver recovery**
- **Tailings disposal**
- **Zinc recovery**
- **Atmospheric leaching**

In comparison with these four steps, copper recovery and mineral processing steps seem to have limited environmental impacts.

In order to potentially improve the “environmental performance” of the process chain (by implementation of an eco-design approach, as a subsequent step for instance), it is necessary to identify the main environmental hotspots, i.e. the input and output flows which are the most impacting from an environmental perspective. With regard to this process chain, the four main environmental hotspots are:

- The **electricity consumed** throughout the whole process chain;
- The **sodium hypochlorite (NaClO) consumed** in the Pb/Ag leaching step;
- The **oxygen consumed** in the atmospheric leaching step;
- The **potential metals emissions to ground and surface waters** that can happen as a consequence of tailings disposal (impoundment is assumed in this case).

4.2.2 BIOLEACHING: BOR CONCENTRATE

The overall LCIA for the process chain developed by Mintek & BOR (that is, including bioleaching and further metals recovery) was performed, considering the contributions of the main process steps to the nine selected impact categories. In particular, “the production of 1 t copper along with 2.16 t zinc, combined with the additional recovery of 0.0076 t silver and 3.12 t lead” generate 132,264 kg CO2-eq in a life cycle perspective (climate change indicator).

Overall, among the different process steps considered in this study, the **silver recovery** step stands out as it dominates all the impact categories in terms of contributions. In addition to silver recovery, the **bioleaching** step can also be singled out as it has the second highest contribution to all the impact categories excepting climate change. In comparison with silver recovery and bioleaching, the other steps (i.e. grinding, Fe removal, adsorption – elution, Cu SX-EW, zinc precipitation and lead recovery) seem to have limited environmental impacts. **Fe removal** appears to have the second contribution in terms of climate change, but its contribution to the other impact categories is rather limited.

In order to potentially improve the “environmental performance” of the process chain (by implementation of an eco-design approach, as a subsequent step for instance), it is necessary to identify the main environmental hotspots, i.e. the input and output flows which are the most impacting from an environmental perspective. With regard to this process chain, the four main environmental hotspots are:

- The **steam consumed** for recycling the hydrochloric acid (HCl) which is further reused for silver recovery;
- The **electricity consumed** throughout the whole process chain, in particular in the bioleaching step;
- The **sulfuric acid (H_2SO_4) consumed** for recycling the HCl (reused for silver recovery) and for the stripping step;
- The **calcium chloride ($CaCl_2$)** that is consumed for silver recovery.

4.2.3 PRESSURE LEACHING: SOMINCOR CONCENTRATE

The overall LCIA for the process chain developed by Outotec (that is, including pressure leaching and further metals recovery) was performed, considering the contributions of the main process steps to the nine selected impact categories. In particular, “the production of 1 t copper cathode along with 3.7 t zinc and 5.7 t lead” generates 76,865 kg CO2-eq in a life cycle perspective (climate change indicator).

Among the different process steps considered in this study, two appear to bear most of the environmental impacts: **lead recovery** and **pressure leaching**. In comparison, the **iron removal** and **zinc recovery** steps contribute to less than 15% for the majority of the impact categories. Finally, the **neutralization** and the **copper recovery** steps appear to have very limited environmental impacts, since their contribution to all the impact categories is below 5% (except for climate change to which the neutralization accounts for 18%).

In order to potentially improve the “environmental performance” of the process chain (by implementation of an eco-design approach, as a subsequent step for instance), it is necessary to identify the main environmental hotspots, i.e. the input and output flows which are the most impacting from an environmental perspective. With regard to this process chain, the four main environmental hotspots are:

- The **oxygen (O_2)** injected in the pressure leaching reactor for oxidation purpose of the input concentrate;
- The **carbon dioxide (CO_2)** used in the lead precipitation reactor during the lead recovery step;
- The **sulfuric acid (H_2SO_4) consumed** for stripping metals in the organic stream resulting from SX during the copper, zinc and lead recovery;
- The **electricity** that is consumed at each step of the process chain, and particularly for the copper recovery and the pressure leaching steps.

4.3 COMPARISON OF THE INTMET RESULTS WITH LITERATURE

To better picture the environmental impacts induced by the INTMET processes, a comparison with other existing metallurgical processes has been carried out. The comparison approach defined in the context of this study is i) solely focused on the copper production and exclusively considers the carbon footprint indicator (climate change indicator in this study); ii) to define a range of carbon footprint values associated with the production of 1 ton of copper through a scientific literature review, regardless of the production routes (hydro or pyrometallurgical routes); iii) to assess whether the carbon footprint associated with the production of 1 ton of copper through the INTMET processes stands within the range of values defined by literature review.

Given that the INTMET process chains are innovative and do not have any existing equivalents, in the sense that they aim at valorizing resources that could not be valorized through any other existing technologies, a direct comparison with other processes would not be relevant. Accordingly, this comparison approach does not aim at concluding about the environmental “benefits” or “deficits” brought by the INTMET processes in comparison with another existing technology, but rather assess whether the environmental impacts generated by the INTMET processes are in line or higher than a panel of existing technologies.

To define the range of carbon footprint values associated with the production of 1 ton of copper, a scientific literature review has been carried out considering 10 LCA studies regardless of the copper production route (Figure 8).

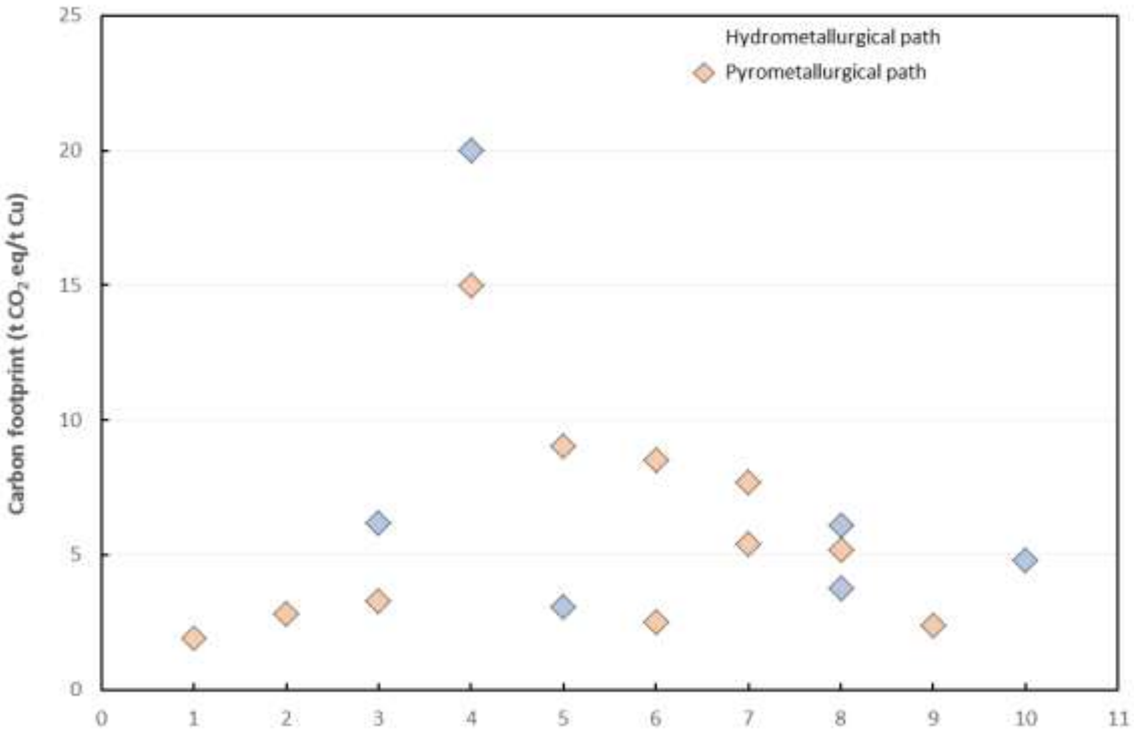

FIGURE 8. CARBON FOOTPRINT OF COPPER PRODUCTION IN LCA STUDIES.

The three process chains considered in this study are multi-output systems as they all yield multiple metals. Therefore, carrying out this comparison requires the apportionment of the environmental impacts between each output metals, so as to compare the impacts relative to 1 ton copper exclusively. In terms of life cycle assessment, different methods allow the apportionment of the environmental impacts between different co-products. In this study, a hybrid approach combining subdivision (recommended by the ISO, 2006b) and economic allocation, that is, allocating the impacts based on the economic value of the co-products (recommended when precious metals are included in the product system; Santero and Hendry, 2016), is implemented. It is to be noted that, although this hybrid method is recommended in the context of precious metals production, other methods are also applicable and can potentially lead to radically different results. Table 6 indicates the carbon footprint values, with respect to the INTMET process chains under study, allocated to the production of 1 ton copper cathode.

TABLE 6. CARBON FOOTPRINT OF 1 T CU PRODUCTION THROUGH THE INTMET PROCESS CHAINS

INTMET process chain	Carbon footprint for 1 ton copper cathode (t CO_2 eq/t Cu)
Atmospheric leaching – CLC ore	6.52
Bioleaching – BOR concentrate	17.3
Pressure leaching – SOMINCOR concentrate	12

Figure 9. CARBON FOOTPRINT OF 1 T CU PRODUCTION THROUGH THE INTMET PROCESS CHAINS COMPARED WITH THE RANGE OF VALUES DEFINED FROM LITERATURE.

compares the carbon footprint associated with the production of 1 ton copper cathode through the INTMET processes with the range of copper carbon footprint defined from the literature review. It is shown that the INTMET copper carbon footprint values stand within the range of values defined from the literature. One possible interpretation from this is that, with regard to copper production, the INTMET processes generate a carbon footprint that does not exceed that of other existing copper production processes.

As aforementioned, the INTMET technologies are innovative and do not have any existing equivalents, therefore no direct process comparison of the environmental burden would be relevant. Accordingly, this comparison does not allow to conclude about the environmental “benefits” brought by the INTMET technologies, it only provides first insights about the “environmental performance” of the latter technologies in the sense that it shows that they generate a copper carbon footprint relatively similar to that of other existing technologies.

However, it is to be noted that there remains room for improving this comparison. Indeed, one objective of the INTMET processes is to valorize the polymetallic features of the ores by recovering different metals such as zinc, lead, silver etc. in addition to copper. Therefore, the comparison, as carried out in this study, is relatively incomplete as it does not account for the impacts allocated to the other recovered metals. To increase the robustness of this comparison, the main areas of improvement would be to:

- Include the impacts associated with the recovery of the other metals through the INTMET processes;
- Perform a literature review of the impacts associated with the production of these other metals and refine the “range of values defined from literature”;
- Consider different impact categories in addition to carbon footprint (e.g. toxicity-related impact categories), as metals production can potentially be responsible for other environmental impacts than greenhouse gases emissions.

It should also be noted that Figure 9. CARBON FOOTPRINT OF 1 T CU PRODUCTION THROUGH THE INTMET PROCESS CHAINS COMPARED WITH THE RANGE OF VALUES DEFINED FROM LITERATURE.

3 does not aim at comparing the INTMET processes between them, as such comparison would not be relevant given that: i) each technology processes different materials (with different compositions and mineralurgies; ii) the system boundaries may differ depending on the case study (for instance, the CLC case study includes ore processing, while the other case studies do not).

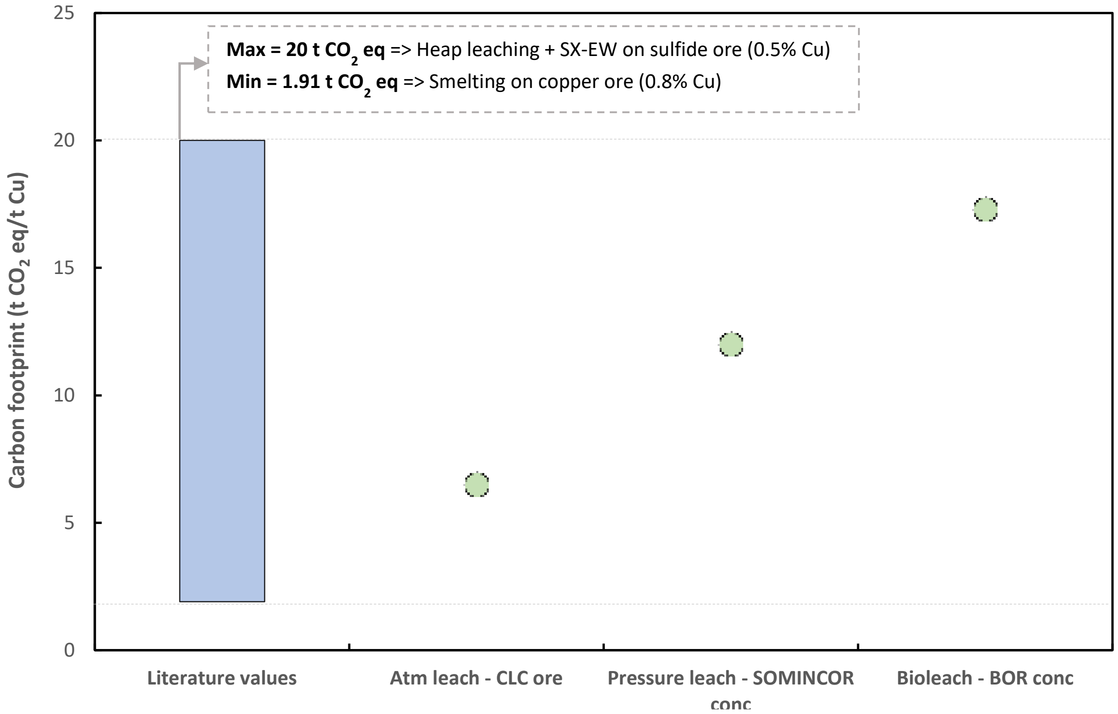

FIGURE 9. CARBON FOOTPRINT OF 1 T CU PRODUCTION THROUGH THE INTMET PROCESS CHAINS COMPARED WITH THE RANGE OF VALUES DEFINED FROM LITERATURE.

5. CONCLUSIONS

This report provides a complete technology assessment carried out with respect to the piloting activities developed throughout the INTMET project. Based on these piloting activities, three case studies have been defined: atmospheric leaching applied on CLC ore, bioleaching applied on BOR concentrate and pressure leaching applied on SOMINCOR concentrate.

The conceptual engineering and the techno-economic assessment of each one of the three technological approaches proposed in INTMET project has been developed after the extensive work performed in pilot plant operations of CLC bulk concentrate using ATM leaching, SOMINCOR bulk concentrate using Pressure leaching and BOR bulk concentrate using Bioleaching.

INTMET hydrometallurgical technologies are specifically designed to provide a suitable solution to every application. The developed technologies can deal efficiently with feed materials such as bulk concentrates and low-grade concentrates containing low tenor of base metals and precious metals, which cannot be processed in existing refineries. For instance, tested polymetallic concentrates samples ranged: 2%-5% Cu, 5%-15% Zn, 3%-10% Pb and 50 ppm-500 ppm Ag.

Developed INTMET hydrometallurgical technologies can be an advantageous alternative to conventional processing technologies, allowing:

- To increase 30% - 50% overall metals recovery in comparison to actual operations.
- To process low-grade and complex ores containing impurities such as Hg, Sb, As, etc.
- To produce in-situ refined metals.
- To recover additionally some critical materials as In or Co.
- To raise mineral reserves, reducing the cut-off.

In definitive, it allows to achieve a more robust and sustainable mining business.

Final economic assessment provides rather positive economic results. An hydrometallurgical plant treating from 0.6 to 1.0 million tonnes per year of bulk concentrate to produce 15 – 25 kt/y Cu metal, 40-60 kt/y Zn metal, 30-80 kt/y Pb metal and 50-100 t/y Ag: IRR varies from 14% to 27% depending on metal production value and NPV ranges 125 to 325 million USD, depending on specific conditions

In relation to the environmental assessment, the life cycle assessment (LCA) results allow the quantification and the analysis of the environmental impacts induced by the three process chains developed in the INTMET project. On the one hand, regarding the atmospheric leaching case study, the results show that most of the impacts are generated by the lead and silver recovery steps. Tailings disposal is also an important stage to take into account from the environmental protection point of view. Regarding the other impact categories, the consumption of reagents such as sodium hypochlorite (NaClO) for Pb/Ag leaching or oxygen for atmospheric leaching appears to be the main contributor to the impacts.

On the other hand, regarding the bioleaching case study, the LCIA results show that silver recovery is responsible for the largest share of environmental impacts considering all the impact categories under study. Steam consumption for recycling the hydrochloric acid (HCl) that is reused for silver recovery as well as the consumption of reagents such as sulfuric acid (H_2SO_4) for recycling the HCl or calcium chloride ($CaCl_2$) for silver recovery are identified as the main environmental hotspots through the contributions analysis.

As for the pressure leaching case study, the pressure leaching and the lead recovery steps appear to bear most of the environmental burden, in an equivalent manner, regarding all the impact catergories analyzed according to the LCIA results. In this case, the main environmental hotspots belong to the reagents and ancillary materials consumption. In particular: the oxygen (O_2) injected in the pressure leaching reactor for oxidation purpose of the input concentrate; the carbon dioxide (CO_2) used in the lead precipitation reactor during the lead recovery step; and the sulfuric acid (H_2SO_4) consumed for stripping metals in the organic stream resulting from SX during the copper, zinc and lead recovery.

To put these LCA results into perspective, a comparison with literature has been carried out focusing on the copper carbon footprint. To do so, the carbon footprint associated with the production of 1 ton copper cathode through the INTMET processes have been compared to a range of copper carbon footprint values defined from the literature review. The results show that, with regard to copper production, the INTMET processes induce a carbon footprint comparable to that of other existing production routes.

In conclusion, this LCA study offers perspectives for subsequently eco-designing the INTMET processes that are foreseen to be implemented at an industrial scale, in the sense that it identifies the main environmental hotspots on which the effort would need to be focused so as to reduce their environmental burden.

6. REFERENCES

AACE International Recommended Practice No. 18R-97. Cost estimate classification system – as applied in engineering, procurement, and construction for the process industries. TCM Framework: 7.3 – Cost Estimating and Budgeting. Rev. March 1, 2016

Norman L. Weiss, 1985. SME Mineral Processing Handbook. Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineering.

Deepak Malhotra, 2009. Recent Advances in Mineral Processing Plant Design. Society for Mining, Metallurgy, and Exploration.

Jan Harmsen. Industrial Process Scale-up, 2nd Edition. A Practical Innovation Guide from Idea to Commercial Implementation. Elsevier.

The chemical engineering plant cost index: https://www.chemengonline.com/pci-home

The London Metal Exchange: https://www.lme.com/

Infomine: http://www.infomine.com/

ISO, 2006a. 14040: Environmental management – Life Cycle Assessment – Principles and framework. International Organization for Standardization.

ISO, 2006b. 14044: Environmental management – Life Cycle Assessment – Requirements and guidelines. International Organization for Standardization.

JRC, 2010. Institute for Environment and Sustainability. Joint Research Centre. European Commission. International Reference Life Cycle Data System Handbook.

JRC, 2011. Recommendations for Life Cycle Impact Assessment in the European context -based on existing environmental impact assessment models and factors. EUR 24571 EN – 2011.

Santero, N., Hendry, J., 2016. Harmonization of LCA methodologies for the metal and mining industry. Int. J. Life Cycle Assess. 21, 1543–1553. https://doi.org/10.1007/s11367-015-1022-4